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3-D Seismic Isolation for Protection of Critical Equipment for the Site C Clean Energy Project

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ABSTRACT

The Site C Clean Energy Project is a new, 1,100 MW hydroelectric generating station on the Peace River in northeastern British Columbia, Canada. Seismic isolation has been adopted to protect more than 150 pieces of equipment deemed critical for dam safety and to meet the project's operational requirements. Three-dimensional seismic isolation platforms are being used to provide operation level protection of critical electrical and electronic control equipment, with a total of 39 platforms throughout the spillway headworks structure. Shake table testing of selected 3-D seismic isolation platforms and equipment was conducted following the framework of IEEE 693-2018, Annex W. Seismic isolation is also being used to protect seismically-vulnerable electrical equipment at the interface of the powerhouse generator step-up transformers and the 500 kV transmission system. The paper will describe the design and testing of the 3-D isolation systems and equipment being implemented on the project and key aspects of their benefits and effectiveness.

Keywords: seismic isolation, 3-D isolation, wire rope isolator, three-dimensional, electrical equipment

INTRODUCTION

The Site C Clean Energy Project is a new, 1,100 MW hydroelectric generating station on the Peace River in northeastern British Columbia, Canada. The main features of the project are a 1,050 m long, 60 m high, earthfill dam and an 800 m roller-compacted concrete buttress that includes the spillways and the six-turbine, generating station (see Fig. 1). Two new 500 kV transmission lines will connect the Site C facilities to an existing substation and the provincial grid.

Although the project is not located in a region of high seismicity, in several places including the spillway headworks there is substantial structural amplification of seismic shaking in the short period range. This fact along with several important project safety and economic design requirements led to the adoption of innovative seismic isolation solutions for key aspects of the project.

Three-dimensional seismic isolation platforms are being used to protect more than 100 pieces of critical dam safety equipment and to ensure full operation following an earthquake. Seismic isolation using wire rope devices is also being used to protect 45 pieces of seismically-vulnerable electrical equipment at the interface of the powerhouse generator step-up transformers and the 500 kV distribution system. The paper will describe the design and testing of the isolation systems being implemented on the project and key aspects of their benefits and effectiveness.

PROJECT PERFORMANCE CRITERIA

The project considered two key levels of seismic hazard: the Design Basis Earth-quake (DBE) and the Maximum Design Earthquake (MDE), with annual exceedance probabilities of 1/2,475 and 1/10,000, respectively. The project design criteria required that flows past the dam shall be safely managed after an MDE, leading to the requirement that all the primary and back-up power supplies and electronic control equipment required to operate the spillway gates be fully operational after an MDE event.

A second important criterion, but associated with the generating capability of the facility, rather than dam safety, applied to much of the seismic design of the power-house and intake. The project owner required that the facility be able to generate electricity within 72 hours of a DBE event. This requirement was not intended to stipulate immediate post-earthquake functionality, rather that it could be met by repair and/or replacement of damaged components or equipment, so long as this could be reasonably achieved within the three-day time-frame.

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Figure 1. Powerhouse, intakes and spillway construction, March 2023

3-D ISOLATION FOR CRITICAL GATE CONTROL EQUIPMENT

Detailed three-dimensional, time-history analyses of the dam civil structures were performed for the project. These analyses incorporated site geologic variability, consideration of an upper, nominal and lower bound foundation stiffness and earthquake directionality effects. In total, five sets of three component ground motions – scaled to the appropriate hazard level – were used in the analyses of the dam and its associated structures.

One of the key products of the spillway and intake/powerhouse structure analyses were Floor Design Spectra (FDS) that were used extensively for the subsequent design of components and equipment. FDS were calculated at numerous locations, termed points of interest (PI) throughout the structures. Fig. 2 shows the PI's in the spillway headworks (labeled as PI-xx in the figure).

Whilst a general seismic qualification level of IEEE 693-2005 High RRS was established for all the project electrical equipment, this level of seismic demand was significantly inadequate when compared to the FDS at the locations of the critical gate control equipment in the spillway headworks. In the spillway headworks there is substantial structural amplification of seismic shaking in the short period range. Fig. 3 shows the 2%-damped response spectra for one PI compared to the IEEE 693-2005 High RRS in the horizontal (a) and vertical (b) directions. Faced with the equipment design challenge of such high seismic demands, three-dimensional seismic isolation was concluded as the only practical means of achieving the required level of equipment protection and performance.

