Engineering
Report E658
November 2012

Probabilistic Seismic Hazard Analysis (PSHA) Model
Volume 1: Methodology

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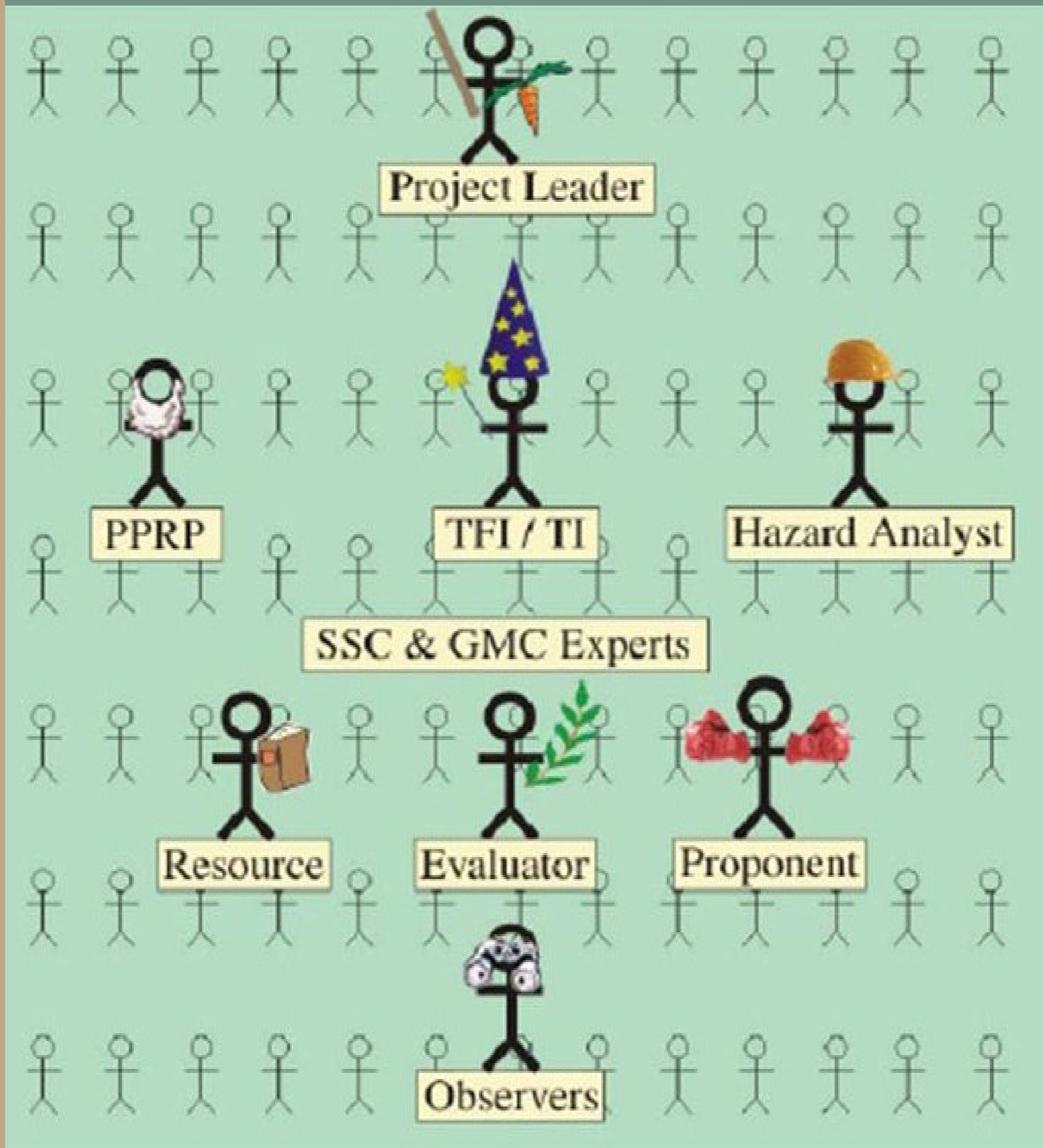

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PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA) MODEL

VOLUME 1: METHODOLOGY

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Report No. E658 - Vol. 1
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WPR-3201

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PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA) MODEL

VOLUME 1: METHODOLOGY

LIST OF VOLUMES

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PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA) MODEL

VOLUME 1: METHODOLOGY

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PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA) MODEL

VOLUME 1: METHODOLOGY

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1.0 INTRODUCTION

This volume is the first of a four part report that presents the BC Hydro Probabilistic Seismic Hazard Analysis (PSHA) Model. It describes the goal and scope of the PSHA, BC Hydro's project requirements, the project team and organizational structure, the PSHA methodology, implementation and quality assurance. The four volumes of the PSHA report are:

Volume 1: Methodology
Volume 2: Seismic Source Characterization (SSC)
Volume 3: Ground Motion Modelling (GMC)
Volume 4: Implementation and Results

In this section, the goal, scope requirements, organization and participants in the project are presented. The PSHA was carried out following the guidance provided by the Senior Seismic Hazard Analysis Committee (SSHAC) (Budnitz et al, 1997; Kammerer and Ake, 2011). The intent of conducting this study was to develop a PSHA model that will provide a technically sound, stable estimate of ground motion hazards at BC Hydro dam sites for the next 10-15 years. Experience suggests that such stability is achievable when in-depth evaluations are performed and comprehensive evaluations of epistemic uncertainties are made (EPRI, 1988; Kammerer and Ake, 2011).

