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Seismic Station Design, Installation and Data Acquisition at Selected BC Hydro Facilities

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ABSTRACT

A campaign-style (semi-permanent) deployment of co-located broadband seismometer and accelerometer sensors has been initiated at selected BC Hydro facilities to record site-specific earthquake ground motion data, to derive the non-ergodic site terms for application to site-specific Probabilistic Seismic Hazard Analysis (PSHA). Like many of BC Hydro's critical dam sites, the selected facilities are characterized as hard rock sites (average shear wave velocity, Vs_{30} = 1500 to 2800 m/s), which necessitates a correction to the existing seismic hazard from the 2012 BC Hydro PSHA that is referenced to Vs_{30} = 760 m/s.

Two solar-powered seismic stations are deployed at each facility to inform the spatial variability of the hard rock response across the site. Each seismic station consists of a three-component force-balance broadband seismometer and a strong motion accelerometer sensor installed side-by-side within a surface metal vault enclosure, which is anchored to a concrete pad cast directly on clean, competent bedrock. The sensors provide a constant amplitude response within the frequency range of interest from 0.01 Hz to 100 Hz. This surface vault approach is the preferred configuration to maximize data quality and minimize installation costs, while permitting access to the equipment for data retrieval and maintenance.

Target locations for the seismic monitoring stations are identified by recording and evaluating the amplitude of ambient noise in the frequency range of interest using a three-component portable tomograph. The importance of these measurements in the selection of a preferred station location is demonstrated alongside constructability and access considerations.

Data are acquired on a continuous basis with sampling rates of 200 Hz for the broadband sensors and 100 Hz for the strong motion sensors to optimize storage on internal and external storage media in miniSEED file format. Ten seismic monitoring stations are installed at five project sites. To date, over 385 earthquake ground motion records with local magnitudes as low as 2.2 have been collected to derive the non-ergodic site terms and characterize the associated epistemic uncertainty, which demonstrates the benefit of minimizing potential sources of noise in station design and construction.

Keywords: instrumentation, site response, hard rock correction, ambient noise, data acquisition

INTRODUCTION

A Probabilistic Seismic Hazard Analysis (PSHA) for 42 BC Hydro dam sites was completed in 2012 [1]. The 2012 BC Hydro PSHA was carried out for a reference site condition defined by a time-averaged shear wave velocity for the uppermost 30 m (V_{S30}) of 760 m/s, such that an adjustment is required to the design spectra to provide input ground motions for dam sites located on hard-rock (i.e. V_{S30} of 1500 m/s to 2800 m/s).

The common approach of calculating Hard Rock Correction (HRC) factors to adjust the seismic hazard is the *Vs*-kappa0 approach [e.g. 2], which requires characterizing the shear wave velocity profile (*Vs*) and the near-surface high frequency attenuation parameter, kappa (κ_0) at the target site of interest, as well as corresponding parameters at the reference (host) site. This approach carries large epistemic uncertainty in characterizing these parameters, which carries through to the HRC factors and the adjusted seismic hazard. An alternative approach for deriving HRC factors involves characterizing the site-specific behaviour by recording ground motions at the target site of interest. The novel methodology of deriving the non-ergodic site response and hard rock adjusted seismic hazard curves using site-specific ground motion data at hard rock sites in British Columbia was developed through an initiative commenced in 2018, which involved a panel of experts and BC Hydro Civil Engineering personnel [3,4]. The derivation of non-ergodic site terms from the measured ground motion data, subsequent derivation of HRC factors and calculation of the adjusted seismic hazard is described in a companion paper [5]. One benefit of this approach is that the epistemic uncertainty (i.e. standard errors) of the site factors can be quantified and carried through the procedure, which ultimately influences the hard rock corrected Uniform Hazard Spectra (UHS). A sufficient compilation of site-specific measurements reduces the uncertainty in the non-ergodic site terms, which can potentially reduce the seismic hazard and impact the final design criteria at the facility.

Although many of the BC Hydro facility sites are equipped with Strong Motion Accelerometers (SMA), none of these has sufficient recordings to enable the calculation of non-ergodic site terms required for application of HRC to PSHA. To address this need, a campaign-style (semi-permanent) deployment of co-located broadband and accelerometer sensors was initiated at select facilities to collect site-specific ground motion records for a large range of earthquake source magnitudes.

