SITE C CLEAN ENERGY PROJECT

Geotechnical Safety Overview Report

February 2021

Executive Summary

BC Hydro conducted extensive engineering studies into the geology of the Site C project area – including the dam site – for decades prior to beginning construction in 2015. These investigations and knowledge of geological features influenced the location and orientation of the project's powerhouse and spillway, as well as the inclusion of a large concrete buttress to enhance the stability of the permanent structures on the project's right bank.

By January 2020, ongoing investigations and analysis of geological mapping and monitoring activities completed during Site C project construction identified that foundation enhancements would be required to increase the stability below the powerhouse, spillways and future dam core areas. By March 2020, BC Hydro, in agreement with the Site C Technical Advisory Board, determined that significant foundation enhancements were required and the cost of those enhancements would be significantly higher than previously expected in 2018.

Throughout the rest of 2020, BC Hydro worked to select and refine the design of the enhancement measures and sought external validation from the Technical Advisory Board and international dam experts to confirm the solution was appropriate and safe.

In fall 2020, BC Hydro identified a two-part solution to improve the stability of the right bank structures. These enhancements will extend the concrete foundation deeper into the bedrock and reduce the water pressures that can build up in the bedrock foundation.

The Site C Technical Advisory Board, which is a global panel of engineering and construction experts, completed a summary assessment of the proposed measures to improve the stability.

Given the scope, cost and schedule implications of the proposed measures, the Site C Project Assurance Board commissioned a further due-diligence review to assist it in its evaluation of the technical integrity of the proposed mitigation measures and to ensure they meet the Canadian Dam Association dam safety guidelines. A third report was also commissioned to review the design of the earthfill dam.

The three independent safety reports identified above are attached as Appendices A, B and C.

Collectively, the reports conclude that:

- the right bank foundation enhancement solutions are appropriate and sound, and will make the right bank structures safe and serviceable over the long operating life of Site C; and
- the Site C earthfill dam can safely be constructed, meeting all Canadian Dam Association dam safety and reliability guidelines.

In the coming months, BC Hydro will continue to advance the right bank foundation enhancement measures to allow the optimization of the design. Optimization is the process to finalize the engineering calculations and determine the final arrangement and specifications for the enhancements.

Work to implement these measures could begin as early as summer 2021 and will be completed by the end of 2023, along with other project activities.

Introduction

Site C will be the third dam and hydroelectric generating station on the Peace River in northeastern British Columbia. Once complete, Site C will provide 1,100 megawatts of capacity, and produce about 5,100 gigawatt hours of energy per year – enough to power the equivalent of 450,000 homes per year in B.C.

Construction on the project began in 2015 and work is now over 50 per cent complete.

This paper provides an overview of the geotechnical investigations that have been completed to date for the Site C project, including the challenges that were encountered on the right bank foundation. The paper also outlines the work to develop an engineering solution that is sound and safe, and summarizes the finding of the three independent technical safety reports that were commissioned to review the Project.

Brief history of the project

BC Hydro completed the W.A.C. Bennett Dam and the G.M. Shrum generating station in 1968 and the Peace Canyon Dam and generating station in 1980. From 1973 onward, investigations continued along the Peace River for the location of a third dam in the Fort St. John area. The present Site C location, seven kilometres south east of Fort St. John, was determined to be topographically and geologically preferable.

In 1978, preliminary design work was undertaken, which confirmed that the current Site C location was the best option. The design work completed at that time was based on an earthfill dam, as a concrete gravity dam was not feasible based on the type and strength of the foundation bedrock.

Site investigation history and project design

The current Site C project was approved in 2014. Site investigations carried out from 1975 to 2014 informed the location and design of the project.

At the time of project approval in 2014, the site investigations were considered state of the art and extensive.

As expected and confirmed in the earliest geological investigations beginning in the 1970s, the shale bedrock in the foundation at Site C contained bedding planes, which are the surfaces that separate two layers of rock. The presence of deep bedding planes within the foundation under the right bank powerhouse and spillway structures, and the potential for displacements along the deeper bedding planes, were identified during the design phase of the project from the 1970s onward.

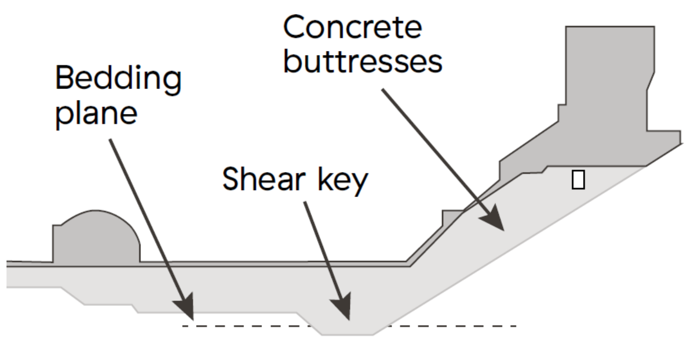
Originally, three alternative designs for earthfill dams were studied, all of which incorporated a spillway on the right bank terrace. The option of locating the power intakes adjacent to the spillway headworks on the right bank terrace and the powerhouse in the river channel next to the right bank was selected for further study.

When the project was deferred in 1983, there were unresolved issues with this design, particularly the potential for differential rebound of the foundation to negatively impact the concrete structures on the right bank.

In 2009, BC Hydro concluded that the historic design for Site C required optimization to meet current seismic, safety and environmental guidelines.

In 2011, BC Hydro updated the design of the Site C dam to rotate the spillway and generating station to extend at a right angle to the dam, parallel to the valley wall on the south bank, and include a large concrete buttress under these structures.

This concrete buttress, which is 800 metres long and up to 35 metres thick, and consists of about 1.7 million cubic metres of roller-compacted concrete, is located overtop of the bedrock. The concrete buttress is secured into the bedrock foundations using a ‘shear key,’ which extends the bottom of the concrete structure deeper into the foundation. The shear key also cuts through an underlying bedding plane, further enhancing the stability of the buttress, as seen in the diagram below.



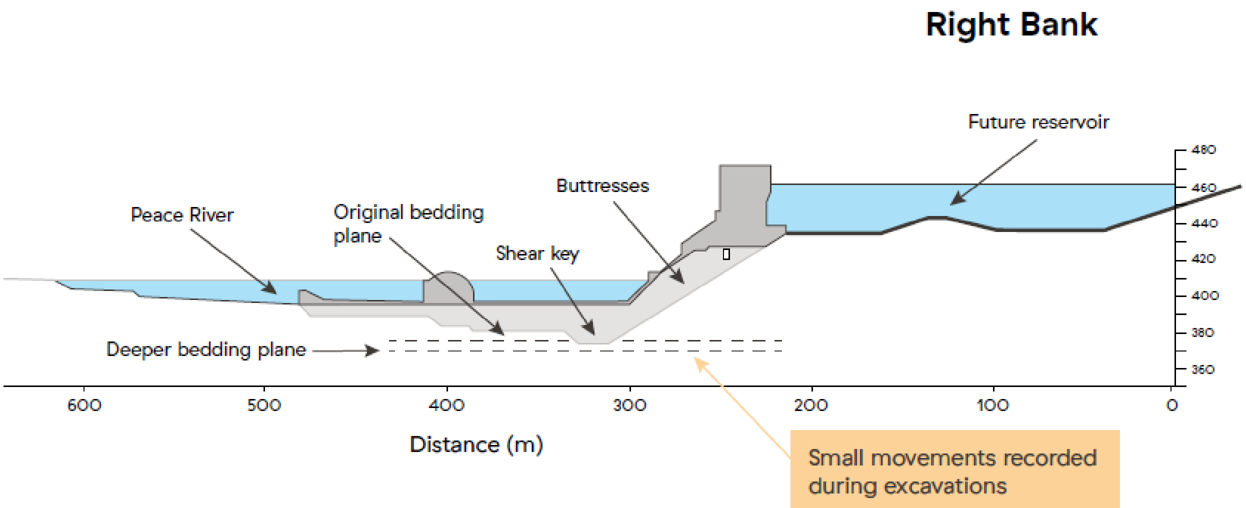
The original design for the Site C buttress extended the shear key about 35 metres below the bottom of the existing river channel and through what was, at the time, the deepest-known continuous bedding plane.