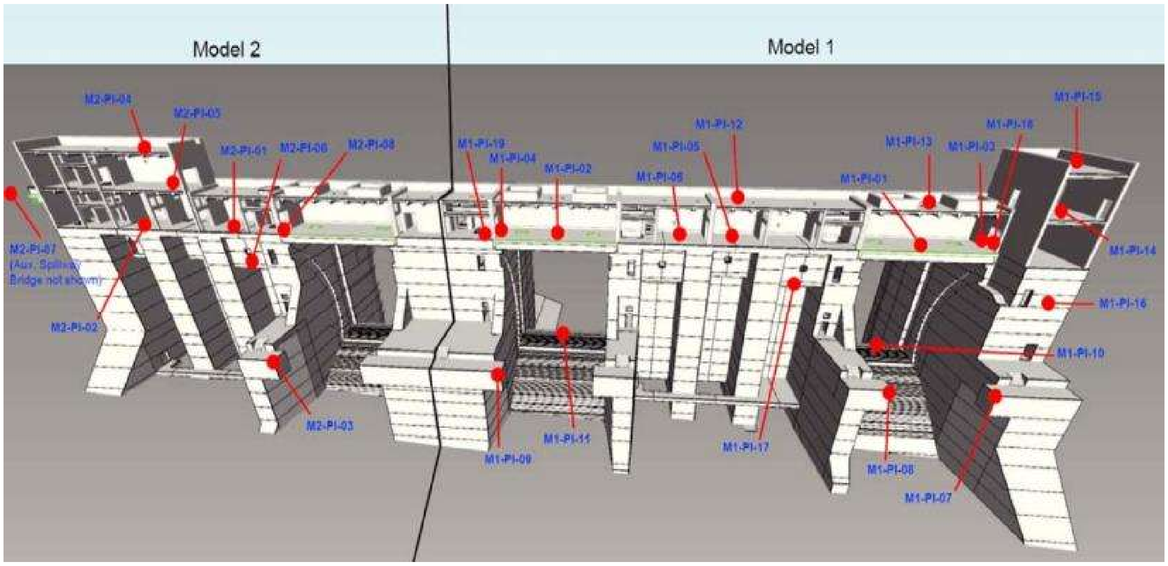
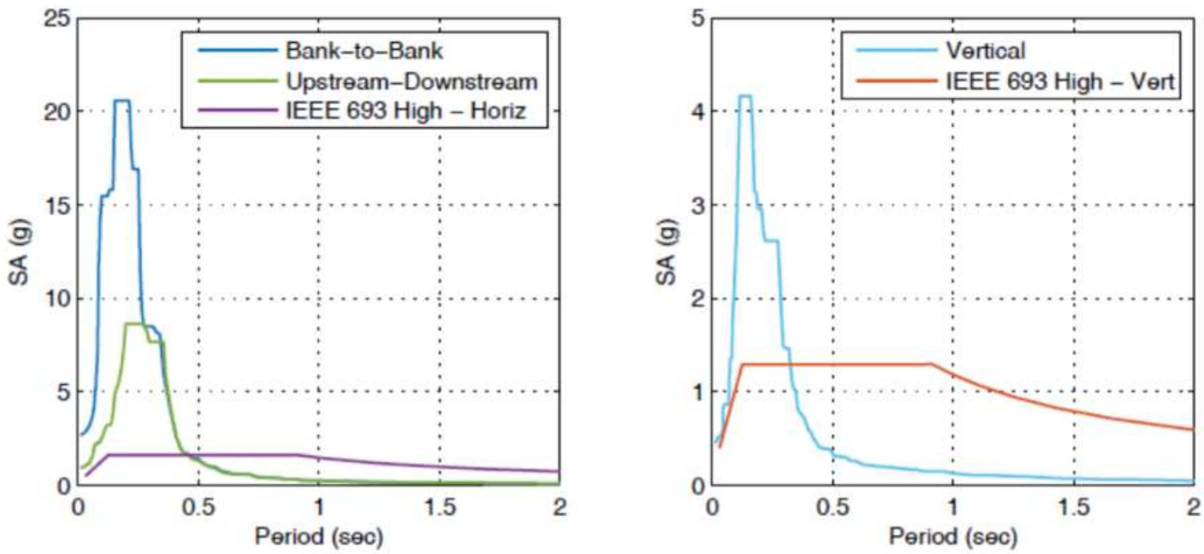


Figure 2. Schematic view of the spillway and headworks structure.



(a) *(b)*

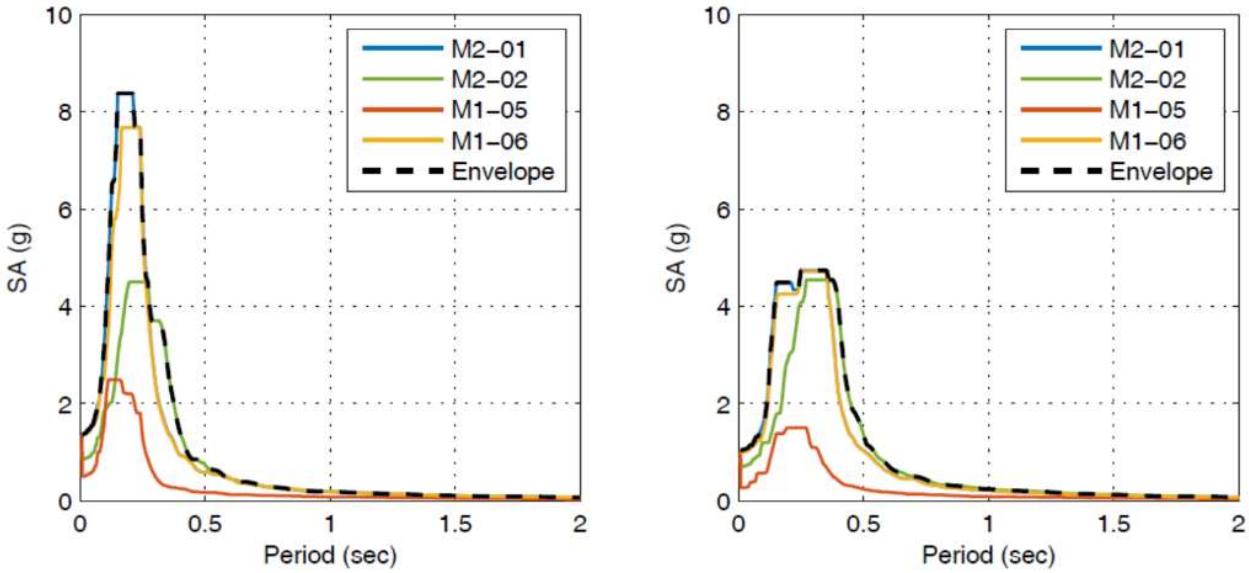
Figure 3. FDS for a PI in the spillway headworks, horizontal (left) and vertical (right).