BC Hydro assets, including dams and hydropower production sites, transmission facilities, office buildings, etc. are located throughout the province. However, in accordance with the user requirements, the PSHA study placed particular focus and detail in the model development parts of the study area where BC Hydro dams are located; a total of 42 sites (41 existing dam sites and one proposed site). As such, nearly the entire province of BC, parts of Alberta and the Northwestern U.S. were part of the study region.

The PSHA was a major programmatic and technical undertaking. The significance of this effort is measured by the project goals (discussed in more detail in Section 1.1) and the size and tectonic diversity of the region:

1. The tectonic diversity of the study region varies from the active plate margin of the Cascadia subduction zone interface which may generate up to **M**9 earthquakes below southwestern BC to the west, to the stable continental interior of eastern BC and Alberta. (Figure 1.1-1).
2. The availability of data to perform the PSHA is very heterogeneous across the province. For much of the study region, there is limited data or large gaps in basic data. For instance, in the eastern part of the study region the historic earthquake catalogue is limited and incomplete due to the low seismicity rates, short duration and limited extent of seismic monitoring (Section 4.3 of Volume 2).
3. Due to low seismicity rates in much of BC and the limited strong motion recording network, there are relatively few strong motion recordings available.
4. Increasing sophistication in the modelling and parameterization of a PSHA requires detailed specification of a number of seismic source properties that were not previously considered in past PSHA studies.
5. There are elements of the PSHA that required new development to support the project objectives, to address new datasets or modelling gaps. These include improvements in seismic source characterization, modelling capabilities (see Section 5 in Volume 2), the use of the single-station sigma modeling approach (see Section 3 in Volume 3) and the development of a new subduction ground motion prediction model (see Section 3 in Volume 3).

The remainder of this section describes the project requirements, goals of the evaluation, project organization, and the participatory peer review process.

1.1 PROJECT REQUIREMENTS AND SCOPE

BC Hydro is the sponsor of the PSHA and an end user of the model. At the conclusion of the project BC Hydro will own, maintain the PSHA model and perform PSHA calculations on an as-needed basis. (BC Hydro, 2012) presents the background, basis of the interest and need to conduct an up-to-date and comprehensive assessment of the seismic hazard in BC and a basis for estimating earthquake ground motions at the dam sites. With the perspective of a sponsor and end user, certain needs and standards that relate to the dam safety program and in-house engineering requirements were identified. The requirements for the project were:

- A PSHA shall be performed using the SSHAC process (Budnitz et al, 1997; Kammerer and Ake, 2011).
- Technical stability of the PSHA model and the stability of the PSHA results over time (for a period of 10-15 years).
- Transparency of the modelling and evaluations that were conducted that supports staff capability to understand and interpret the basis for the PSHA inputs, and as might be required in the future to refine or update elements of the PSHA inputs,
- Establish an in-house capability to implement and use the PSHA (software and inputs) for evaluation of other BC Hydro asset sites (other than the 42 dam sites).

A key requirement was that the PSHA results as determined from the SSC and GMC inputs remain technically stable for the next 10-15 years following the completion of the project. During this period, it was expected that estimates of seismic hazard at the various dam sites not be subject to significant change as new information becomes available. Stability in the PSHA results is important due to the value of the investment in the PSHA product and the impact that changes in the hazard results have on dam safety assessments and future costs of seismic modifications..

Technical stability is achieved by conducting an assessment of uncertainties (aleatory and epistemic) through a comprehensive, transparent, understandable evaluation and integration process that is consistent with the current state-of-knowledge in the earth sciences. Once completed, the PSHA documentation also facilitates the ability to conduct periodic re-assessments of the inputs to the models due to the emergence of new data, methods, and concepts. The need to adapt to changes in internal goals, its regulatory environment and the intended applications for the PSHA is noted.

In the context of a dynamic scientific environment, stability of the PSHA inputs is defined in the context of the SSHAC goal. The inputs are judged to be stable (and thus the PSHA results as well) if future modifications (due to new developments in the next 10-15 years) based on new data or interpretations fall within the body and range of the epistemic uncertainty distributions captured in the PSHA inputs. Having a high reliability of meeting this stability requires that comprehensive evaluations of the state-of-knowledge of the technical community be carried out in order that a sound and technically defensible distribution of the PSHA inputs is developed[1].

Meeting the goal and standards defined by the SSHAC and user requirements is the responsibility of the Technical Leads and Integrators (TI), and in its oversight role, the Participatory Peer Review Panel (PPRP). The TI has intellectual ownership and responsibility for the evaluations and the development of technically defensible distribution of inputs to the PSHA;. The PPRP has three principal responsibilities. The first concerns the oversight and implementation of the SSHAC guidelines with respect to the evaluation and integration process. Secondly, the PPRP provides a technical review of the scientific evaluations that are performed and the development of the distribution of PSHA inputs. The PPRP also considers the adequacy of the documentation of the evaluation and integration process, data, analyses and results. The PPRP closure letter endorsing the implementation of the SSHAC process and the technical quality of the PSHA is provided in Appendix B.