This updated project design met seismic guidelines and could withstand a significantly larger earthquake than the previous historic design. This project design met the highest recommendations of the Canadian Dam Association and had input and feedback from engineers who are globally recognized for their technical knowledge and experience with hydroelectric projects around the world.

Mapping and instrumentation monitoring activities: 2015 to present
Prior to the start of construction in July 2015 and during the design phase of Site C, geotechnical risks were identified for the Site C project indicating, among other risks, that there was the potential of instability of the bedrock foundation under the right bank structures – the powerhouse and the spillways.

In accordance with best engineering practice, geological mapping has been carried out throughout construction to fully verify the geological model and the project design, and instrumentation was installed to monitor the behaviour of the rock mass during construction.

In 2018, during the excavation for the spillway buttress, small movements (millimetres) began to occur on a bedding plane below the bedding plane through which the shear key intersects. These small displacements indicated that the shear strength along bedding planes deeper than the shear key bedding plane may be lower than what was initially assumed in the design basis. These small displacements, other instrument data, and the results of geological mapping led to a re-assessment of the expected strength of the bedrock at this depth.



The re-assessment took place during 2018 and 2019. It involved analysis of the interlock of the foundation, strength of the bedding planes below the base of the buttresses and other aspects of the foundation rock, as well as the expected water pressures in the foundations resulting from the future reservoir. The focus was to gather and assess additional information on the foundation and determine whether other aspects of the bedrock foundation that contribute to its overall stability would at least partially compensate for the lower strength of the bedding plane below the base of the buttress.

Had the re-assessment shown that the stability models could be updated on this basis, then any required mitigation would have been relatively modest (e.g. drainage and grouting changes to reduce water pressure acting on the structures).

However; further analyses and additional data indicated that these other aspects of the foundation did not provide enough resistance to compensate for the lower strength of the bedding plane. By January 2020, BC Hydro had concluded that more significant foundation enhancements would be required and communicated the findings to the Project Assurance Board. At that time, neither the preferred solution nor the magnitude of the forecast costs for the remediation were known, and the potential forecast costs progressively increased after the initial concepts were developed and evaluated.

Identifying the enhancement solutions

In early 2020, the Site C project design team was augmented with additional external experts to develop potential mitigation measures and confirm the preferred solution using detailed analyses and conservative parameters.

By the spring, several stabilizing measures were evaluated in a structured process that gathered input from the project's design, dam safety, environment, construction, estimating, and finance teams. In addition to increased drainage across the right bank, the two favoured solutions that emerged were large diameter concrete-filled steel pipe piles and concrete shear walls.

Through summer 2020, recommended conceptual designs were developed for the approach channel, spillway buttress and powerhouse buttress. A preferred solution was identified in fall 2020. At that time, the Technical Advisory Board and Project Assurance Board both supported and approved the recommended mitigation measures put forward by BC Hydro.

The results of recent fieldwork provide further confidence that the proposed foundation enhancement solution is robust, is in accordance with the guidelines of the Canadian Dam Association and international best practice, and can be further optimized in the final design stage.

Providing for a safe fix

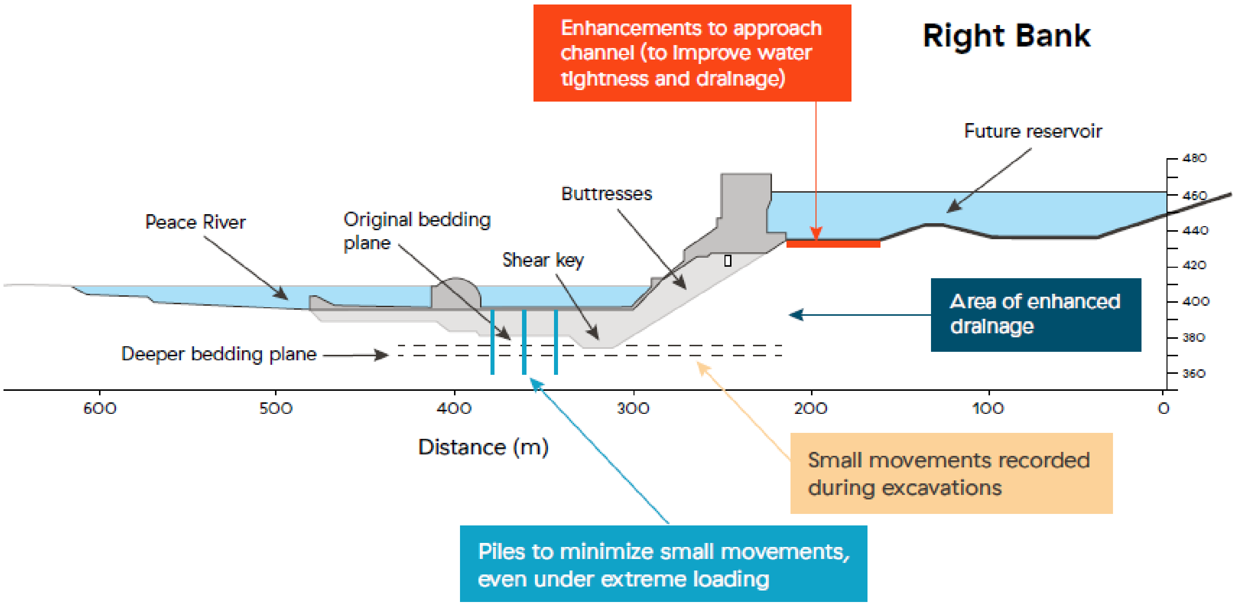
BC Hydro has identified a two-part solution to improve the stability of the right bank structures: extend the foundation deeper into the rock; and further reduce the water pressures that can build up in the bedrock foundation.

The solution addresses the as-found geological conditions under the powerhouse and spillways and will provide a reliable solution for the stability and long-term operation of the project.

The first part of the solution is to improve the strength of the concrete buttresses beneath the right bank structures by anchoring the buttresses deeper into the rock below.

Vertical steel and concrete piles will extend the function of the shear key by drilling through the deeper bedding plane into the stronger rock below it. There will be up to 125 piles installed, each up to 2.5 metres in diameter, that will extend the foundation a further 15 to 25 metres into the bedrock. The design of the piles system extends the foundation to a depth where undetected weak bedding planes can't affect the stability and long-term performance of the structure.

The second part of the solution is to further improve the water tightness of the approach channel and increase drainage within the rock behind the buttresses. The approach channel directs water around the earthfill dam and into the generating station. BC Hydro will enhance the approach channel liner and increase drainage to reduce water from seeping into the foundation when the reservoir is filled.



External safety reports

The first review of the right bank foundation enhancements was a summary assessment from the Site C Technical Advisory Board, which is a global panel of third-party engineering experts reporting to the Project Assurance Board. The Technical Advisory Board provides arms-length technical review of all aspects of the project, including the development of the right bank foundation enhancement measures.

Given the scope, cost and schedule implications of the proposed measures, the Site C Project Assurance Board commissioned a further due-diligence review to assist it in its evaluation of the technical integrity of the proposed mitigation measures and to ensure they meet the Canadian Dam Association dam safety guidelines. A third report was also commissioned to review the design of the earthfill dam.

This additional review of the right bank foundation enhancements was undertaken by two internationally recognized dam experts appointed by the Project Assurance Board: John France and Dr. Kaare Höeg. They were specifically chosen because they are both recognized globally for their expertise in hydroelectric dams and because neither had any involvement with the Site C project to date.

Mr. France has more than 41 years of experience in engineering consulting and design and most of his technical work for the past 33 years has focused on dams and water retention structures. Recently, he chaired the investigation into the Oroville dam spillway failure.

Dr. Höeg is Professor Emeritus in the Department of Geosciences at the University of Oslo in Norway. He was President of the International Commission on Large Dams between 1997 and 2000 and has been an expert consultant for many dam engineering projects in Norway and around the world.