This paper describes the design and installation of the BC Hydro seismic monitoring stations, which demonstrates a balance between the need to collect high quality data with consideration for constructability, access and cost. The importance of ambient noise measurements in the selection of target station site locations is discussed, as well as practical data acquisition aspects for the collection of a continuous data record in semi-remote environments.

PROJECT SITES AND SEISMIC STATION LOCATIONS

To date, ten semi-permanent seismic monitoring stations have been installed at five BC Hydro project sites in British Columbia, as shown in Figure 1 and described in Table 1.

Figure 1. BC Hydro facility locations where co-located broadband seismometer and accelerometer sensor stations are installed.

Table 1. Summary of BC Hydro Seismic Monitoring Stations.

Facility	Seismic Station In-Service Date	Bedrock Geology	Station	Number of event records (to date)	
Site 1	Mar 2020	coarse grained granodiorite	1 2	97 211	(Sep 2022)
Site 2	Jun 2020	basaltic lava	1 2	44 33	(Aug 2022)
Site 3	Jul 2020	medium grained andesite	1 2	85 53	(Jul 2022)
Site 4	Nov 2021	thinly interbedded argillite and chert	1 2	19 16	(Oct 2022)
Site 5	Oct 2022	granitic gneiss and mica schist	1 2	26 26	(Mar 2023)

SEISMIC STATION DESIGN

A campaign-style (semi-permanent) deployment approach was implemented with the intent to collect sufficient ground motion records at each project site to derive the non-ergodic site terms for application of HRC to PSHA.

The seismic stations were designed to meet the following requirements:

- Maximize data quality and minimize installation costs;
- Protect equipment from weather elements and be waterproof;
- Accommodate personnel access to the equipment for manual downloading of the data and any required maintenance;
- Include a secure enclosure to prevent tampering with the equipment;
- Enable the equipment to be removed and relocated to another project site for installation, if desired;
- Enable upgrade to a permanent seismic station site in future, as required.

A surface vault installation was selected as the preferred approach to meet the design requirements for the semi-permanent stations, as illustrated in Figure 2. Each seismic station consists of a co-located installation of a three-component force-balance broadband seismometer and a strong motion accelerometer sensor installed within a metal vault enclosure anchored to a concrete pad, which is cast directly on and anchored to clean, competent bedrock. The intent of the concrete pad is to facilitate representative measurements of bedrock ground motion over the full range of expected earthquake magnitudes using broadband (weak motion) and strong motion sensors.

Nanometrics Inc. (Nanometrics) of Ottawa, Ontario was awarded a contract through a public bid process to supply the seismic monitoring equipment, design the installation, and provide technical support and training for the installation and commissioning of the seismic instrumentation to BC Hydro personnel.

Surface Vault Design

The design of the surface vault incorporated lessons learned from the design and construction of Natural Resources Canada (NRCan) broadband seismic stations [6].

Key design considerations for the surface vault were as follows:

- Limit height to length ratio of concrete pier to mitigate amplification effects in the concrete slab;
- Physically separate and insulate an inner concrete sensor pad within the larger concrete pad to mitigate the effects of temperature fluctuations or other external forces on the broadband measurements;
- Reduce air space within the vault enclosure with thermal insulation to optimize temperature stability and mitigate long period noise/drift in the broadband seismometer;
- Limit use of reinforcement or rock anchors in inner sensor pad to mitigate any potential for magnetic interference or vibrational noise in the frequency range of interest.