A principal project requirement is to establish an in-house capability to use and maintain the PSHA model. This requirement leads to a level of documentation and model familiarisation that ensures staff has sufficient knowledge of the elements of the PSHA and the capability to use the tools for performing PSHA calculations.

[1] It is important to recognize that it cannot be guaranteed that all future interpretations will be explicitly represented in the composite uncertainty distribution that is developed. However, if the composite distribution is truly determined, the likelihood that new interpretations will fall outside the distribution should be small, while recognizing that new discoveries could be made that are not foreseeable. In the 10-15 year period following completion of the PSHA, the occurrence of such significant developments are generally not anticipated.

1.2 PSHA GOAL

The PSHA was conducted following the 1997 SSHAC guidelines. Among its recommendations, the SSHAC establishes a clear goal for a PSHA, and the assessment of ground motion hazards and in particular the development of the inputs to the analysis. The guidelines originally defined the overall goal for the PSHA as follows:

> *The goal of a PSHA is to develop inputs that represent the composite distribution of the informed scientific community.*

Based on a decade of experience implementing the SSHAC process, additional guidance was developed by the USNRC ((Kammerer and Ake, 2011). This new guidance re-states the overall goal for the PSHA in the following terms:

> *The fundamental goal of a SSHAC process is to carry out properly and document completely the activities of evaluation and integration, defined as:*
>
> *Evaluation: The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis.*
>
> *Integration: Representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessments of existing data, models, and methods).*

The assessment of earthquake ground motion hazard (seismic hazard curves) at a site and the quantification of epistemic uncertainty in the estimate of ground motion hazards are directly tied to the development of the PSHA inputs (i.e. SSC and GMC). The SSHAC goal recognizes there is uncertainty in the inputs to the PSHA that is attributable to limited or incomplete datasets, diverse scientific understanding (epistemic uncertainties) and process variability (aleatory uncertainties)[2]. Achieving the SSHAC goal requires that evaluations be conducted such that a complete understanding of the state-of-knowledge of the

[2] See Appendix A "Glossary and Definitions" for definitions of epistemic and aleatory uncertainties.

technical community is achieved and sources of uncertainty are identified and modelled in a technically sound, complete and transparent fashion.

1.3 STUDY REGION

The PSHA study region covers most of BC, part of the northwestern US and part of Alberta to the east as shown in the map in Figure 1.3-1. The map identifies the location of BC Hydro dam sites and highlights areas of 200 km radius around each site, which provides a perspective on the size of the study region.

1.4 LEVEL OF ANALYSIS

In the SSHAC guidelines, different levels of analysis are described to meet different sponsor needs/requirements. In this PSHA, the GMC and the SSC were conducted as SSHAC Level 3 evaluations. A key element of a Level 3 analysis is the holding of workshops and team meetings as part of the data gathering process, including presentations by resource and proponent experts, discussions with the experts and evaluation of modelling alternatives.

1.5 PROJECT ORGANIZATION

The PSHA involved a team of earth scientists and engineers with specialist experience in earthquake hazards, seismology, ground motion, and seismic source characterization. As part of the SSHAC process, the roles and responsibilities of the project participants are defined and listed in Table 1.5-1. Figure 1.5-1 shows the overall organization of the PSHA. Table 1.5-2 lists the individuals who served as part of the project leadership and the participatory peer review panel members. Individuals are listed as are their affiliations and roles in the project.

Table 1.5-3 identifies the members of the GMC Team including the TI and others who served in support roles. The names, affiliations and roles of team members in the project are given in the table.

Table 1.5-4 identifies the SSC Team members including the TI, the evaluation team and others who served in support roles. The team members, their affiliations and roles in the project are given in the table.

In addition to the members of the GMC and SSC teams, a number of resource experts participated in the project. Volumes 2 and 3 identify the various resources experts who participated in the project for the SSC and GMC respectively.

1.6 FUTURE REVIEW OF THE PSHA MODEL

A PSHA is a complex undertaking involving a comprehensive review and evaluation of all relevant earth science information; data analysis; review and development of alternative interpretations of the data; sensitivity analysis and feedback; and final evaluation and integration. The GMC and SSC models that are a product of the SSHAC process are the result of evaluations wherein the model elements (scientific interpretations, data analysis) are founded on current scientific information and understanding. In the future, BC Hydro will have to consider the potential impact that new scientific information has on the PSHA model inputs and the assessment of ground motion hazards. Such an undertaking must be done in the context of the present model, the interpretations they represent and their basis that is documented (i.e. are any new data consistent/inconsistent with the modelled interpretations) and represented in the current models.

1.7 USE OF THE PSHA MODEL

The PSHA model was developed primarily for purposes of estimating the ground motion hazard at BC Hydro’s 42 dam sites (including the proposed Site C) shown on Figure 1.3-1 with areas of 200 km radius delineated around each site. These areas were used to guide the seismic source and ground motion characterization. The development of the PSHA model was more detailed inside the collective areas encompassed by the overlapping radii than the remaining areas of the study region (Figure 1.3-1). This was especially the case where there were many dam sites clustered together as on Vancouver Island and the Lower Mainland, the Bridge River area, the southwest Interior, and the Peace Region. In the north coastal region, where Falls River and Clayton Falls dams were located and where there iwas limited data, the model was not as detailed.