Finally, the Project Assurance Board commissioned Mr. France and Dr. Höeg to complete a second report, as their original assignment did not include a review of the Site C earthfill dam design and construction.

All three reports have now been received by the Site C Project Assurance Board and Province of British Columbia.

Synopsis of each safety report

Technical Advisory Board: Summary Statement on Safety of Dam Structures

The Project Assurance Board requested a summary assessment from the Technical Advisory Board related to its confidence in the design of the Site C dam structures, particularly with respect to safety and the adoption of best practices. The summary assessment was requested to assist the Project Assurance Board in its evaluation of the technical integrity of the foundation enhancement solution.

The Technical Advisory Board concludes that "the requirements for safe design have been honoured as an over-arching principle in all phases of the project, from initial feasibility to current construction" and that BC Hydro "has identified and evaluated appropriate changes to the design for the RCC buttress foundations."

Note: See Appendix A for full Summary Statement on Safety of Dam Structures.

Site C Technical Review Panel Report #1: Foundation Enhancement Report

Mr. France and Dr. Höeg were tasked with reviewing the following aspects of the work being completed by the project team:

- The characterization of the rock and the properties of the rock mass, bedding planes and shears.
- The design of the seepage control measures in and under the approach channel;
- The water loads assumed in the rock given the seepage control measures;
- The multiple accounts evaluation leading to the selection of piles as the preferred enhancements;
- The results of the field trials to determine the lateral pile load/deflection characteristics;
- The methods of analysis being used to estimate the behaviour of the completed works on the right bank;
- The acceptance criteria proposed for normal and extreme loads, including target factor of safety and displacement thresholds;
- The methods used to translate the results of the geotechnical analyses to the structural requirements for the piles; and
- The process to be used for optimization of the number, size, and spacing of the piles and the resulting optimized configuration.

Mr. France and Dr. Höeg conclude "the proposed approach is sound and capable of making the right bank structures both safe and serviceable," provided several details are addressed in the analysis and design. These details are currently being addressed by BC Hydro as the design progresses to implementation.

In addition, Mr. France and Dr. Höeg state they are “not aware of any other structural foundation enhancement alternatives that could have been considered.”

Note: See Appendix B for Site C Technical Review Panel Report #1.

Site C Technical Review Panel Report #2: Earthfill Dam Report

Mr. France and Dr. Höeg’s second report was on the earthfill dam design and construction.

Mr. France and Dr. Höeg write that, based on the studies that have been completed to date, they are “confident that a safe earthfill dam structure can be constructed at Site C meeting the Canadian Dam Association dam safety guidelines.” In addition, they state that the earthfill dam type is a particularly appropriate choice for the foundation conditions at Site C, because it provides a greater ability to accommodate the type of foundation bedding planes located at the dam site, and its design is tolerant of movement.

Mr. France and Dr. Höeg acknowledge there is some uncertainty about the foundation conditions for the earthfill dam as that area has yet to be excavated, mapped, and grouted. Despite this, they conclude that the available geotechnical and geological information is satisfactory to characterize the foundation conditions under the earthfill dam, and BC Hydro’s planned instrumentation program is reasonable and appropriate for monitoring and responding to construction-generated pore water pressures and movements to ensure adequate stability and safety can be maintained.

Note: See Appendix C for Site C Technical Review Panel Report #2.

Next steps

In the coming months, BC Hydro will advance the right bank foundation enhancement measures to final design, to allow detailed cost estimating and scheduling to be carried out. Once available, detailed cost and schedule information will be used to assess alternate commercial strategies for the delivery of the work, and construction will commence.

The right bank foundation enhancement costs are included in the current updated Site C cost estimate.

Within the spillway, piling could commence as early as the summer. At the powerhouse, work will start with an excavation within the powerhouse tailrace prior to the start of piling, as early as the fall of 2021.

Within the approach channel, excavation of overburden and bedrock is continuing. Once excavation is completed, the foundation of the channel will be prepared prior to the commencement of lining, grouting and the installation of drain holes.

The right bank foundation enhancement work will be completed at the same time as other project work and is not anticipated to have any further impacts on the project schedule.
BC Hydro expects to complete this work by the end of 2023. The cost of the right bank foundation enhancement work is also included within the current Site C cost estimate.

Site C Clean Energy Project

Technical Advisory Board

Summary Statement on Safety of Dam Structures

January 22, 2021

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1. Introduction

The design of the Site C Project was conceived on the basis of satisfying all Canadian Dam Association (CDA) guidelines for ensuring the safety of such structures. This was supplemented by worldwide expertise and the experience that BC Hydro together with its engineering consultants has in designing, building and operating such structures. Parameters were developed for Site C that assured CDA compliance would be met, and these were incorporated in a Design Basis Memorandum (DBM), which has been followed as the project developed.

The Project Assurance Board has requested a summary assessment from the Technical Advisory Board (TAB) related to their confidence in the design of the dam structures associated with the Site C Project, particularly with respect to safety and the adoption of best practices. The context of the request is to assist the Project Assurance Board in the evaluation of the technical integrity of the Project as it proceeds to finalize the foundation enhancements that have been found necessary in the right bank of the main dam.

The summary assessment has been developed in response to five questions which are addressed sequentially below.

2. Questions

1. ***Were the analysis and investigations that formed the basis of the design at the time of the authorization for construction of the Project appropriate and in accordance with best practices?***

Investigations for the Site C Project began in 1973. In 1978, it was confirmed that the current site was preferable. The current project was approved in 2014. The specific site investigations that began in 1975 and continued to project approval are listed in Appendix A.

In accordance with best practices:

i. BC Hydro is an experienced dam owner/operator and together with its engineering consultants had intimate knowledge of the geological challenges associated with dam construction at Site C. This arose from their experience elsewhere along the Peace River, an awareness of how severe geotechnical considerations prevail eastward in Alberta and Saskatchewan, and a detailed appreciation of the valley rebound geomechanics that created the complex conditions that had to be addressed.

ii. BC Hydro retained independent Technical Advisory Boards for the period 1978-1989 when feasibility of the Base Case design was evolving and thereafter from 2010 to date when the project was renewed and progressed through final design into construction. This is an established practice for major hydroelectric projects and allows for leading international experience to be introduced into the planning, design and construction.

iii. BC Hydro and the Engineering Design Team (EDT) retained individual Subject Matter Experts (SME) as appropriate for additional advice throughout the process.

iv. Notwithstanding the comprehensive investigations carried out in the 1970s, additional investigations were initiated in 2008 which concluded that the geological/geotechnical model that had been developed and the associated Base Case design remained valid. This involved diversion tunnels within the left bank of the river valley, an embankment fill dam across the valley, and the powerhouse/spillway structure at the right bank of the valley.

In 2010 the EDT undertook an optimization to compare alternate arrangements to either validate the Base Case or modify it before proceeding to final design. This was an important step in the evolution of the design, and the TAB recommended that a formal structured decision-making process be adopted. It was heavily weighted to minimize geotechnical risk. The earthfill dam with the RCC buttress was confirmed as the preferred general arrangement and this conclusion was supported by the SMEs and the TAB.

At the time of the implementation design in 2014, the deepest bedding plane shear that was identified as potentially impacting the stability of the right bank structure was bedding plane BP 33 at El. 378 m. Hence the foundation of the RCC buttress was set at El. 375 m, 3 m below BP 33. An assessment of a bedding plane shear below this level was also undertaken. However, the assumed resistance for this feature did not indicate a concern with respect to satisfying safety design criteria.

Finally, the need for adoption of the Observational Method was recognized and implemented as an integral part of assessing safe design, construction and long-term performance.

In the view of the TAB, the evolution of the design to the time of authorization, both consistently and diligently, was in accordance with best practices.

2. Were the practices being used during construction of the Project to confirm foundation conditions in accordance with best practices?

The final design adopted for construction employed an RCC buttress on the right bank primarily because this configuration was assessed to be optimal among the alternative choices to manage the geotechnical challenges associated with constructing on or adjacent to the right bank. Nevertheless, uncertainties existed, and they were recognized.