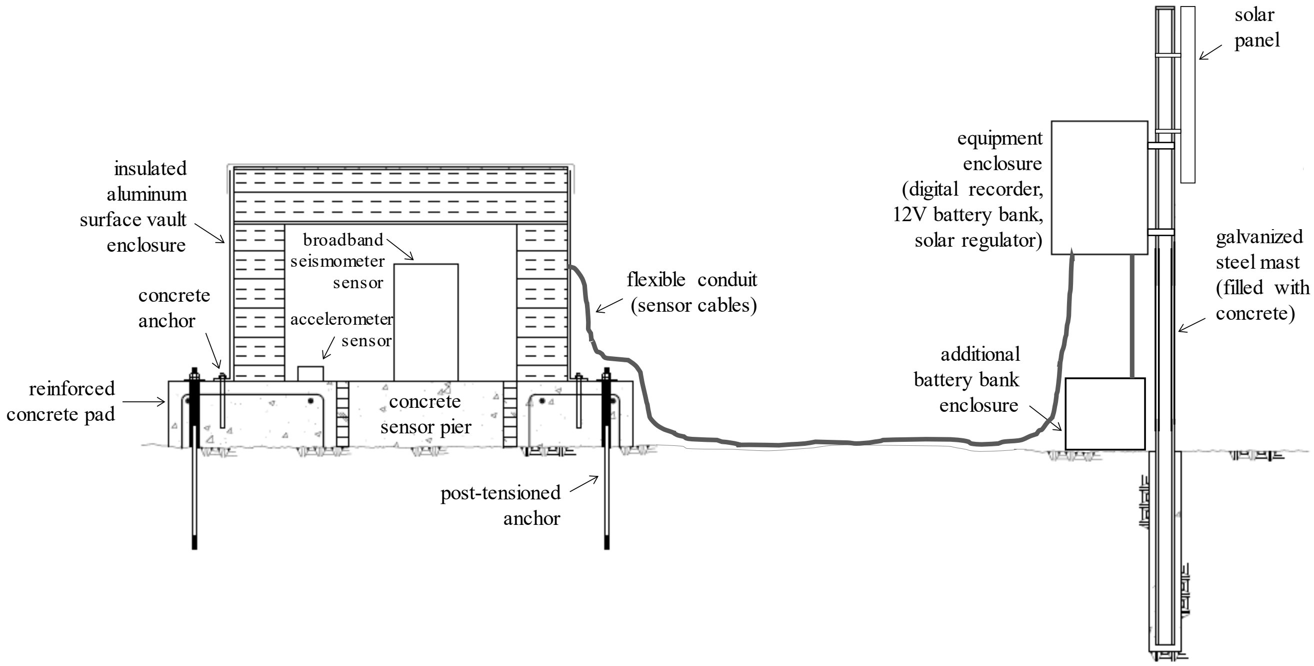

Figure 2. Seismic Station Design Schematic.

A concrete pad design supplied by Nanometrics was implemented at Site 1 with design modifications introduced by BC Hydro, which included specifying stainless steel rebar to improve durability, reducing the number and positioning of rock anchors used to pin the outer concrete ring pad, and removing any reinforcement or anchors from the inner sensor pad. The design was further developed by BC Hydro prior to installation at subsequent project sites, as illustrated in Figure 2. Features of the BC Hydro design include the following.

- Four post-tensioned anchors at the corners of the outer reinforced concrete ring pad. These were designed to maintain a positive attachment to the bedrock over the full range of peak ground accelerations (PGA) predicted for BC Hydro facilities in the 2012 BC Hydro PSHA model, whether the pad is constructed on flat or sloping bedrock.
- No reinforcement or anchoring of the inner concrete sensor pad to mitigate these as potential sources of noise in broadband sensor measurements; inner sensor pad offset from centre to enable the strong motion accelerometer to be bolted directly to the anchored reinforced concrete outer ring pad.
- A light reinforcement cage consisting of stainless steel (non-ferrous) reinforcement bars, and the use of stainless steel anchors in the outer concrete ring pad to mitigate the possibility of magnetic interference.
- Consideration for the effect of a variable snow pack on the aluminum vault enclosure and galvanized steel mast. A heavier gauge vault enclosure is specified for equivalent snow loads in excess of 5 kPa up to 12 kPa. Similarly, a taller and larger diameter mast is specified for these conditions to maintain the solar panel above the expected maximum height of the snow pack in winter months.

The concrete pad was designed to facilitate representative measurements of ground motion at the bedrock surface without interference from the surface vault itself. For concrete pad installations on bedrock, the possibility of soil-structure interaction effects amplifying the high frequency part of the earthquake signal (> 10 Hz) is small and may be considered negligible [7]. The geometry of the concrete pad mitigates amplification of the bedrock ground motion with a maximum height to width ratio of 0.5. The specified width of the reinforced concrete pad is 1.8 m and the height ranges from a minimum of 0.25 m to a maximum of 0.92 m for installation on sloping ground (up to 20 degree slope). The width of the inner sensor pier is 0.6 m. The natural frequency of the concrete pad was calculated to be in excess of 5000 Hz, which is well outside the frequency range of interest (0.01 Hz to 100 Hz).

Sensors and Equipment

A key performance requirement of the seismometer and accelerometer sensors was that together they would accurately capture ground motions between 0.01 Hz and 100 Hz. The instrument noise (self-noise) of the accelerometer must be low enough to resolve ground motions accurately below the clip level of the seismometer, and together with the seismometer provide a constant amplitude response within the frequency range of interest. The Trillium Horizon broadband seismometer and the Titan strong motion accelerometer sensors supplied by Nanometrics were selected to meet the specified performance requirements.