A two-step approach was taken to achieve the seismic protection of the critical components required to be immediately available and fully operational after an MDE event for spillway and low-level outlet gates. The two-step process involved: a. qualifying the critical equipment to IEEE Std 693-2005 High RRS level by shake table testing of the equipment, and b. providing additional protection in the form of 3-D seismic isolation platforms to ensure that the shaking experienced by the equipment on the platforms is reduced to a level not more than the IEEE Std 693-2005 High level. One exception to the shake table testing requirement was for the station service transformers which were qualified by analysis per the requirements of IEEE Std 693-2005.

IEEE Std 693-2005 does not provide detailed recommendations for equipment with seismic protective systems or for equipment on isolation platforms. The above approach is essentially that prescribed for Category 3 equipment in IEEE Std 693-2018, Annex W [1]. Category 3 equipment is equipment with protective systems which is required to be shake-table tested but for several reasons outlined in IEEE Std 693-2018, cannot be tested together with the protective system [2]. For the Site C Clean Energy Project, the design and manufacturing of the equipment and isolation platforms occurred simultaneously and therefore, shake table testing of the actual equipment on the platforms was not possible.

Isolation Platform Seismic Loading

The spillway includes three wire rope hoist operated radial gates and six hydraulically operated low level outlet gates. All of these gates have complete operational redundancy with primary and back-up power supplies and electronic control equipment. As such, depending on the specific equipment, there are numerous units of the same equipment, and therefore isolation platforms, throughout the spillway headworks. The spatial variability of the platforms necessitated an enveloping approach to the relevant point of interest FDS for the platform design process. Fig. 4 shows examples of envelope design spectra for one particular isolation platform. The figure shows the enveloping of all FDS for the upper bound and lower bound foundation stiffness assumptions, (a) and (b), respectively. Sets of earthquake time histories were then generated to match the envelope spectra, using original project time histories from the spillway headworks as seed motions, and finally, these time histories were used for the nonlinear time-history verification analyses and the performance validation shake table tests.



(a) *(b)*

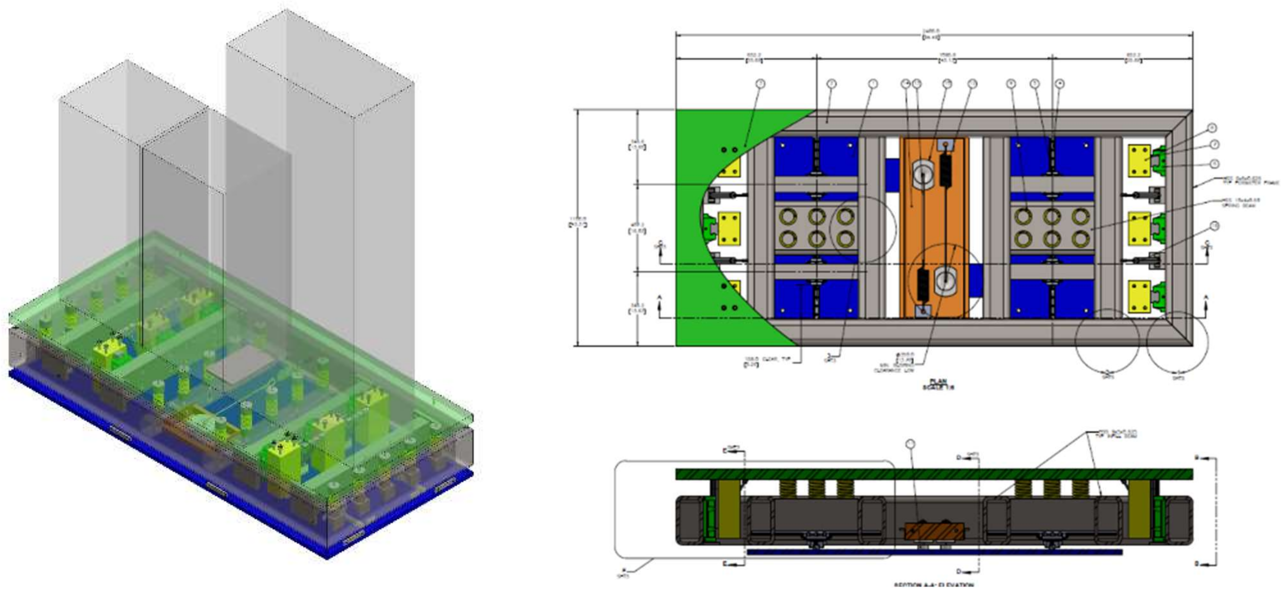
Figure 4. Enveloped spectra for upper and lower bound foundation stiffnesses (a) lower, (b) upper.

Isolation Platform Designs

The 3-D isolation platforms are all based on a common design concept and followed the same general design process. The horizontal and vertical isolation functions are fully de-coupled and comprise different functional mechanisms. Horizontally, the platform is free to move in any direction on very low friction cross-linear bearings with a rolling resistance about 0.1% to 0.3% of the supported weight. The horizontal restoring force and damping is provided by a proprietary Multi-Directional Spring Unit which has a flag-type hysteresis that provides a bilinear loading stiffness and about 13-15% equivalent viscous damping [3, 4, 5]. The vertical isolation system operates on top of the horizontal system and comprises linear vertical springs, linear viscous dampers and linear guides to eliminate rocking deformations and ensure vertical-only translational movement. Fig. 5(a) shows a typical isometric view of a platform and Fig. 5(b) typical cross-sections with the key functional components.