Best practices in the face of geotechnical uncertainties is to employ the Observational Method (OM). This relies on comprehensive instrumentation to validate that the ground response is performing in a manner consistent with the design intent. To be effective, it also assesses the practicality of invoking mitigative measures if observations and related analyses reveal that they are necessary. The OM to be adopted at Site C is documented in detail in the project records (see Appendix B). It relies on both skillful installation of the appropriate instruments and diligent interpretation. It also relies on validation of the geological model by observations and mapping to confirm that conditions being encountered are as anticipated or whether design modifications are required. BC Hydro has considerable experience with the application of the OM and it was implemented in an effective manner.

Considerable monitoring of the RCC buttress excavation and construction was intended to be executed from the Right Bank Drainage Tunnel (RBDT) prior to the start of the RCC excavation. The construction of the RBDT did not occur in a timely manner, which resulted in an incomplete history of the response of the rock during the excavation of the powerhouse buttress foundation. This was ultimately addressed by instrumentation and drainage measures installed from the surface. As anticipated, excavation-induced movements were observed but none were regarded as sufficiently consequential to affect the design.

In concert with these observations, detailed geological mapping was conducted and compiled in state-of-the-art software that integrated all geological information obtained on site in a three-dimensional framework. This attention to detail, which is invaluable, provides another example of best practices employed at Site C.

Following the recorded movement history associated with the powerhouse excavation and RCC placement, the instrumentation to monitor the spillway excavation was revised and inclinometers that monitor bedding plane slip were installed to depths below El. 375 m, the bottom of the RCC foundation. While potential slip at greater depths had been considered in the design, the resistance along these deeper bedding planes was assessed to be too high to make them critical to the design.

As excavation continued for the spillway, small movements, about 5 mm, developed at El. 372 m at a location now referred to as BP 33e. In many projects, monitoring to this accuracy either would not be undertaken or would not be reliable, and such small movements would not be regarded as consequential. A measure of the best practices executed at Site C is the reliability of the data and the commitment to interpret all data that informs matters of safety.

This latter commitment, making use of numerical modelling techniques that have only become practical and reliable in recent years, revealed that the frictional resistance was significantly less than presumed values adopted in the design for bedding planes. These low values were consistent with lower bound values determined from laboratory tests. When used in design, the factors of safety associated with extreme load cases, as specified for the project, appeared to be no longer satisfied, prompting a comprehensive study of foundation enhancements to assure dam safety.

The application of the OM produced results as intended in an expedient manner. It is the view of the TAB that without the commitment to best practices, reliable monitoring of the small displacements of concern could not be assured and the related interpretation may have been highly uncertain. The OM in practice relies on a contingency design to be implemented in the event conditions are worse than anticipated and observed. In this case, the contingency case for bedding plane slip at depths below El. 372 m adopted a frictional resistance of 16º. Neither the EDT nor the TAB anticipated that these apparently tight features would mobilize a resistance of ≈11º, near the lower limit encountered in laboratory testing. It could be surmised that had they done so, the mitigation design might have involved foundation enhancements similar to those currently under consideration.

3. Has the project team evaluated and identified the appropriate changes to the design for the RCC buttress foundation?

The project team has identified and evaluated appropriate changes to the design for the RCC buttress foundations. This was accomplished by utilizing field geologic information, evaluating field instrumented data and engaging in a detailed and intensive program of “state-of-the-art” structural analysis based upon the information gained from the detailed geologic, hydro-geologic and structural engineering.

Findings in the right bank arising from the geological / geostructural synthesis have raised concerns with respect to satisfying some of the original Design Basis Memorandum (DBM) requirements. The assessment of these concerns has progressed along a path that originally considered that factors of safety associated with extreme loading cases would not be satisfied. This is no longer the case since newly obtained data on rock strength and stiffness at depth support the view of the TAB that such factors of safety can be satisfied. However, the reassessment of the design has recognized the need to provide measures that would reduce deformations of the supported rock to the degree practical and this is now the primary focus of the foundation enhancements. This will prevent the evolution of loading conditions associated with substantial rock weakening that were not specifically foreseen in the original DBM with the data available at that time for analysis. In addition, extra foundation enhancements provide the robustness and resilience to respond to residual uncertainties that might exist. The TAB and the Engineering Design Team (EDT) engaged in extensive discussions evaluating the new information, the logic of past design assumptions, particularly for the extreme case, the appropriate analyses to be used going forward to analyze the situation in more detail, and a schedule to develop executable enhancement measures.

As a result of recent information and understanding of the foundation conditions within the right bank, the EDT had investigated several foundation enhancements options to increase the stability of the right bank powerhouse and spillways buttresses. Systems containing shear walls, large diameter piles, prestressed anchors, and concrete filled tunnels were considered.

Since it was and is a very complex condition to analyze both geologically and structurally, an evaluation was conducted using a Multiple Accounts Analysis (MAA). This process helps establish an optimal solution to meet the project objectives; dam safety, regulatory, and engineer-of-record requirements; and achieve owner and operator acceptance. The optimal solution considers construction safety, environmental issues, the long-term quality of the project infrastructure, technical risk, constructability, operability, schedule and cost.

The MAA is effective in integrating multiple points of view, with flexibility in efficiently doing sensitivity studies by modifying the weightings if there is interest in assessing the robustness of the conclusions. It also provides a valuable record of the decision-making process.

The MAA was conducted on both the powerhouse and spillway buttresses and considered several options to increase the stability of the structures. Various options were considered to reduce the driving forces, such as controlling the water load on the structures by introducing drainage facilities and others introduced restraining forces such as anchors and tendons. Still others considered structural foundation features developed within the structures and anchored within the rock foundations, such as shear walls and large diameter piles.

4. Does the design of the Project, including processes followed during construction, incorporate principles of a safe design?

The Site C Project does incorporate safe design as well as construction processes and principles for safe development of a large hydroelectric project. As described in the response to Question 1 above, the best practices have incorporated BC Hydro’s and its consulting design team’s experiences as well as the advice of several independent and world-wide technical experts. Various alternative project arrangements were evaluated in favor of a more robust and safe design, as well as construction. The safe design principles have been practiced throughout the project, beginning with geotechnical studies in the 1970s and continue through to today, where numerous good practices, like the Observational Method of monitoring the performance of structures during construction, perform a safety function. In other areas, geologic studies and mapping of foundations are conducted to verify anticipated properties and thus safe and efficient designs. The geologic maps and geotechnical studies that are developed during construction not only facilitate and guide competent designs and construction but also form a record for both construction and future reference, should it be necessary.

In addition, the TAB anticipates that the operations manual will ensure that all elements of the facility that are critical for safety will continue to perform as intended.

Methods used in developing safe hydraulic structures at Site C utilize both numerical as well as physical modelling for design of hydraulic structures. The hydraulic structures are major structures and demand special attention for safe and efficient functioning. Major hydraulic structures like the spillways, gates and penstocks are designed to withstand extreme events like floods and earthquakes and must be designed to safely handle these events while also being constructible.

A significant feature of the safety in design is developing and adhering to design criteria developed for the project. This establishes the criteria required by BC Hydro to ensure overall safety and the commitment by the EDT to meet them. Specific criteria are established and factors of safety, which reflect the reserve resistance of the structures against failure, are defined. Different load cases are also specified that must be investigated. The criteria and load cases are consistent with international practice and the practice recommended by the Canadian Dam Association. In addition to meeting the target factors of safety, the current design also recognizes the need to satisfy the limiting deformation criteria. The TAB expects that BC Hydro's existing dam safety program will embrace the long-term assurance of safe performance through its operations manuals and other aspects of its safety program.