Thermal stability is an important consideration for collecting accurate data when low-noise broadband sensors are used, particularly at the low end of the frequency range (< 1 Hz) [e.g. 8]. Layers of rigid insulation were used to line the inside the sealed aluminum surface vault, a single layer of rigid insulation was installed around the perimeter of the inner sensor pier, and an insulating cover was installed over the broadband seismometer to mitigate the effects of ambient temperature fluctuations on the broadband measurements.

As illustrated in Figure 2, the seismic station layout includes a pole-mounted 180 W solar panel to supply power to the system and an equipment enclosure to house two 12 V batteries, a solar regulator and a 24-bit Centaur-6 digital recorder. Sensor cables are routed through watertight, non-metallic flexible 5 cm diameter conduit and connected to the digital recorder. Electrical grounding of the instrumentation and bonding of the metal enclosures was achieved by routing a separate insulated copper conductor from the equipment enclosure to the inside of the surface vault enclosure, where it is connected to a grounding electrode encased in the concrete pad. The aluminum vault is bonded to the grounding electrode using a grounding lug internal to the vault enclosure.

At project sites with limited solar exposure, an additional two-battery bank was connected in parallel and housed in an external, insulated enclosure at the base of the mast with cable routed through flexible conduit to the main pole-mounted enclosure. The four 100 Ah battery bank increased the capacity two-fold, from approximately two weeks (with only two batteries) to over one month with no solar charge. The larger battery bank improved reliability for continuous data collection at stations with more limited solar exposure, particularly through the winter months. Gel-type batteries were sourced for their durability and performance over traditional lead-acid batteries, as they are less susceptible to damage, perform more consistently over a wider temperature range, and have a longer lifespan before requiring replacement.

Equipment Mast

The lower third of the mast is grouted into bedrock and the inner annulus of the entire length of the mast is filled with concrete to mitigate the potential for vibration due to wind or other forces, which could negatively impact the recorded seismic signals. The mast is physically separated from the edge of the concrete pad by at least two metres in typical installations (maximum height of mast 1.8 m above grade), and by at least five metres when a taller mast is used in larger snow pack applications (maximum height of mast 3 m above grade). These specified offset distances ensure that the distance between the mast and sensor is greater than the height of the mast to minimize the potential interaction between the two, and allow for a practical station footprint and reduced length of sensor cables. The natural frequency of each mast type is approximately 3 Hz or 6 Hz, for the nominal 7.5 cm and 10 cm diameter pipe, respectively. These frequencies fall within the signal measurement range of interest, so some level of noise interference may be expected at that frequency. This is an area of future study to quantify the noise effect of the mast installation (if any) on the broadband measurements.

STATION SITE SELECTION

Two seismic stations were planned and deployed at each project site to inform the variability of the hard rock site response at the facility and to provide redundancy. The intent of the measurements is to characterize the non-ergodic site response of a given facility using ground motion records that are free of any interference from nearby infrastructure. However, the proximity of the facility precludes true "free field" measurements. The station site selection must balance a requirement for low ambient noise levels with constructability and access considerations.

Target locations for construction of the seismic monitoring stations were selected by BC Hydro based on the following criteria:

- Proximity to facility (within ~1 km) but away from the dam and/or very steep topographic features;
- Very shallow depth to competent bedrock;
- Low ambient noise levels;
- Ease of access;
- Good solar exposure;
- Within BC Hydro property boundary;
- Low probability of vandalism;
- Potential for permanent deployment in future (power supply and communication considerations).

A site visit was performed at each facility to identify candidate locations for the installation of seismic instrumentation using the criteria outlined above. Ambient noise measurements were carried out at each candidate station location using a 3-component portable tomograph (TROMINO BLU manufactured by MoHo S.R.L.) to assess the amplitude of noise in the frequency range of interest. Initially, ambient noise recordings consisted of approximately 30 minutes of continuous measurement along three orthogonal axes (North-South, East-West, Vertical) at a sampling frequency of 128 Hz. At Facility Sites 4 and 5, the sample duration was extended to 50 minutes at a frequency of 512 Hz to increase the bandwidth for evaluation.