The platform designs were initially developed using equivalent linear and response spectrum methods. Subsequently, detailed nonlinear time-history verification analyses were performed on a subset of the designs, selected to be representative of the entire range of all the platform designs.

There are a total of 39, 3-D seismic isolation platforms on the project, comprising 15 different designs, to protect the gate control and associated power supply equipment. The platforms range in size from the smallest at only 0.7 x 1.2 m in plan, supporting a single item of control equipment of 380 kg, up to the largest at 2.75 x 12.0 m in plan which supports 30,391 kg of transformer and switchgear. The quantity of each design varies from just one unit for each of ten platforms, up to nine units for the most commonly-used design. Additional information on the design of the seismic isolation platforms and placement within the spillway headworks can be found in [7].



(a) *(b)*

Figure 5. Typical seismic isolation platform, isometric view.

Shake Table Testing of Isolation Platforms

Shake table performance validation tests of two platform designs were performed at the University of Nevada, Reno. The smallest platform, denoted S07, and a second design, denoted S15, were selected for the shake table tests. S07, because of its small size, was the most mechanically challenging of all the platform designs, and S15 was selected to be representative of the mid-range of platform sizes. It is noted that the largest platform designs could not be tested because of the lack of shaking tables of the appropriate size (to accommodate the platforms) and three-dimensional performance capabilities. The weight of the supported equipment is an important factor in the horizontal and vertical dynamic behavior of the isolation platforms. The parallel design and manufacturing of the equipment and the isolation platforms did not allow the use of the actual equipment for the platform shake table tests, instead equipment mock-ups that accurately represented the weight, stiffness, and center of mass characteristics of the equipment were included in the tests. Fig. 6 shows a schematic isometric view of isolation platform S15 with mock-ups of three pieces of equipment. Steel plates of appropriate thickness are attached at discrete levels within the equipment frames to accurately represent the overall weight and center of mass of each piece of equipment. Figs. 7(a) and 7(b) show platforms S07 and S15, respectively, including the equipment mock-ups, on the UNR six degree-of-freedom shake table.

Each isolation platform was subjected to the two sets of three-direction time histories described previously, first at 50% of the MDE input level followed by100% MDE input. At each level the test was repeated with the time history input rotated 90 degrees as the orientation of the isolation platforms may be in the upstream-downstream or bank-to-bank directions. Fig. 8(a) shows the acceleration time history response in the X direction (which corresponds to motion in the long direction of the platform) for platform S15 subjected to the 100% MDE, upper-bound motion. It is seen that the acceleration response is significantly reduced from that of the shake table input. Although not shown here, a similar reduction was seen in the orthogonal (Y) horizontal direction. Fig. 8(b) shows the vertical acceleration response of the isolation platform compared to the shake table input. Although not as pronounced as in the horizontal direction, significant reduction can be seen.

The shake table test results confirmed that the platform designs effectively reduced both the horizontal and vertical equipment demands to below the IEEE Std 693 High RRS levels for the MDE level of shaking (Fig. 9). Additional beyond-MDE level tests were also undertaken, up to 150% of the MDE input, to confirm that the platforms did not reach their displacement capacity limits even for 50% higher inputs.