Analyses have shown that the biggest factor contributing to the potential instability of the spillway and powerhouse RCC buttresses is water loading within the right bank hillside. A recent hydrogeologic study was conducted to determine and evaluate the in-situ permeability of the various rocks in the right bank. This concern and ability for rock formations to conduct water, both laterally and vertically within the formations, was recognized in the tender design with the provision of a Right Bank Drainage Tunnel and by minimizing the potential for water ingress into the hillside from above by water-proofing the approach channel above the slope. However, the behaviour of the hillside upon excavation has shown an extended potential for relaxation movement and cracking, possibly extending into the approach channel. This has necessitated the robustness of channel waterproofing arrangements to be reviewed as well as the means of generally ensuring the drainage of the hillside. Maximum reliability is essential to achieve the controlling loading requirements in the design. Various arrangements are now being developed and evaluated by the Engineering Design Team (EDT), all of which the TAB supports in principle, with some comments on matters of detail. A detailed Failure Mode Analysis (FMA) is presently being conducted to evaluate all aspects of the approach channel watertightness and robustness.

The evolution of the selected design strategies is documented in a report on the structured decision-making analyses based on the Multiple Account Analysis methodology. In this procedure, a distinction is made between “musts” and “wants”. Not violating the design criteria, as reflected by the DBM, is categorized as a “must”. With respect to the approach channel, the current FMA also emphasizes the need to minimize risk through adoption of the As Low As Reasonably Practicable (ALARP) considerations.

The development of good and safe practices both during design and during construction is founded in the following elements and principles in order of importance, namely Safety, Quality, Schedule and Budget. Safety is a “must” principle and must be adhered to and practiced, ensuring the safety of all involved in the project. Quality during design, as well as quality of the constructed project, is also a “must” element and feature, since the completed project is a minimum 100-year commitment to the Owner. Quality is an element that ensures both safety in design as well in construction. The elements of Schedule and Budget are “wants” and affect both design and construction.

5. What is the status of the earthfill dam with regard to safe design?

These issues have recently been addressed in TAB reports 21A, 22 and 23. Excerpts follow. The current status remains unchanged.

Excerpt from TAB Report 21A, dated April 2020

Question 4. Does the Board have any comment on the earthfill dam foundation review?

The status of design of the stability of the earthfill dam on its foundation was summarized, together with the past foundation characterization that controlled stability. Detailed assessment of current conditions suggests that this foundation characterization be revised based on the more detailed information currently available.

Progress with respect to this revision suggests that the controlling foundation conditions are more severe than previously used in design with respect to 1) residual strength 2) additional roughness, 3) continuity and depth of controlling bedding planes, and 4) post peak brittleness. The magnitude of pore pressures both at the end of construction and with post construction dissipation remain uncertain and this also has to be considered in the reassessment of stability.

The TAB supports the current effort to advance revised operational properties and to update the stability analysis related to the original design criteria. In so doing, the TAB recommends the following:

1. A distinction should be made for a most likely case (MLC) and reasonably worst case (RWC). Appropriate factors of safety should be recommended for each case and it is recognized that the observational method should be used where appropriate to identify if the reasonably worst case is developing. If the RWC is

developing, a default design will have to be implemented to bring the RWC up to the appropriate standard and must be demonstrated as feasible.

2. It is conceivable that the distinction between the MLC and the RWC will not be large given the significant brittleness displayed by the laboratory data with respect to the shear strength of the bedding planes.

3. It should be recognized that many agencies adopt lower factors of safety when design is based on residual strength or close to it.

The role of the application of the 3D analysis should be considered in these analyses because of the potential large 3D contributions to stability.

Excerpt from TAB Report No. 22, dated June 2020

Question 6. Does the TAB have any comment on the status of the studies on the foundation conditions for the earthfill dam?

Arising from the new findings at the Right Bank, it was timely to undertake an updated assessment of the design of the earthfill dam, particularly related to its foundation. This was presented to the TAB for review on May 8, 2020.

The update contained: 1) a review of the foundation geology, 2) a review of the shear strength mobilized along bedding planes, 3) a review of the rock mass strength, 4) a consideration of the model adopted to forecast pore pressures, 5) stability analyses in both two and three dimensions, 6) an assessment of Right Bank deformations, and 7) a summary of the proposed path forward utilizing the observational method.

New information had become available not only from the Right Bank investigation, but also from studies for the design of the cofferdam by the Contractor and from foundation responses. This has resulted in improved foundation characterization leading to some minor changes in excavation for the dam core trench. Shear strength characterization is little changed from that adopted in design but knowledge of deeper weak bedding planes has revealed some potential reduction in Factor of Safety without involving three-dimensional considerations. There has been increasing reliance on three-dimensional restraints in practice and the TAB is of the view that they can be adopted at Site C, given precedence elsewhere. There has been limited advance with respect to pore pressure response during construction. Stability analyses have assumed that they will dissipate during construction, prior to reservoir filling and this remains a matter of observational confirmation.

One matter of conceptual advance in the design of the earthfill dam is the re-casting of the design in terms of a Most Likely Case (which is the business case and has a Factor of Safety of 1.5) and the Reasonable Worst Case (which is the contingency case and has a Factor of Safety of 1.1). Observations during construction will be designed to discover whether conditions consistent with the Reasonable Worst Case might be developing. Invoking a Factor of Safety of 1.1 limits the opportunity for unacceptable deformations to develop while a Factor of Safety acceptable for operating conditions is being restored. The updated design has demonstrated that adding downstream berms is one practical method to increase stability if warranted.

Based on this updated review and extension of the observational method to formally recognize both the Most Likely Case and the Reasonable Worst Case, the TAB is content with the status of the studies on the foundation conditions for the earthfill dam and the proposed way forward.

Excerpt from TAB Report No. 23, dated October 2020

> *Question 3 - Does the TAB believe the information presented to date from the u/s cofferdam (pile installation, grouting and piezometric response) and the core trench (mapping, grouting and performance monitoring) supports the Most Likely Case or is the trend towards a Reasonably Worse Case for the earthfill dam?*

The status of the studies on the foundation conditions for the earthfill dam was last reviewed and discussed in Report No. 22, submitted in June 2020. As presented, best practice for the design and construction of dams on clay shale foundations employs the observational method in a precautionary-based design. A distinction is made in design between the Most Likely Case (MLC) which is the basic business case and requires a Factor of Safety under operational conditions of 1.5 and the Reasonably Worst Case (RWC) which is evaluated to recognize the residual uncertainties that exist prior to construction and requires a Factor of Safety of 1.1. The RWC is evaluated to ensure that no uncontrollable displacements could develop while a contingency design is implemented to provide adequate reserve resistance for the service conditions. The development of the required mitigation measures is part of the RWC design assessment.

To date, no information from any studies on performance observations have been obtained to modify the design basis for the earthfill dam. Observations and assessment of performance have always been part of the design. Comprehensive monitoring of deformation and pore pressure are being adopted and if either indicate that conditions are leading to the RWC condition, downstream slope-flattening is recognized as a proven mitigation measure in such cases and would most likely be favoured. Depending on the detailed response, additional advanced deformation analyses might be undertaken to assess the consequences of the trends observed.

However, at the right abutment of the dam, the powerhouse restricts the opportunity to invoke such measures to a large extent and tolerable deformations are more restricted. Recent construction for the earthfill dam indicates that foundation movements are directed toward the river valley, and not toward the powerhouse. These are favourable observations. Nevertheless, consistent with precautionary-based design, it would be prudent to assess local structural details at the powerhouse service bay boundary that would accommodate additional foundation deformations if they were to occur in this direction. However, deformations in this critical direction are already restrained by three-dimensional effects which limit the scale and likelihood of the need for any mitigation.

3. Summary

In the view of the Technical Advisory Board, the requirements for safe design have been honoured as an over-arching principle in all phases of the Project, from initial feasibility to current construction. In addition, best practices have been adopted from the initial site investigation studies to the current implementation phase. They are expected to continue to the end of construction and thereafter into operation.

Respectfully submitted,

Dr. Norbert R. Morgenstern

Dr. Wynfrith Riemer

Mr. Joseph L. Ehasz, P.E.