The tomograph was firmly positioned on exposed rock and levelled prior to measurement. The sensor orientation was kept constant at each candidate site to enable a comparison of the raw and processed records. Data were collected with a plastic bucket placed over the sensor to protect it from wind and solar exposure, to limit the effect of these noise sources on the measurements. The ambient noise time history records were trimmed at start and end to remove noise associated with the operator accessing the unit, then processed to calculate the Horizontal-to-Vertical Spectral Ratio (HSVR) and Power Spectral Density (PSD) across the frequency range of interest. The mean HSVR curve is an indicator of site amplification and ideally should reside around unity at hard rock sites. The PSD curve provides a measure of noise amplitude across the frequency band. These outputs enabled a quantitative ranking of the suitability of each candidate site for seismic monitoring based on the relative amplitude of background noise. Sites were evaluated qualitatively using the other criteria listed above to select the two most suitable sites for construction of the seismic stations.

The importance of ambient noise measurements is demonstrated in Figure 3, which compares the PSD curves for the suite of candidate locations surveyed at Site 5. Generally high ambient noise levels exist at this facility, due to existing infrastructure and operation activities. However, Locations 5 and 6 demonstrate considerably higher noise levels and were excluded from further consideration as potential seismic monitoring station sites. Figure 3 also includes a comparison of Site 5 with the mean PSD for a candidate station location at Site 4, which is characterized by much lower ambient noise levels, especially at higher frequencies.

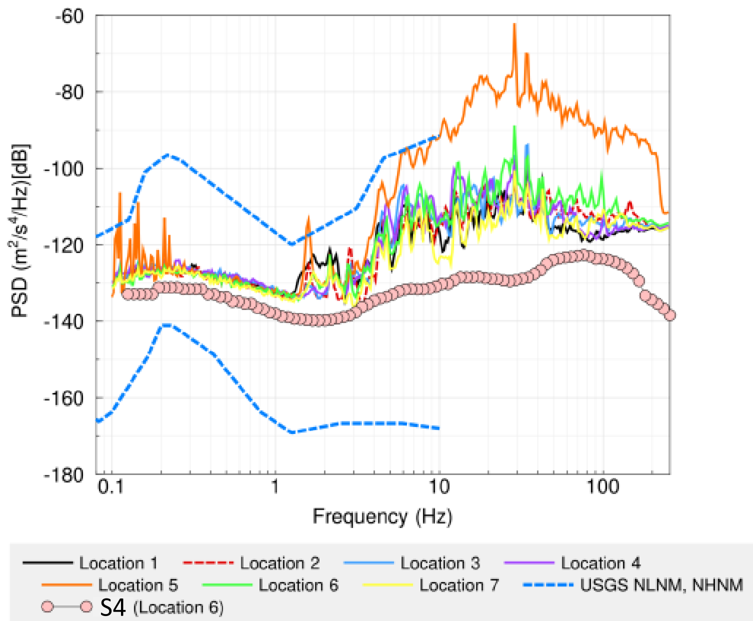

Figure 3. Comparison of mean PSD of measured ambient noise at candidate seismic station locations at Site 5. Mean PSD at a Site 4 candidate location and the U.S. Geological Survey New Low/High Noise Models (NLNM, NHNM) are shown for comparison.

STATION CONSTRUCTION AND INSTALLATION

The construction and installation of the seismic monitoring stations has been carried out internally through a collaboration between BC Hydro Construction Services and Engineering personnel to develop in-house capability and to promote consistent, high-quality, cost-effective installations.

Key work items for the construction of the seismic monitoring stations are listed below, which focus on thoughtful station layout and careful preparation of the bedrock surface to promote bonding of the concrete and rock.

- Clearing, grubbing and construction of safe access for construction, operation and maintenance of the seismic station.
- Earthworks including leveling of site, holes for pole mounts and foundations, overburden excavation and exposure of bedrock.
- Staking out location and orientation of the concrete pad and solar panel mast in consultation with Engineering personnel.
- Cleaning and preparation of bedrock surface for placement of the concrete pad, which consisted of:
  - Machine and hand excavation of the overburden and weathered rock;
  - Cleaning of the rock surface by hand methods that may include brushing, air or water, as required.
- Constructing concrete pad on the cleaned bedrock surface as per the Drawings and Specifications.
- Installing vault enclosure on the concrete pad as per the Drawings and Specifications.
- Installing equipment mast in bedrock as per the Drawings and Specifications.