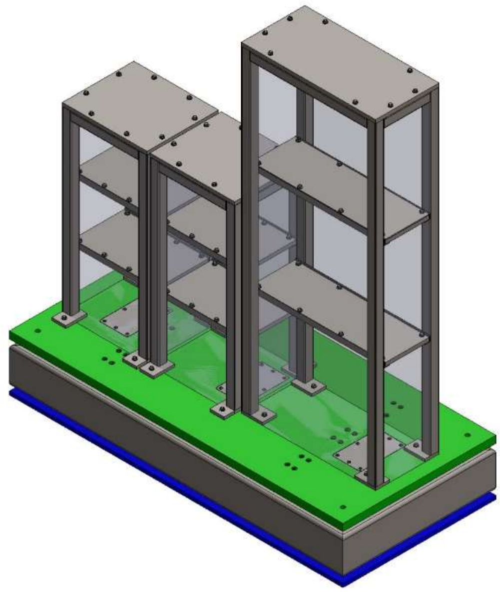
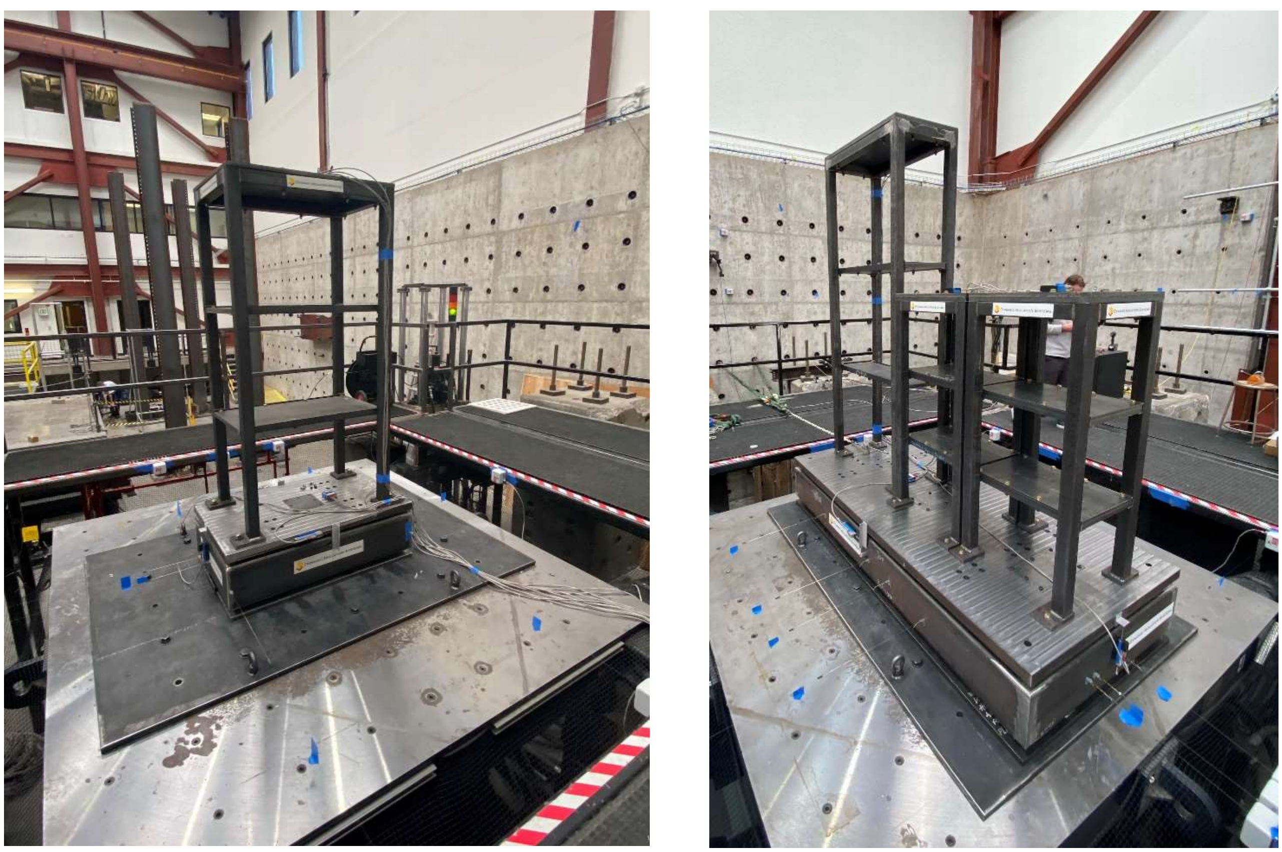
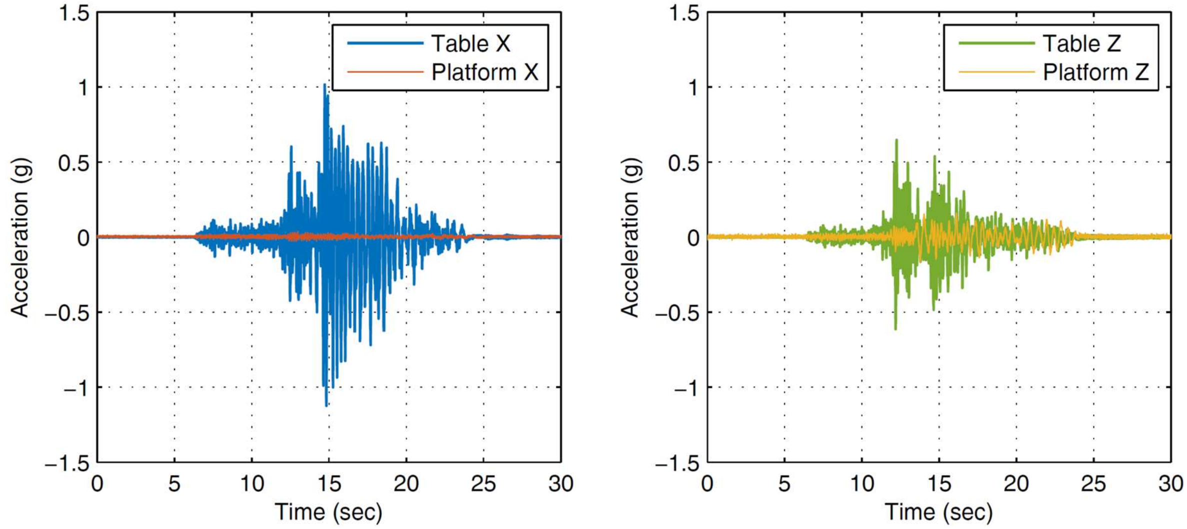


Figure 6. Schematic isometric view of isolation platform S15 with mock-ups of three pieces of equipment.