Dr. Peter J. Mason

Appendices

Appendix A – List of Site Investigations

Site investigations at Site C began in 1975. At the time of project approval in 2014, the following investigations had been completed:

- 211 diamond drill holes with a total length of over 13,600 m
- 29 large diameter (0.9 m) drill holes (LDH) with a total length of 1,810 m. The deepest LDH was 96 m
- 202 percussion drill holes with a total length of over 3440 m
- 271 rotary holes with a total length of over 18,180 m
- 10 sonic drill holes with a total length of over 610 m
- 10.4-m-wide 45 m long test chamber on the left bank
- 5 exploratory adits (tunnels) with a combined length of 950 m. Adits 3 and 5 are on the right bank
- 268 test pits with a total depth of 1230 m
- 12 exploratory trenches with a total length of 1,220 m
- 29 seismic lines with a total length of over 13,000 m

Appendix B – References

Site C (2017) Site C Clean Energy Project - Implementation Design RCC Buttress - Observational Method, prepared by Klohn Crippen Berger Ltd. and SNC-Lavalin Inc. for BC Hydro. BKS-03-122

Technical Advisory Board (April 2020) - Site C Clean Energy Project - Meeting No. 21A Report

Technical Advisory Board (June 2020) - Site C Clean Energy Project - Meeting No. 22 Report

Technical Advisory Board (October 2020) - Site C Clean Energy Project - Meeting No. 23 Report

Site C Technical Review Panel
John W. France, P.E., D.GE, D.WRE and Kaare Hoeg, PhD
REPORT NO. 1
January 22, 2021

EXECUTIVE SUMMARY

The Project Team has, with the support of the independent Technical Advisory Board, decided on the installation of drilled piles downstream of the powerhouse and spillway structures as the preferred right bank foundation enhancement approach. In our opinion, the proposed approach is sound and capable of making the right bank structures both safe and serviceable, however, several details still need to be addressed in the analysis and design. The Project Team is currently progressing the analyses and designs to address these details, and we look forward to reviewing the work as it progresses.

Significant investigations of the right abutment at Site C were completed during the pre-design and design phases of the project, and additional investigations have been completed after the observation of unexpected movements in the right abutment during excavation. The additional investigations showed that there are low strength, persistent bedding planes even deeper in the foundation than anticipated. The investigations, analyses, and evaluations have been and are being completed following current best professional practice methods. In our opinion, the available information, in combination with information being developed from on-going investigations and evaluations, provides adequate data for the design of the foundation enhancements.

Drilled piles were selected as the preferred foundation enhancement after consideration of a range of possible options and completion of a multiple accounts analysis to compare alternatives. We are not aware of any appropriate structural foundation enhancement alternatives that were not considered in this evaluation, and the selection of the drilled pile alternative is reasonable and well supported.

As part of the design development for the foundation enhancement, the final pile system configuration will be optimized, after final selection of design and performance criteria. We look forward to reviewing the optimization work.

INTRODUCTION

Data from geotechnical instrumentation for the Site C Project has indicated that the right bank foundation has lower strengths and stability than anticipated in the original design, and that remedial measures are required.

Hydroelectric projects are considered low risk – high consequence structures. BC Hydro has concluded that the subsurface movements, and related potential instabilities, that have been identified on the right bank pose undue risks. Certain foundation enhancements have been proposed by the Project Team to address these risks.

The Technical Advisory Board (TAB) for the project has been involved in the development of the remedial measures. Nevertheless, given the scope, cost and schedule implications of the proposed remedial measures, the Project Assurance Board (PAB) has decided to have an additional Third-Party Due Diligence Review undertaken of the proposed remedial measures. That review is being completed by a Technical Review Panel (Panel) composed of two individuals: Mr. John W. France of the United States and Dr. Kaare Hoeg of Norway. The Panel has been tasked with reviewing the following aspects of the work being completed by the Project Team:

- The characterization of the rock and the properties of the rock mass, bedding planes, shears, etc.
- The design of the seepage control measures in and under the approach channel.
- The water loads assumed in the rock given the seepage control measures.
- The multiple accounts evaluation leading to the selection of piles as the preferred enhancement.
- The results of the field trials to determine the lateral pile load/deflection characteristics.
- The methods of analysis being used to estimate the behaviour of the completed works on the right bank, including stability and deformations under the range of expected normal loads to extreme loads, and unanticipated performance of the seepage control measures.
- The acceptance criteria proposed for normal and extreme loads, including target factor of safety and displacement thresholds.
- The methods used to translate the results of the factor of safety based geotechnical analyses to the structural requirements for the piles, considering applicable limit states and structural codes.
- The process to be used for optimization of the number, size, and spacing of the piles and the resulting optimized configuration.

BC Hydro further asked the Panel to address the following six questions:

1. Do the geotechnical investigations completed to date, coupled with the information from the geotechnical instrumentation at the site and the proposed field-testing program, provide adequate data on which to base the design of the foundation enhancements?
2. Is the proposed approach to the right bank foundation enhancements capable of making the right bank structures:

a) safe – i.e. meet the Canadian Dam Association Dam Safety Guidelines and stability requirements set out in the Project Design Basis[1] provided by BC Hydro?
b) serviceable – i.e. displacements and deformations within the limits set out in the Project Design provided by BC Hydro?

3. Is the proposed approach to optimization of the right bank foundation enhancements (number, size and spacing of piles) capable of resulting in a cost-effective solution that can accommodate any reasonably foreseeable geological conditions encountered during construction? Are there any value engineering considerations that could be included in the design program?
4. Is the proposed approach to estimating, scheduling and procuring the enhancements reasonable? Are there other things that could be considered that would increase the level of confidence in the cost estimate prepared by BC Hydro?
5. Were the engineering attributes considered in the multiple accounts evaluation thorough?
6. Are there any other foundation enhancement measures that could have been considered?

Work completed by the Panel to date includes participation in introductory Project Team briefings to the Panel, participation in web-based Project Team briefings to the TAB, participation in web-based discussion sessions with the Project Team, review of documents provided to the Panel by the Project Team, Panel Team discussions, and preparation of this report.

FINDINGS

The analysis and design work related to the planned foundation enhancements for the right abutment of Site C is still in progress at the time of preparation of this report. In the remainder of this section, the Panel provides its initial responses to the six questions posed by BC Hydro based on the information that has been presented to the Panel to date. The Panel's responses to the six questions will be updated in future reports based on further work to be done by the Project Team.

[1] As amended to:

1. Update foundation properties based on recent investigations, including lateral pile tests.
2. Update the sliding stability analysis for the right bank including geological model, load cases, method, and criteria.
3. Specify design approach and acceptance criteria.

1. *Do the geotechnical investigations completed to date, coupled with the information from the geotechnical instrumentation at the site and the proposed field-testing program, provide adequate data on which to base the design of the foundation enhancements?*

   In our opinion, yes, the available information, in combination with information being developed from on-going investigations and evaluations, provides adequate data for the design of the foundation enhancements.

   Significant investigations of the right abutment at Site C were completed during the pre-design and design phases of the project, and additional investigations have been completed after the observation of unexpected movements in the right abutment during excavation. The investigations have included geologic mapping of surface exposures and exploratory adits, small and large diameter drill holes, geophysical surveys, and advanced field and laboratory testing.

   Field instrumentation was installed to monitor the buttress slopes during excavation and to update the geological model and geotechnical shear strength and deformation parameters (following the "observational method"). Experts with previous experience with similar shale foundation conditions have participated in the geotechnical evaluations.

   After the unexpected right bank slope movements, back analyses were completed to evaluate the movements, and additional investigations were undertaken to provide input for design of the foundation enhancements. It was found that persistent bedding planes with low shear strength exist even deeper in the foundation than previously anticipated, which has significant impact on the foundation enhancement measures considered and designed.

   The work completed at the site has allowed for a very good characterization of the geological, geotechnical, and engineering conditions in the right abutment, including the rock mass, rock stratification, bedding planes, relaxation joints and shears. Analyses and evaluations have been completed following current best professional practice methods.