The relative position of the mast with respect to the surface vault in practice is dictated by the ground surface conditions, optimum solar exposure, and available sensor cable length. A typical station layout makes use of 5 m sensor cable lengths. However, 10 m long sensor cables provide improved flexibility to field-fit the optimal mast location without risk of cable stretch or creating a tripping hazard. Solar panels are mounted vertically to prevent snow accumulation and oriented as best as possible to achieve southern exposure.

Sensor Installation

Prior to sensor installation, all equipment was configured and bench tested according to the procedures from the manufacturer. Sensor installation consisted of placing the broadband sensor on the concrete sensor pier and levelling the sensor using adjustable feet. The strong motion accelerometer was anchored to the reinforced concrete pad using the supplied anchor bolt. Both sensors were oriented true North, using an analog compass set to the appropriate declination for the area.

Each sensor was calibrated and a foot stomp test performed to provide visual confirmation that the sensors were operating correctly and recording the imposed ground motion. The instrument response was downloaded for each sensor and digitizer configuration for use in evaluating the measured ground motions.

DATA ACQUISITION AND PROCESSING

Data Acquisition and Storage

A performance requirement of the equipment was to sample data continuously and support sampling rates of 200 Hz and 400 Hz on all six seismic channels (three channels for the seismometer and three channels for the accelerometer). For the campaign-style (semi-permanent) deployment, a minimum storage capacity of two months of continuously-recorded data on all six seismic channels sampled at a minimum of 200 Hz was required, with accessibility for manual download.

Data are currently being acquired on a continuous basis with sampling rates of 200 Hz for the broadband sensors and 100 Hz for the strong motion accelerometer sensors to meet the frequency range requirements while optimizing data storage.

Data are stored on internal and external storage media in miniSEED file format. The Centaur digital recorders are equipped by default with 8GB of internal memory storage, with the option to add an internal SD card to increase the internal memory. The internal memory is configured so that once it reaches capacity it will start recording the newest data over the oldest stored data (ring memory). Based on the current sampling frequencies the internal 8GB memory was found to reach capacity in approximately 6 weeks. A secondary removable 32 GB SD card installed in the Centaur serves as a data backup (effective storage capacity of 29 GB). As a precautionary measure, data were manually downloaded from the seismic stations on a six-week interval by replacing the removable SD card, prior to the internal memory reaching its storage capacity. Recent upgrades to a 32 GB internal memory permit much less frequent visits, approximately every 6 months. However, quarterly site visits are targeted to enable an inspection of the station, sensors, batteries and equipment combined with manual data retrieval.

A field check log is completed at each site visit and stored with the raw data files, which documents the details of the data download and memory status, the visual check of the equipment, and the review and image capture of software user interface screens that report out sensor details and status of equipment.

Poor or no cellular coverage at most facility locations precludes the use of remote telemetry to evaluate sensor health or retrieve data automatically. Although this functionality is still being considered for select application, manual data retrieval remains the most cost effective option for the expected lifespan of the stations.

Data Processing

Following data retrieval in the field, all of the raw accelerometer and seismometer data are extracted and checked for completeness using an automated quality assurance routine. This process confirms whether a continuous data record exists, or if data gaps resulting from low battery voltage or other causes need to be investigated.

An existing earthquake event catalog is queried to identify and extract associated ground motion records from the seismic monitoring station data for further analysis. All of the accelerometer and seismometer data are extracted, producing six time series for each event. Following typical notation, the three accelerometer components are labeled HNE, HNN, and HNZ; and seismometer channels are labeled HHE, HHN, and HHZ. Each time series is baseline corrected, tapered (1% of the time series length at each end), filtered from 0.01 Hz to the Nyquist frequency (equivalent to 100 Hz for seismometer records and 50 Hz for accelerometer records), and has the instrument response removed. Figure 4 illustrates acceleration time series recorded at both Stations 1 and 2 at Site 1, corresponding to a magnitude 3.8 crustal earthquake event. The difference in ambient noise amplitude between these two stations is evident in the time series data.