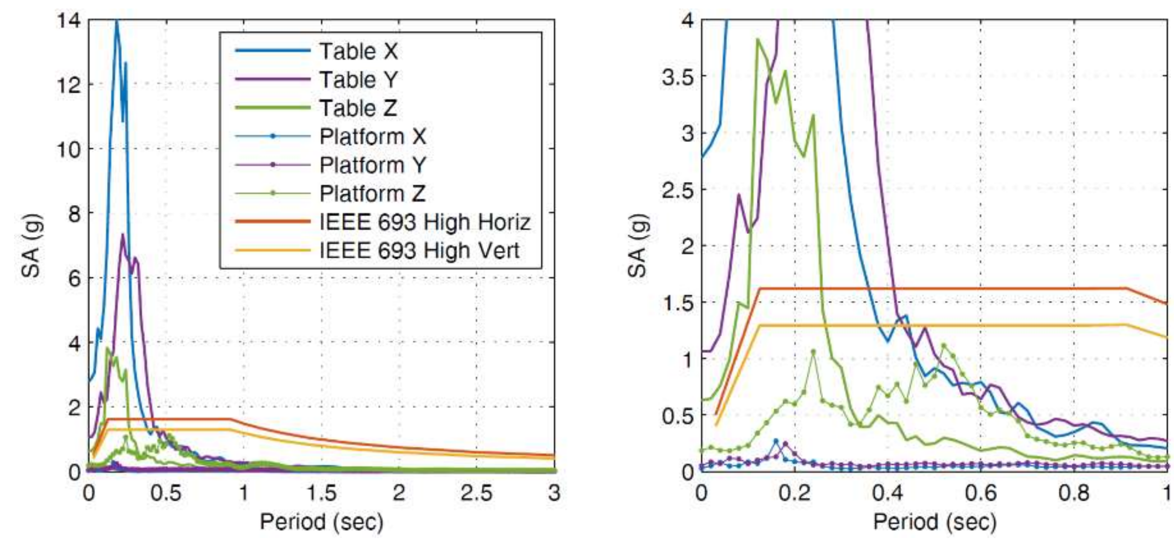
(a) *(b)*

Figure 7. Photos showing Platforms S07 (a) and S15 (b) with equipment mock-ups on the six degree-of-freedom shake table at University of Nevada, Reno.



(a) *(b)*

Figure 8. Comparison of shake table input acceleration and the resulting acceleration measured directly on top of the isolation platform in the horizontal X direction (a) and vertical Z direction (b).



(a) *(b)*

Figure 9. Comparison of horizontal and vertical spectra below and on top of platform S15 (Table and Platform), respectively and IEEE 693-2005 High RRS. Enlarged view (b) more clearly shows the top of platform responses.

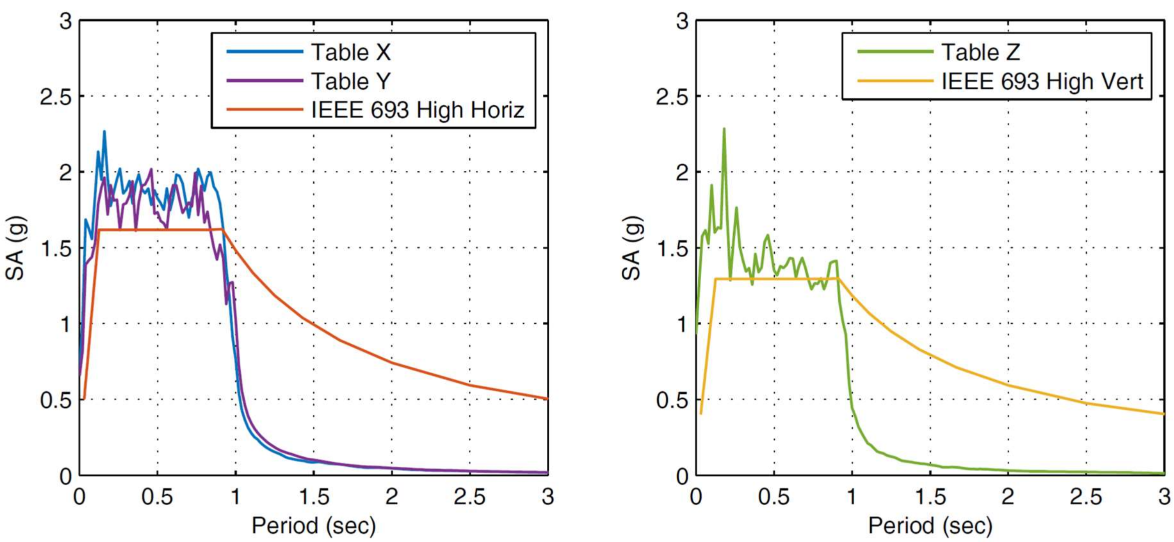
Shake Table Testing of Equipment

All the equipment to be installed on the 3-D isolation platforms, with the exception of the station service transformers, was separately qualified to the IEEE Std 693-2005 High RRS level via shake table testing. Two shake table test programs conducted at the University of British Columbia were undertaken by BC Hydro to qualify a total of 12 different items of equipment. IEEE Std 693-2005 allows for qualification of equipment by group, with a successful qualification test of the most seismically vulnerable piece of equipment in the group serving as the basis for qualification of all other equipment items in the group. Most of the equipment supported on the isolation platforms are cabinets or rack-mounted items, which allowed for a straight-forward grouping criteria to be applied. Fig. 10(a) shows two Protection and Control panels mounted on the shake table while (b) shows a 3.6m tall satellite antenna.

A three component set of synthetic input motions was developed to envelope the IEEE Std 693-2005 High RRS. Each piece of equipment was shake table tested with the motions scaled to 50% and 100% of the High RRS. In addition to the time-history shake table testing, a resonant frequency search test was performed before and after each seismic test to determine the equipment's natural frequency and to identify any significant changes in the natural frequency which might indicate damage requiring further assessment. As shown in Fig. 11, the table response spectra envelope the RRS between 1.1 and 33 Hz (0.03 and 0.9 seconds) within a -10% / +50% tolerance as required by IEEE Std 693-2005.

(a) *(b)*

Figure 10. Photos showing equipment mounted on the shake table at the University of British Columbia.



(a) *(b)*

Figure 11. Plots showing the horizontal (a) and vertical (b) table response spectra meeting the requirements for IEEE 693 Std. High RRS loading.