For sites located outside the areas delineated in Figure 1.3-1, the Civil Design-Geotechnical department should be consulted to assess whether the level of detail in the model is adequate for a proposed application.

1.8 QUALITY CONTROL AND ASSURANCE

BC Hydro Engineering practice requires that all engineering work and products be checked and reviewed. Given that seismic ground motions are critical inputs to engineering designs, the seismic hazard assessments that are performed to estimate design ground motions must also be checked and reviewed.
In general terms, checking and reviewing for typical engineering design activities are defined as follows.

Checking is an independent verification of work elements that includes confirmation of:

- completeness – project scope is met, design conforms with the Design Basis, assumptions are indicated, all relevant data are considered;
- accuracy - design is based on sufficient data of adequate quality, calculations are correct, and
- consistency - applicable codes, standards and safety requirements are met.

Reviewing is a separate independent evaluation of the adequacy of the work which includes confirmation that:

- all applicable requirements (e.g. owner and regulatory requirements) are met,
- the design methodology is current and appropriate,
- checking has been carried out and is thorough and complete,

- risks have been identified and managed,
- appropriate alternatives have been considered,
- documentation is adequate, and
- there are no outstanding or unresolved issues.

BC Hydro's internal quality control and assurance procedures (PSDP – Quality Assurance) apply to traditional engineering design processes. However, it is recognised the PSHA project does not completely fit this mold. Consequently, the checking and reviewing process outlined above was applied only to certain components of the PSHA project.

The PPRP is charged with the review and validation of the SSHAC process as it is implemented and its viability with respect to achieving the SSHAC goal. In this context, the SSHAC process, including the participatory peer review process, has a built-in evaluation and review element that largely replaces most of the checking and review process for a traditional engineering design activity.

There are some components of the GMC and SSC modelling, which were identified for a checking and review process more directly analogous to a traditional engineering design activity.

1.9 VOLUME ORGANIZATION

Section 2 describes the PSHA methodology.

Section 3 describes the SSC evaluation process and the elements of the SSC modeling. Section 4 describes the ground motion characterization effort.

Section 5 describes the PSHA implementation and seismic hazard calculation process.

Cited references are provided in Section 6.

Appendix A contains a glossary of acronyms and detailed definitions for the various earth science, seismic hazard and seismological terms used in this report.

The closure letter from the PPRP is reproduced in Appendix B.

Table 1.5-1: PSHA Roles and Responsibilities

Role	Responsibility
Project Sponsor	The project sponsor provides the financial support for the project and is the owner of the PSHA when it is completed; including the inputs, results and documentation.
Project Leader	Takes managerial and technical responsibility for organizing and executing the project. The project lead 'owns' the study results in the sense of having intellectual responsibility for the project's technical validity.
Technical Integrator	Responsible for developing the technically defensible distribution of inputs to the PSHA.
Evaluation Staff	The role of the evaluation staff (including the TI) is to conduct the evaluation in a manner consistent with the goals and standards of this project.
Participatory Peer Review Panel	The responsibility of the Peer Review Panel is two-fold. They are to serve as participatory reviewers of the evaluation process that is implemented to insure the process is consistent with the SSHAC guidelines, and second to provide technical review of the SSC and GMC evaluations that are performed and the models that are developed.

Table 1.5-2: Project Management, Technical Leads and Peer Review Panel

Participant/Affiliation	Role
Stephen Rigbey BC Hydro	Project Sponsor
Robert Schubak BC Hydro	Project Manager
Kofi Addo BC Hydro	Project Co-Lead
Martin McCann Jack R. Benjamin & Associates, Inc.	Project Co-Lead
Kenneth Campbell Kenneth W. Campbell Consulting	Participatory Peer Review Panel
Kevin Coppersmith Coppersmith Consulting	Participatory Peer Review Panel
J. Carl Stepp Earthquake Hazard Solutions	Participatory Peer Review Panel

Table 1.5-3: GMC Team Members

GMC Participant/Affiliation	Role
Kofi Addo BC Hydro	GMC Technical Integrator Project Co-Lead
Norm Abrahamson University of California, Berkeley	GMC Technical Integrator
Robert Youngs AMEC Geomatrix	GMC Technical Integrator
Nick Gregor	Evaluator
Gail Atkinson University of Western Ontario	Evaluator
Brian Chiou	Analyst
Walter Silva Pacific Engineering & Associates	Analyst
Thomas Cheng Sinotech Engineering Consultants, Taiwan	Resource Expert (Data)
Miguel Carrasco	Resource Expert (Data)
John Zhao GNS Science, New Zealand	Resource Expert (Data)

Table 1.5-4: SSC Team Members

SSC Participant/Affiliation	Role
Martin McCann Jack R. Benjamin & Associates, Inc.	Project Co-Lead SSC Technical Integrator
Martin Lawrence BC Hydro	SSC Technical Integrator
Dean Ostenaa Fugro-William Lettis & Associates, Inc.	SSC Technical Integrator
Ivan Wong URS Corporation	SSC Technical Integrator
John Clague Simon Fraser University	Evaluator
Kathryn Hanson AMEC Geomatrix	Evaluator
Ram Kulkarni URS Corporation	Analyst
Roland LaForge Fugro-William Lettis & Associates, Inc.	Analyst
William Lettis Fugro-William Lettis & Associates, Inc.	Evaluator
Dan O’Connell Fugro-William Lettis & Associates, Inc.	Analyst
Susan Olig URS Corporation	Evaluator
Bert Swan AMEC Geomatrix	Evaluator
Jeff Unruh Fugro-William Lettis & Associates, Inc.	Evaluator
Robert Youngs AMEC Geomatrix	Analyst
Judy Zachariasen URS Corporation	Evaluator