   Some of the key conclusions that have been reached in the analyses and evaluations are:

1. An active wedge has not developed in the rock mass behind the roller compacted concrete (RCC) buttress; the rock mass consists of strata of intact rock between numerous, nearly horizontal bedding planes, with only limited shears between bedding planes.
2. Close to the excavation face, steeply dipping relaxation joints likely are present, as observed in other locations along the river.
3. Shear strengths on the bedding planes have likely been reduced to near their residual values. Persistent bedding planes with low shear strength exist even deeper than anticipated under the RCC buttress shear key.
4. A release plane does not appear to have been developed in the passive resistance zone (break-out zone) downstream of the powerhouse and spillway structures.

Based on the information provided to us, these conclusions appear to be well supported by the available data, the analyses, and the evaluations performed.

2. *Is the proposed approach to the right bank foundation enhancements capable of making the right bank structures:*
   c) *safe – i.e. meet the Canadian Dam Association Dam Safety Guidelines and stability requirements set out in the Project Design Basis provided by BC Hydro?*
   d) *serviceable – i.e. displacements and deformations within the limits set out in the Project Design provided by BC Hydro?*

The Project Team has, with the support of the independent Technical Advisory Board, decided on the installation of drilled piles downstream of the powerhouse and spillway structures as the preferred right bank foundation enhancement approach and concept. In our opinion, the proposed approach is sound and capable of making the right bank structures both safe and serviceable, however, several details still need to be addressed.

The Project Team is currently developing the specific design basis criteria that will be used to design the pile foundation enhancement. The principal design criterion will be to limit the deformations in the foundation to provide both safety and serviceability. The Panel agrees with this approach. Limiting the foundation deformations will provide for safety by preventing the development of an active wedge in the rock behind the RCC buttress and preventing rupture of the lining system to be installed in the approach channel. To address serviceability, the foundation deformations must be limited so that deformations of powerhouse components and spillway gate systems remain within acceptable limits. Stability of the foundations (factors of safety) is being checked to demonstrate compliance with CDA safety guidelines and project design basis requirements.

Some aspects of the planned deformation and stability analyses are currently being developed and finalized. However, with proper application of available characterization information, the resulting design should appropriately address safety and serviceability.

3. *Is the proposed approach to optimization of the right bank foundation enhancements (number, size and spacing of piles) capable of resulting in a cost-effective solution that can accommodate any reasonably foreseeable geological conditions encountered during construction? Are there any value engineering considerations that could be included in the design program?*

   The optimization of the pile design is currently in process. The Project Team is considering alternate pile configurations (e.g. diameters, steel configuration, etc.) as part of the process. The initial estimates of the number of required piles were based on stability analyses that considered the possible presence of or development of an active wedge behind the RCC buttress. Currently, stability analyses are being completed based on a sliding block model, bounded on the upstream side by either a single, full-height relaxation joint or a sliding plane along the rock mass-buttress interface. For both cases, the required numbers of piles are significantly less than originally estimated with the active wedge model.

   Value engineering considerations were included in the multiple accounts analyses (MAA) commented on below.

   A number of details must be worked out for the pile optimization, but we are confident that a pile design can be developed that is cost-effective and capable of accommodating reasonably foreseeable geological conditions encountered during construction.

4. *Is the proposed approach to estimating, scheduling and procuring the enhancements reasonable? Are there other things that could be considered that would increase the level of confidence in the cost estimate prepared by BC Hydro?*

   The approach to estimating, scheduling, and procuring the enhancements is awaiting finalization, or at least further development, of the designs of the piles. Our comments on this question will be provided after further development and specifications of the design.

5. *Were the engineering attributes considered in the multiple accounts analysis thorough?*

   Based on a review of the information provided to us concerning the multiple accounts analysis of the potential foundation enhancement alternatives, the engineering attributes considered appear to have been systematic, thorough, and reasonable.

6. *Are there any other foundation enhancement measures that could have been considered?*

   We are not aware of any other structural foundation enhancement alternatives that could have been considered.

   Additional drainage measures may be used to reduce lateral water pressures and uplift forces under the RCC buttresses. At this time, such additional measures do not appear to be required. If water pressures during the lifetime of the structures rise to values higher than anticipated during design, suitable mitigating drainage measures may be implemented without making any structural changes. Recognition of possible changes in drainage conditions over time and the inclusion of design measures to accommodate drainage mitigation measures are not unusual in current dam design practice.

STATEMENT OF LIMITATIONS

The Panel functioned as independent reviewers of the methodologies used by the Project Team for analysis and design of the proposed enhancements, based on information provided by the Project Team. Given the large amount of work being completed by the Project Team and the associated documentation, it was not possible for the Panel to perform a detailed review of all of the material in the available time. In particular, the Panel has not performed detailed checks of calculations and designs completed by the Project Team. Such detailed checks are provided by the quality control/quality assurance programs for the project. The Panel provides its opinions concerning the methods and approaches being used based on information provided by the Project Team. However, the ultimate decisions and responsibilities for the designs remains with the BC Hydro.

Our review services were performed within the limits prescribed by BC Hydro in a manner consistent with the level of care and skill normally exercised in the current standard of professional engineering practice. No other representation to BC Hydro, expressed or implied, and no warranty or guarantee is included or intended.

Respectfully submitted,

John W. France

Kaare Hoeg

Site C Technical Review Panel
John W. France, P.E., D.GE, D.WRE and Kaare Hoeg, PhD
REPORT NO. 2
February 15, 2021

EXECUTIVE SUMMARY

Additional analyses of the earthfill dam are still in progress, in light of performance observed on the right abutment. However, based on the studies that have been completed to date, we are confident that a safe earthfill dam structure can be constructed at Site C meeting the Canadian Dam Association (CDA) Dam Safety Guidelines. Further, it is our opinion that the earthfill dam type is a particularly appropriate choice for the foundation conditions at Site C, because of 1) the ability to accommodate the low strength foundation bedding planes with flatter earthfill dam slopes, as necessary to provide stability and 2) the earthfill dam's tolerance of deformations, particularly when designed with wide core, filter, and transition zones, as is the case for the Site C earthfill dam design.

The available analyses indicate that for long term steady state conditions, after construction-generated pore water pressures have dissipated, the current earthfill design meets CDA stability guidelines for both the Most Likely Case (MLC) and the Reasonably Worst Case (RWC), both of which we believe have been reasonably estimated. Analyses completed to date also indicate that, for construction conditions including estimated pore water pressure generation and dissipation during construction activities, the CDA stability guidelines can be met with the current earthfill dam design for the MLC and with the addition of a relatively modest amount of stabilizing fill at the downstream slope and toe for the RWC. Further, analyses have indicated that increases of up to 20 percent in factor of safety can be achieved by readily constructible additional berm and toe fill configurations if that should be needed.

In our opinion, the Project Team's estimates of construction-generated pore water pressures are reasonable based on available data. However, the construction-generated pore water pressures constitute one of the greatest uncertainties in the analysis, which must be and are being recognized in evaluating dam safety and the construction schedule/cost risks.

It is our understanding that the additional berm and toe fill configurations referenced above which could increase construction phase stability beyond that required for the RWC are within the Project Team's current budgetary proposal. Part of the Project Team's mitigation strategy to reduce the risk of impacting the schedule during construction is a plan for placement of additional fill downstream of the downstream cofferdam to create a staging area and provide additional stability during construction. The additional staging area fill is sufficient to meet CDA guidelines for the RWC.

In the very unlikely, but not impossible, event that observed deviation from expected performance is greater than expected (deviates from the RWC), such deviations could still be safely addressed by additional downstream fill placements or temporarily pausing fill placement to allow construction-generated pore water pressures to dissipate. However, such measures could further impact cost and schedule.

In our opinion, the available geotechnical and geological data are satisfactory to characterize foundation conditions for purposes of the earthfill dam design, and the planned observational approach and instrumentation program for the earthfill dam is reasonable and appropriate for monitoring and responding to construction-generated pore water pressures and movements during construction so that adequate stability and safety can be maintained.

INTRODUCTION

The Technical Review Panel's (Panel's) original assignment did not include review of the Site C earthfill dam design and construction, but BC Hydro subsequently asked the Panel to expand its assignment to include review of this structure and the Panel agreed.