Acceptance criteria were defined to verify post-test operability of the equipment. The equipment was energized before, during and after the shake table testing with monitoring during the tests performed by BC Hydro. Both BC Hydro and the UBC test facility performed post-test structural inspections and BC Hydro performed post-test functionality testing. The shake table testing program confirmed that all equipment remained energized during the testing and was functional following the tests. The project required that all other equipment not installed on the isolation platforms also be qualified to IEEE Std 693-2005 High, with most specifications requiring that the qualification be by shake table testing. These qualifications were performed by the equipment manufacturers themselves either specifically for the Site C Clean Energy Project or previously as is common practice in the electrical industry.

Production testing protective system devices

In addition to the shake table performance validation tests of the platforms, component testing of the various isolation system devices was performed as part of the platform manufacturing process. This included stiffness verification tests of the springs for both the horizontal and vertical isolation mechanisms, and cyclic dynamic tests of the fluid viscous dampers in the vertical isolation system.

ISOLATION OF 500 KC EQUIPMENT

The use of seismic isolation to protect high-voltage distribution equipment at the interface to the transmission grid utilized a quite different approach from that for the gate control equipment and was undertaken to meet a different performance goal. Large and seismically-vulnerable equipment associated with nine 500 kV generator step-up transformers is mounted on tall reinforced concrete fire walls that surround each transformer (Fig. 12). Due to the height of the walls, this equipment is subjected to significantly amplified seismic shaking. Each transformer includes a Motor-Operated Disconnect switch (MOD), a Capacitive Voltage Transformer (CVT), a Surge Arrester (SA) and three insulator posts. The PI spectra at these equipment locations on the fire walls, in some cases, substantially exceeded the levels of shaking to which the equipment had been seismically qualified so it was highly unlikely that the equipment would sustain the PI level of shaking without failure (see Fig. 13 which shows the PI spectra for the MOD and CVT, (a) and (b), respectively). Whilst the project design basis did not explicitly prohibit equipment damage, the expectation of the resumption of electricity generation within 72 hours of a DBE event meant that a repair-or-replace approach was not feasible considering both the short time-frame and the potentially large amount of equipment damage.

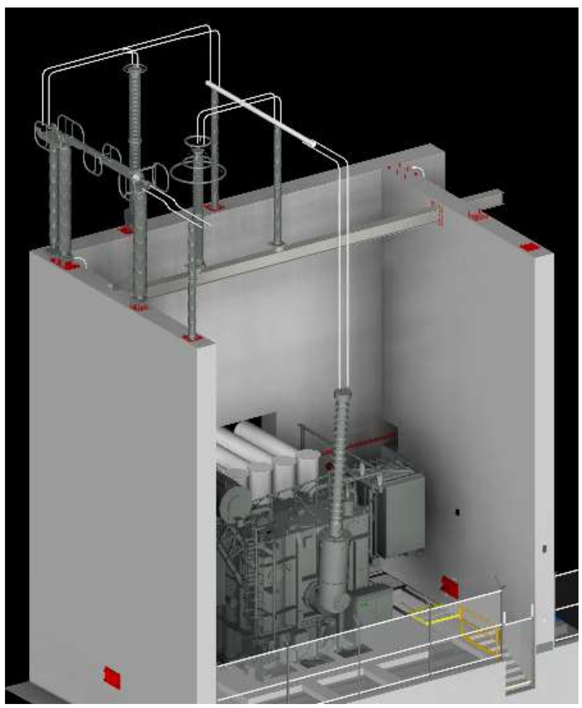
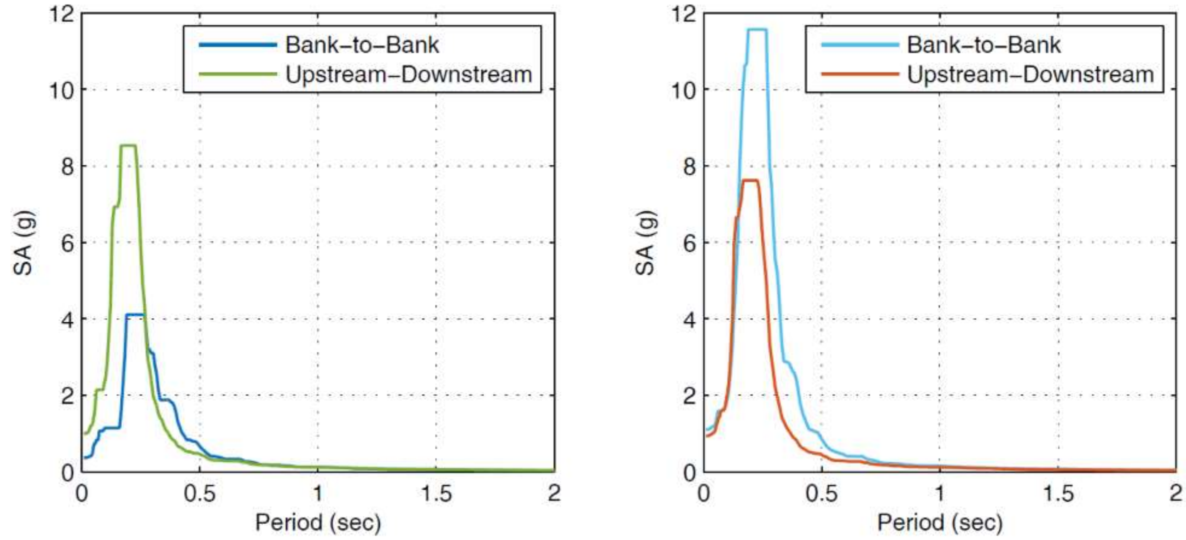


Figure 12. 500 kV equipment on top of GSU transformer fire walls.