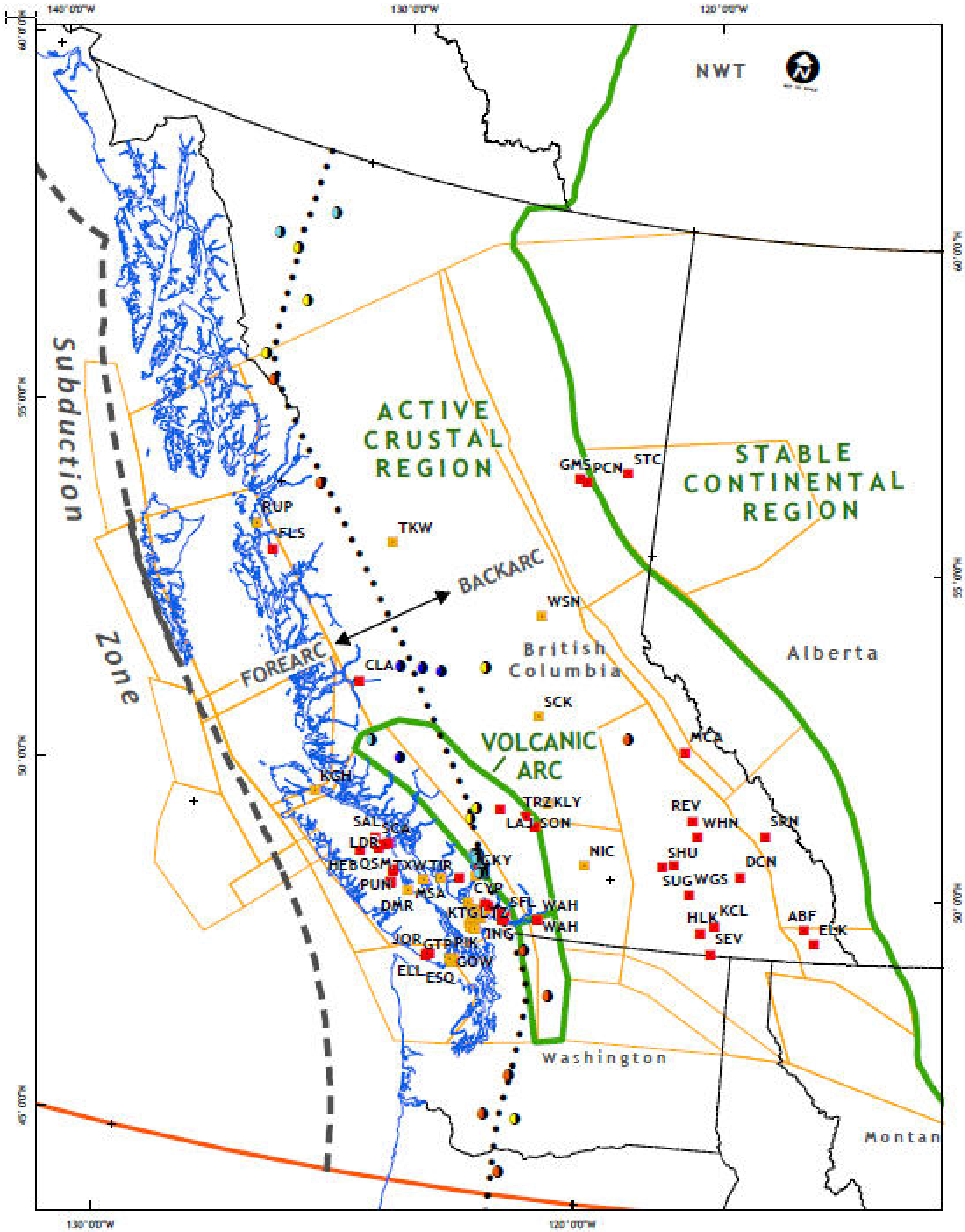
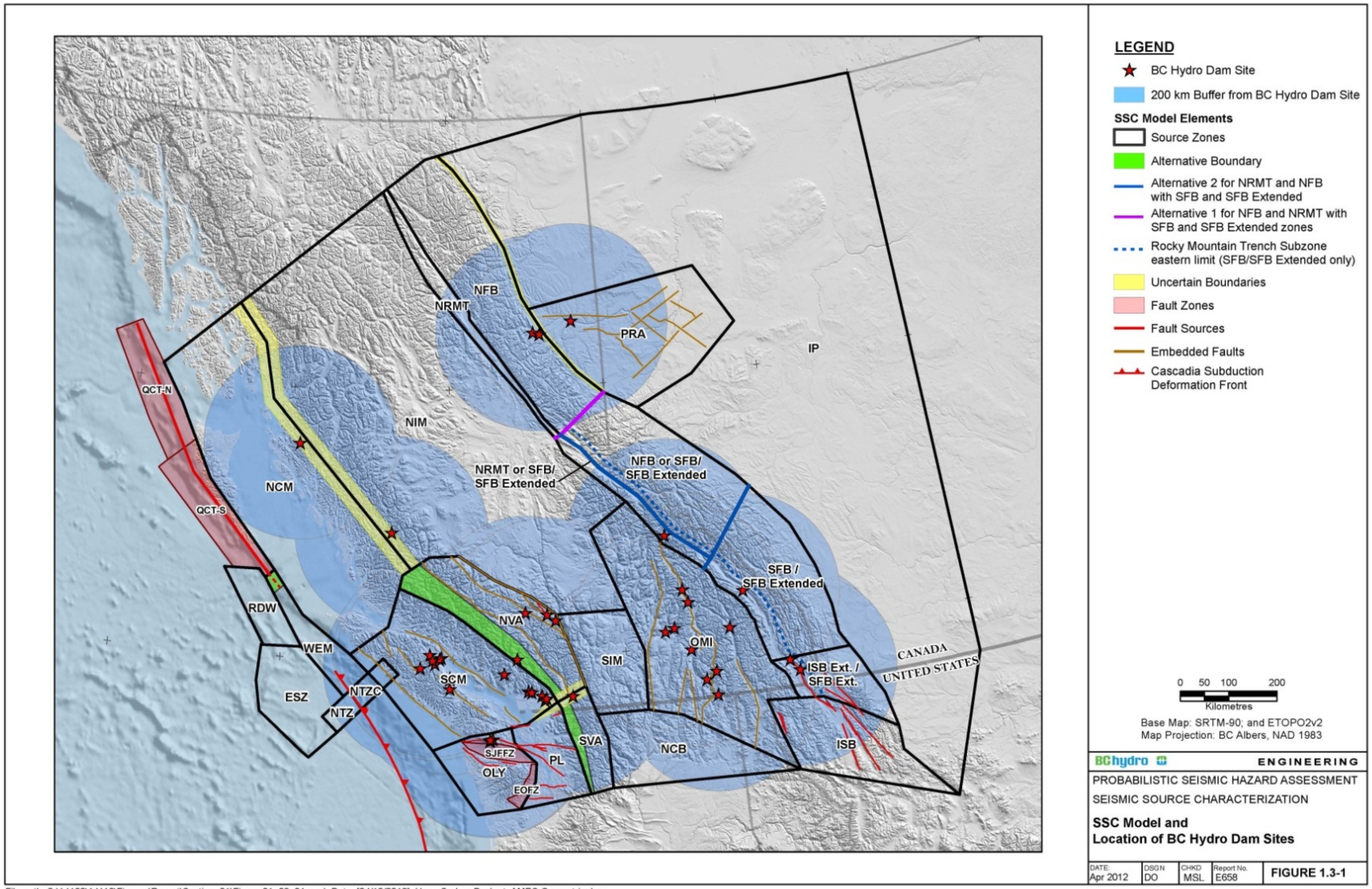