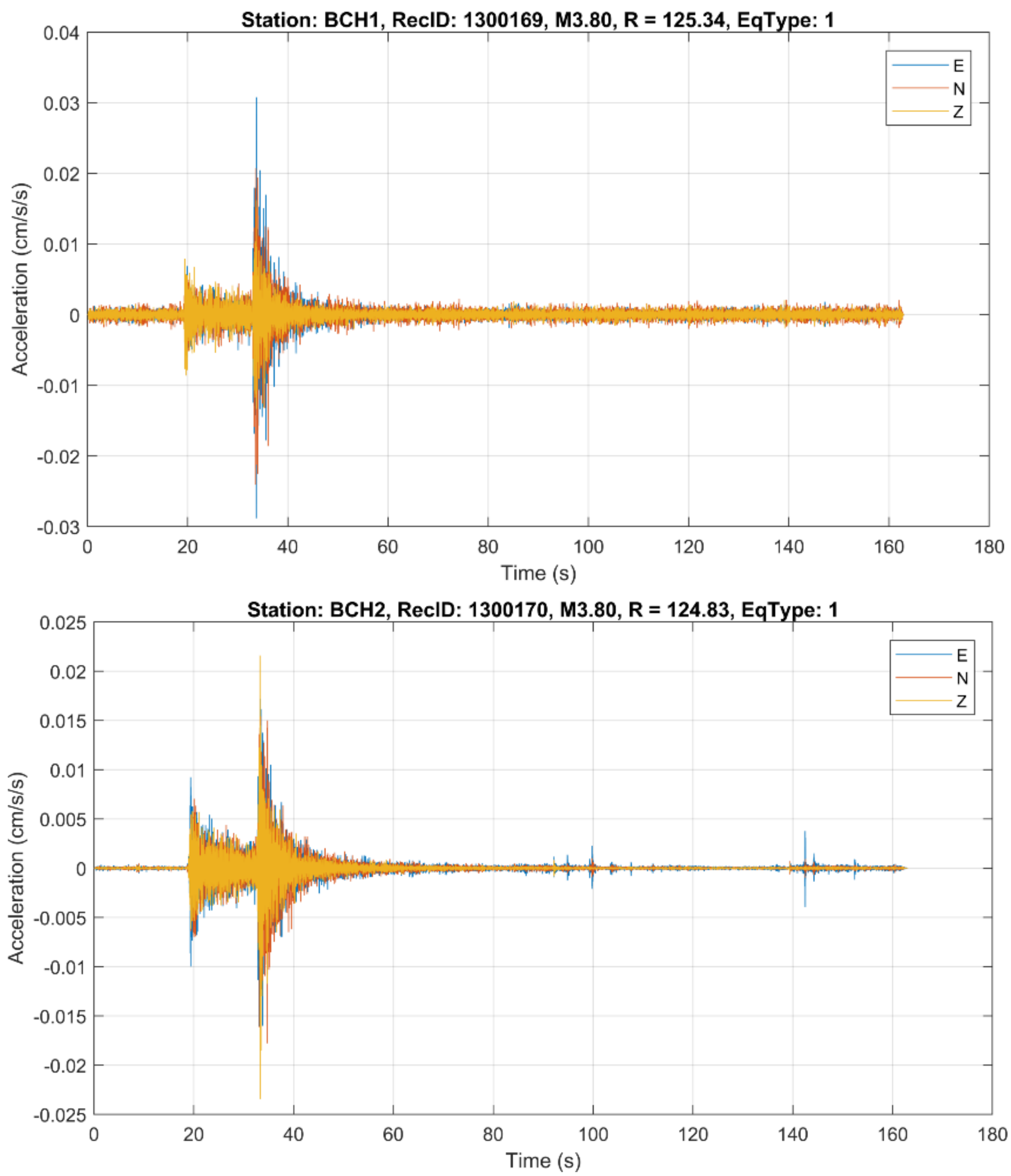

Figure 4. Three-component broadband seismometer record collected at Site 1 Station 1 (top) and Station 2 (bottom) corresponding to a M3.8 crustal earthquake event at a hypocentral distance of 124.8 km.

Table 1 lists the total number of event records extracted from the continuous data collected to date at each seismic monitoring station, which correspond with earthquakes with a local magnitude as low as 2.2. The magnitude-distance distribution of the ground-motion database collected to date at Site 1 is illustrated in Figure 5. The Site 1 database includes 97 and 211 event records at Stations 1 and 2, respectively. The difference in the number of event records reflects the relative ambient noise levels at each station. Higher ambient noise levels at a station may preclude some records from meeting the minimum signal to noise threshold to be considered useful for determining the site response. Nevertheless, the significant number of quality records collected over a two-year period at Site 1 has exceeded the minimum required to effectively estimate the non-ergodic site terms and characterize the epistemic uncertainty of the site response [5]. This demonstrates the utility of collecting high quality site-specific ground motion data and confirms the importance of minimizing potential sources of noise in station site selection, design and construction.