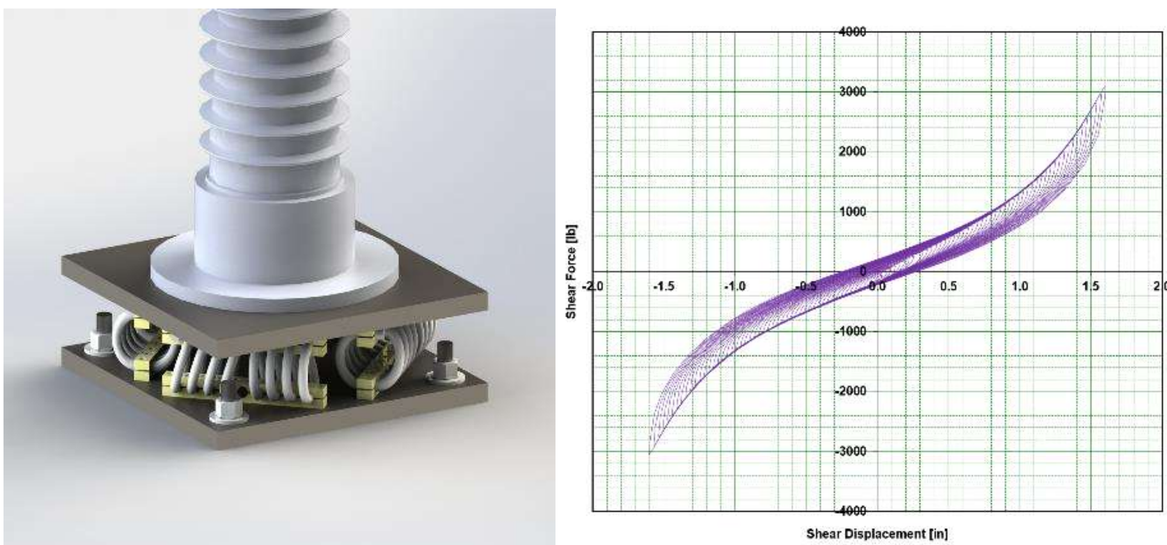
Seismic isolation was therefore selected to provide a higher level of protection to the 500 kV equipment to meet the project performance objective. The details of the equipment, and their locations atop the fire walls (and for some, on beam elements) presented significant constraints and challenges for isolation. Wire Rope Isolators (WRIs) were ultimately selected (Fig 14 (a)), which while providing some flexibility in the horizontal and vertical directions, offer the primary benefit of rocking mode flexibility which achieves substantial reductions in seismic bending demands on taller, slender equipment.

A detailed nonlinear finite element study was undertaken to evaluate the response of the MOD, CVT, SA and insulators supported on WRIs. The equipment was modelled with expected stiffness and mass properties while each of the WRIs was modelled using two elements in parallel, a piece-wise linear force-deformation backbone curve in combination with a nonlinear damper to represent the physical behavior of the WRI shown in Fig 14(b).



(a) *(b)*

Figure 13. PI spectra at the location of the MOD (a) and CVT (b).



(a) *(b)*

Figure 14. Wire rope isolator installation configuration (a), and shear hysteretic behavior (b).

To determine the seismic response at each location of the equipment, a detailed finite element analysis of the fire walls had previously been completed. The nonlinear time history analysis of the equipment on the WRI platforms made use of the five, three-component time histories which defined the wall motion at each location.

The analysis determined the maximum bending moments at the base of each component for the case when the equipment was mounted on WRIs and when it was fixed directly to the top of the wall or beam. In all cases, the mean maximum bending moments for the equipment mounted on WRIs were below the manufacturer's published rating. This was not the case for the equipment fixed directly to the top of the walls or cross beam (i.e., without WRI isolation). In several cases the response atop the WRIs was five to ten times less than for the case when the equipment was rigidly mounted. The analyses also evaluated the displacement at the top of the equipment, which is important for the bus work interconnects. It was observed that even when flexibility was added to the base of the equipment in the form of a WRI platform, the deformation at the top of the equipment was less than for the case when the equipment was fixed at its base. In some instances, the isolated equipment displacements.

Tests of the WRI devices were undertaken to establish the detailed properties used in the nonlinear design analyses, and production tests of all WRI devices was performed prior to equipment installation.

CONCLUSIONS

The Site C Clean Energy project is using two types of seismic isolation to achieve enhanced seismic protection of a wide range of critical equipment. High-performance 3-D isolation platforms are used to achieve post-MDE functionality protection of gate control equipment critical to reservoir water level control and dam safety, and wire rope isolation is used to protect 500 kV electrical equipment at the interface to the regional grid, ensuring post-DBE event generating capability. The implementation of the isolation systems utilized nonlinear analyses, shake table systems testing and spring, damper and wire rope device testing to confirm properties and behavioral characteristics.

ACKNOWLEDGMENTS

Many others at the authors' companies have participated in and contributed to the design and implementation of seismic isolation for the Site C equipment. Equipment qualification shake table testing was performed at the University of British Columbia, Vancouver, Canada, and 3-D seismic isolation platform shake table performance validation testing at the University of Nevada, Reno, USA. The valuable work of all others involved and these testing laboratories is gratefully acknowledged.

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