Figure 1.1-1: Major Tectonic Belts and Geological Provinces in the Study Region



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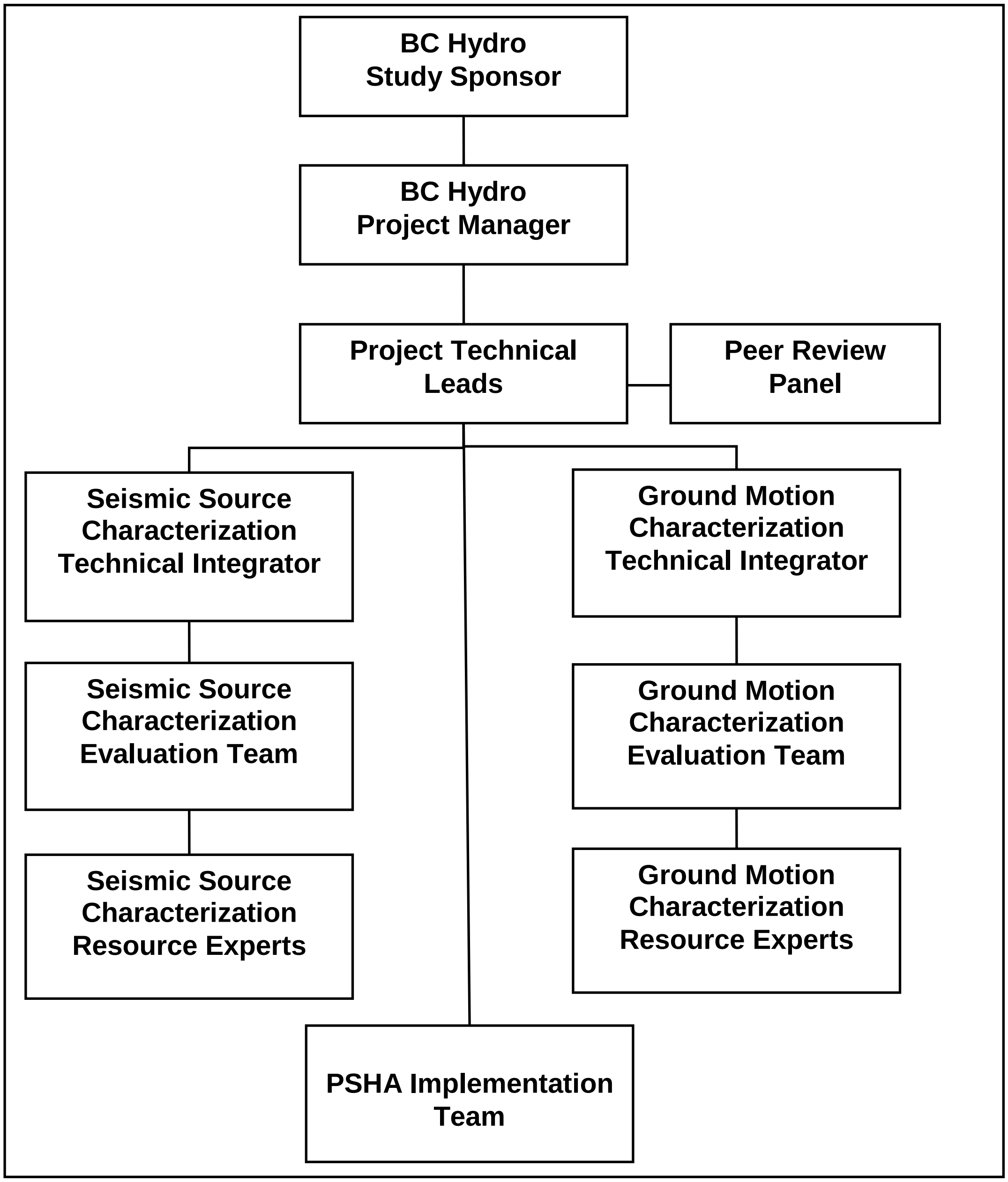