The geotechnical investigations for the Project did not include the portion of the earthfill dam foundation beneath the main river channel, as it was not considered safe to use barge mounted equipment due to the river currents.

Portions of the earthfill dam core trench have been excavated on the left and right banks. The exposed bedrock at the base of the core trench in these locations has been mapped and foundation grouting is being performed.

Mapping and grouting of the right bank portion of the core trench identified shears that affected the stability of the right bank section of the earthfill dam. A shear key has been added to improve stability and reduce dam displacements for the right bank section of the earthfill dam, and a three-dimensional analysis has been undertaken to verify that acceptance criteria will be met.

Installation of piles in the cutoffs of the upstream and downstream cofferdams and the associated investigations have provided more information on the foundation across the main river channel.

After completion of the upstream and downstream cofferdams, the remainder of the core trench will be excavated, mapped, and grouted. Until this work has been completed and assessed, there is uncertainty about the foundation conditions for the earthfill dam and whether the current design will meet the acceptance criteria or whether some further enhancements will be required.

There are also uncertainties concerning the piezometric response of both the bedding planes in the foundation and the till core and the strengths of discontinuities (bedding planes and shears) in the foundation.

In Report 21A the Technical Advisory Board (TAB) introduced the concepts of the Most Likely Case (MLC) and the Reasonably Worst Case (RWC) and how these concepts should be considered in the design.

The observational approach is planned to verify the design of the earthfill dam during construction. The geotechnical instrumentation will directly measure the piezometric responses in the core and on the foundation bedding planes and inclinometers will indirectly indicate the strength of the foundation. If the observations indicate that the RWC is developing, design modifications would be implemented to meet acceptance criteria.

The TAB for the Project has been involved in the development of the design for the earthfill dam. Nevertheless, given the possibility of required design changes and the experience with unexpected performance during right abutment excavations, the Project Assurance Board (PAB) has decided to have an additional Third-Party Due Diligence Review completed for the earthfill dam design by this Technical Review Panel. The Panel has been tasked with reviewing the following aspects of the work being completed by the Project Team:

- The geotechnical investigations for the earthfill dam completed to date and the geotechnical instrumentation for the earthfill dam and cofferdams.
- The characterization of the rock and the properties of the rock mass, bedding planes, shears, etc. that control the stability of the earthfill dam and its foundations.
- Pore pressure assumptions during and at the end of construction.
- Adaptations of the design and stability analysis that have been identified to date in consideration of experience on the right abutment.
- Strategies to be adopted to further adapt the design, if necessary, based on mapping of the core trench across the riverbed and/or information obtained from geotechnical instrumentation during construction.

Work completed by the Panel to date related to the earthfill dam includes participation in three web-based Project Team briefings/discussion sessions with the Team, participation in web-based Project Team briefings to the TAB, review of documents provided to the Panel by the Project Team, and preparation of this report.

FINDINGS

Updates to the Site C earthfill dam design in light of the right abutment experience are still in progress at the time of preparation of this report. In particular, the Project Team is completing three-dimensional stability and deformation analyses for the earthfill dam. The Panel has been briefed on the foundation geology and earlier analyses, which have included parametric studies evaluating ranges of estimates for shear strengths and pore water pressure generation during dam construction. In the remainder of this section, the Panel provides initial findings based on the information that has been presented to the Panel to date. The Panel's findings will be updated in future reports based on further work to be completed by the Project Team.

Based on the information that has been presented, the Panel provides initial findings regarding earthfill dam safety, construction schedule/cost risks, geotechnical/geological investigations, and the observational approach and instrumentation.

Earthfill Dam Safety

The available analyses indicate that for long term steady state conditions, after construction generated pore water pressures have dissipated, the current earthfill design meets CDA stability guidelines for both the Most Likely Case (MLC) and the Reasonably Worst Case (RWC).

The Project Team has estimated pore water pressures that will be generated during construction in the earthfill dam core and in the foundation bedding planes for the MLC and RWC. The estimated construction pore water pressures are consistent with pore water pressures measured to date during construction of the upstream cofferdam and the Relocated Surplus Excavated Material (RSEM) sites, and these estimated pore water pressures seem reasonable. However, the construction-generated pore water pressures constitute one of the greatest uncertainties in the analysis, which must be and are being recognized in evaluating dam safety and the construction schedule/cost risks.

Analyses completed to date indicate that, for the estimated construction pore water pressure generation and dissipation, the CDA stability guidelines can be met with the current earthfill dam design for the MLC and with the addition of a relatively modest amount of stabilizing fill at the downstream slope and toe for the RWC. Analyses have indicated that increases of up to 20 percent in factor of safety can be achieved by readily constructible berm and toe fill configurations, if that should be needed.

Based on the range of parametric studies that have been completed, we are confident that a safe earthfill dam structure can be constructed at Site C meeting the Canadian Dam Association (CDA) Dam Safety Guidelines.

In our opinion, the earthfill dam type is a particularly appropriate choice for the foundation conditions at Site C. The slopes of an earthfill dam can be flattened as necessary to provide stability even with the low strength foundation bedding planes. In addition, an earthfill dam is tolerant of deformations, particularly when designed with wide core, filter, and transition zones, as is the case for the Site C earthfill dam design.

Construction Schedule/Cost Risks

The Project Team is well aware of potential impacts to schedule and cost that could result from higher than expected construction-generated pore water pressures or other unexpected foundation and earthfill dam performance, and strategies are being developed to limit the impacts of such occurrences.

Based on the completed analyses, downstream toe berm and fill placements within the currently planned contingencies will most likely address any observations. As noted above, readily constructible berms and fills, which we understand would be within the current budgetary proposal, could increase factors of safety by up to 20 percent, according to the completed analyses. The challenge would be to implement any required changes in a manner that does not adversely affect schedule and cost.

The Project is planning for placement of additional fill downstream of the downstream cofferdam to create a staging area and provide additional stability during construction. The additional staging area fill is sufficient to meet CDA guidelines for the RWC. This additional stability is part of a mitigation strategy to reduce the risk of impacting the schedule during construction, if higher than anticipated pore water pressures are encountered.

Although we believe that it is very likely that any observed unexpected performance could be addressed within the current budgetary proposal, the possibility of deviations from expected behavior greater than the RWC cannot be entirely ruled out. Such greater deviation from expectations could still be safely addressed by additional downstream fill placements or temporarily pausing fill placement to allow construction-generated pore water pressures to dissipate. However, such measures could further impact cost and schedule.

Geotechnical/Geological Investigations

Although geotechnical and geological investigations have been limited to areas outside of the riverbed, we believe that the available data from the earthfill dam investigations and the construction of cofferdams, combined with knowledge of the rock formations obtained from the right abutment investigations, is satisfactory to characterize foundation conditions for purposes of the earthfill dam design.

Observational Approach and Instrumentation

In our opinion, the planned observational approach and instrumentation program for the earthfill dam are reasonable and appropriate. After the experience on the right abutment, the Project Team has added instruments to the originally planned three earthfill dam instrumentation sections and added two more earthfill dam instrumentation sections. The planned instruments should be sufficient to monitor the construction-generated pore water pressures and movements during construction so that adequate stability can be maintained.

STATEMENT OF LIMITATIONS

The Panel functioned as independent reviewers of the methodologies used by the Project Team for analysis and design of the earthfill dam, based on information provided by the Project Team. Given the large amount of work being completed by the Project Team and the associated voluminous documentation, it was not possible for the Panel to perform a detailed review of all of the material in the available time. In particular, the Panel has not performed detailed checks of calculations and designs completed by the Project Team. Such detailed checks are provided by the quality control/quality assurance programs for the Project. The Panel provides its opinions concerning the methods and approaches being used based on information provided by the Project Team. However, the ultimate decisions and responsibilities for the designs remains with BC Hydro.

Our review services were performed within the limits prescribed by BC Hydro in a manner consistent with the level of care and skill normally exercised in the current standard of professional engineering practice. No other representation to BC Hydro, expressed or implied, and no warranty or guarantee is included or intended.

Respectfully submitted,

John W. France

Kaare Hoeg