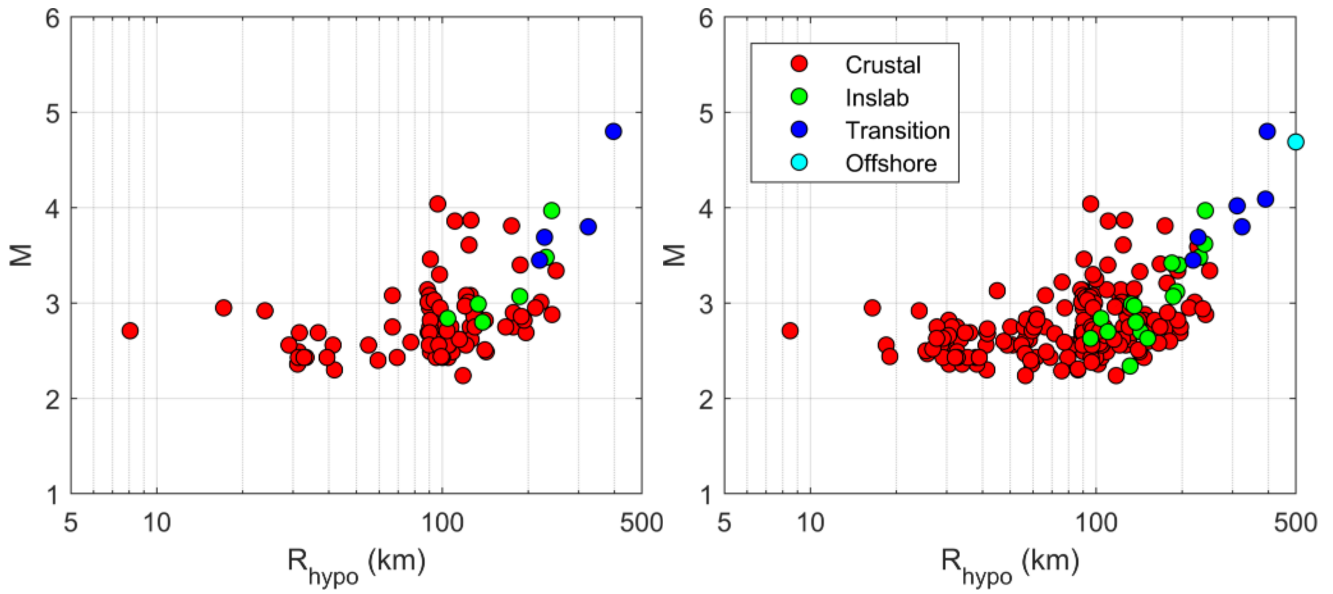

Figure 5. Distribution of earthquake moment magnitude versus hypocentre distance for all records collected at Station 1 (left) and Station 2 (right) at Site 1 between March 2020 and September 2022. Events are colour-coded according to earthquake type.

CONCLUSION

BC Hydro has installed ten semi-permanent seismic monitoring stations to record earthquake ground motions at five facilities in the province for the purposes of carrying out site-specific adjustments to existing PSHA results at hard rock sites. The number and quality of ground motion records collected to date suggest these stations are meeting performance expectations and serving their intended purpose to provide ground motion records to derive the non-ergodic site terms at each facility. This validates the importance of minimizing potential sources of noise in station design and construction. Careful site preparation to clean and expose a competent bedrock surface prior to concrete placement, mitigating amplification and potential for vibrational noise in the design and construction of the concrete pad, and promoting temperature stability within the sensor vault all contribute to representative measurements of bedrock ground motion over the target frequency band of 0.01 to 100 Hz for a wide range of earthquake magnitudes, using the combination of broadband (weak motion) and strong motion sensors.

The importance of ambient noise measurements as a criterion in the selection of candidate station locations can not be overstated. The measurements are relatively straightforward and provide tremendous insight to the variation in noise levels across the site and the suitability of specific locations, as well as serving to highlight potential challenges in collecting quality data at specific frequencies where the signal to noise threshold may be low.

As reported in a companion paper [5], approximately one to 1.5 years of data recorded in an active seismic region (approximately 70 useable earthquake events) is sufficient to estimate the non-ergodic site terms and characterize the epistemic uncertainty at a given project site over most frequencies of interest. Consequently, the expected duration for operating seismic monitoring stations to derive the non-ergodic site response is up to two years, and up to five years in less seismically active regions.

ACKNOWLEDGMENTS

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