Figure 1.5-1: PSHA Organization Chart

2.0 PSHA METHODOLOGY

This section describes the general aspects of the PSHA methodology, including the seismic hazard aleatory model and the assessment of epistemic uncertainties.

2.1 PSHA Aleatory Model

The PSHA approach is based on the model developed principally by Cornell (1968). The occurrence of earthquakes in a seismic source zone or on a fault is modelled as a Poisson process. The Poisson model is widely used and is a reasonable assumption in regions where data is sufficient to provide only an estimate of average recurrence rate (Cornell, 1968). The occurrence of earthquake ground motions at a site that may exceed a specified level is also a Poisson process, if (1) the occurrence of earthquakes is a Poisson process, and (2) the probability that any one event will result in ground motions at the site that exceeds a specified level is independent of the occurrence of other events.

The probability that a ground motion parameter "Z" exceeds a specified value "z" in a time period "t" is given by:

(2-1)

where $\nu(z)$ is the average annual frequency of events in which Z exceeds z per unit time (typically one year). It should be noted that the assumption of a Poisson process for the number of events is not critical. This is because the mean number of events in time t, $\nu(z) \bullet t$ can be shown to be a close upper bound of the probability $P(Z > z)$ for small probabilities (less than 0.10) that generally are of interest for engineering applications. The average annual number of events in which Z exceeds z is obtained by summing the contributions from all sources, that is:

(2-2)

where $\nu_n(z)$ is the mean annual number (or rate) of events associated with seismic source n for which Z exceeds z at the site. The parameter $\nu_n(z)$ is given by the expression:

(2-3)

where:

$\alpha_i(m^o)$ = annual frequency of earthquakes on source i above a minimum earthquake magnitude, m^o;

$f_i(m_i)$ = probability density of earthquake size for source i for earthquakes between m^o and a maximum magnitude for the source, m^u;

$f_i(r|m)$ = probability density for distance to an earthquake of magnitude m occurring on source i, r;

$P(Z > z|m,r)$ = probability that given an earthquake of magnitude m that occurs a distance r from a site that the ground motion exceeds the specified level z.

Figure 2.1-1 shows the elements of the PSHA methodology. The following sub-sections describe the seismic source characterization and ground motion parts of the PSHA model.

2.2 Seismic Source Characterization

Three general types of earthquake sources are characterized in the PSHA: (1) fault sources; (2) seismic source zones (volumetric zones), and (3) seismic source zones and embedded faults. The Cascadia subduction zone interface (a fault source) and crustal fault sources are modelled as three-dimensional fault surfaces and details of their behaviour (e.g., faulting style) are incorporated into the source characterization. The relatively deep Wadati-Benioff intraslab earthquakes and crustal seismicity are modelled by (1) seismic source zones where earthquakes are assumed to occur randomly, and (2) by the distribution of historical seismicity assumed to be stationary in space and smoothed using a Gaussian filter.

The geometric parameters for fault sources include faulting style, fault location, segmentation model, dip, and thickness of the seismogenic zone. The earthquake recurrence for a source (the magnitude-frequency relationship) includes the recurrence model type and the model parameters such as the recurrence rate (slip rate or average recurrence interval for the maximum event), slope of the recurrence curve (*b*-value), and maximum magnitude.

Magnitude-frequency distributions for earthquake occurrences in crustal sources were modelled using four alternative recurrence models: 1) the truncated exponential model, 2) the characteristic earthquake model, 3) the maximum magnitude model, and the 4) alternative characteristic model. Observations of historical seismicity and paleoseismic investigations suggest that the characteristic and the maximum magnitude recurrence models are more applicable for individual faults, whereas seismicity in broader fault zones or regions is better fitted by a truncated exponential model (e.g., Aki, 1983; Schwartz and Coppersmith, 1984; Youngs and Coppersmith, 1985; Pantosti *et al*., 1993; Wesnousky, 1994). The alternative characteristic recurrence model, which was developed as part of this project, is used for seismic source zones where there is evidence to suggest a limited number of fault sources could produce the largest earthquakes in the zone (see Section 3 and Volume 2).

2.3 GROUND MOTION CHARACTERIZATION

In a PSHA, estimates of earthquake ground motion are made using ground motion prediction equations (GMPE). These equations estimate ground motions as a function of earthquake magnitude, source-site distance, style of faulting and site conditions. GMPEs provide a best estimate (median) ground motion and its aleatory variability (randomness). To take into account the epistemic uncertainty in the GMPEs, the uncertainty in individual models (due to lack-of-fit to data) and differences in alternative modelling interpretations associated with different model types, variations in datasets, etc. are considered.

In the BC Hydro PSHA, the NGA models were used to model ground motions associated with earthquakes (see Section 4 and Volume 3) that occurred in active crustal sources. For seismic sources in the stable continental interior, alternative models available in the literature were evaluated and used. Probability weights were assigned to each alternative GMPE based on its technical merit and the evaluation by the GMC TI.

To estimate ground motions from Cascadia subduction zone earthquakes, a new prediction model was developed.

2.4 SSHAC PROCESS

The standard for conducting PSHAs is the SSHAC process as originally developed in 1997 (Budnitz et al, 1997) and as recently updated by the USNRC (Kammerer and Ake, 2011). The SSHAC process establishes high-level principles for conducting a PSHA; defining the goal of the analysis, establishing organizational responsibilities, identifying processes to support the process of achieving the goal, etc. Since the publication of the initial guidelines, a number of Level 4 and Level 3 analyses have been performed. Following the start of this project, the US Nuclear Regulatory Commission (USNRC), an original sponsor of the SSHAC development project, sponsored an update to the guidelines to improve the guidance based on more than ten years of experience of their use. Of the lessons learned that were shared by users, were the advantages and disadvantages of Level 4 evaluations and the benefits of Level 3 evaluations (Kammerer and Ake, 2011).

The SSC and GMC teams conducted a SSHAC Level 3 analysis, each with a Technical Integrator (TI) team of experts. In each case, the responsibility of the TI was to implement a process of evaluation and integration in which consideration was given to the complete set of data, models, and methods proposed by the larger technical community. Through a process of integration the TIs developed a distribution of inputs to the PSHA that represented the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessments of existing data, models, and methods).

An important component of Level 3 analyses is the process of evaluation and integration, key elements of which include:

- Project workshops
- Team meetings
- TI integration meetings
- Peer review
- Documentation

For both the GMC and SSC, extensive literature searches, project workshops and meetings were held with resource and proponent experts. These experts were invited to present datasets and their assessments of current models and interpretations. Engaging these experts was an important element of the evaluation and the identification of the current breadth and depth of scientific understanding and uncertainty in the technical community.

The responsibility of the TI is to serve as evaluator experts who must review and evaluate the available scientific evidence, interact with other experts, assess and model sources of epistemic uncertainty, and ultimately integrate alternative models and interpretations into a distribution. This process is iterative and takes place through interaction (discussions, debate) within the evaluation teams and with other experts (at workshops or meetings). It is the responsibility of the TI to evaluate the state-of-knowledge (data, models) and the state-of-scientific understanding (as represented by alternative scientific interpretations) through a series of interactions and feedback, and ultimately integrate the results of the evaluation into a probabilistic model. This process establishes a clear and important responsibility missing in conventional scientific interactions in general and typical expert elicitation processes in particular.

2.5 PEER REVIEW

As recommended in the SSHAC guidelines (Budnitz et al, 1997; Kammerer et al, 2011) a participatory peer review process was implemented for the PSHA. The Participatory Peer Review Panel (PPRP) has two primary responsibilities:

1. It serves as a participatory reviewer of the evaluation and integration process that is implemented to ensure the process is consistent with achieving the SSHAC goal, and
2. Provides technical review of the evaluations that are performed and the models that are developed.

As part of this project, the PPRP participated in all of the SSC and GMC workshops as well as a number of the project working meetings, including PSHA results review meetings. In addition, the panel reviewed draft and draft final versions of the SSC and GMC reports. Lastly, the PPRP reviewed the final draft versions of Volumes 1 and 4 of the PSHA report. Appendix B contains the PPRP closure letter that provides the panel's endorsement of the implementation of the SSHAC process and the study technical integrity.

2.6 DOCUMENTATION

As part of its guidelines, the SSHAC identified the importance of preparing complete and transparent documentation of the evaluations that form the basis of the PSHA inputs. Experience in performing Level 3 and 4 PSHAs has shown the considerable effort required to prepare the documentation is valuable for understanding the evaluations that are the basis for the models and that serve as a future reference to assess the importance of new information. A major part of documenting the inputs to the PSHA includes the documentation of the present state-of-knowledge (datasets available at the time, scientific understanding of the present-day tectonics, seismology, etc.). This documentation includes the available information; which was used directly in the evaluation, as well as information that may not have contributed at all, in a clear and complete manner in order that a time, content, and value stamp can be placed on the information that forms the basis for the evaluation. This is particularly valuable in the future as others evaluate the importance of information that becomes available in the future.

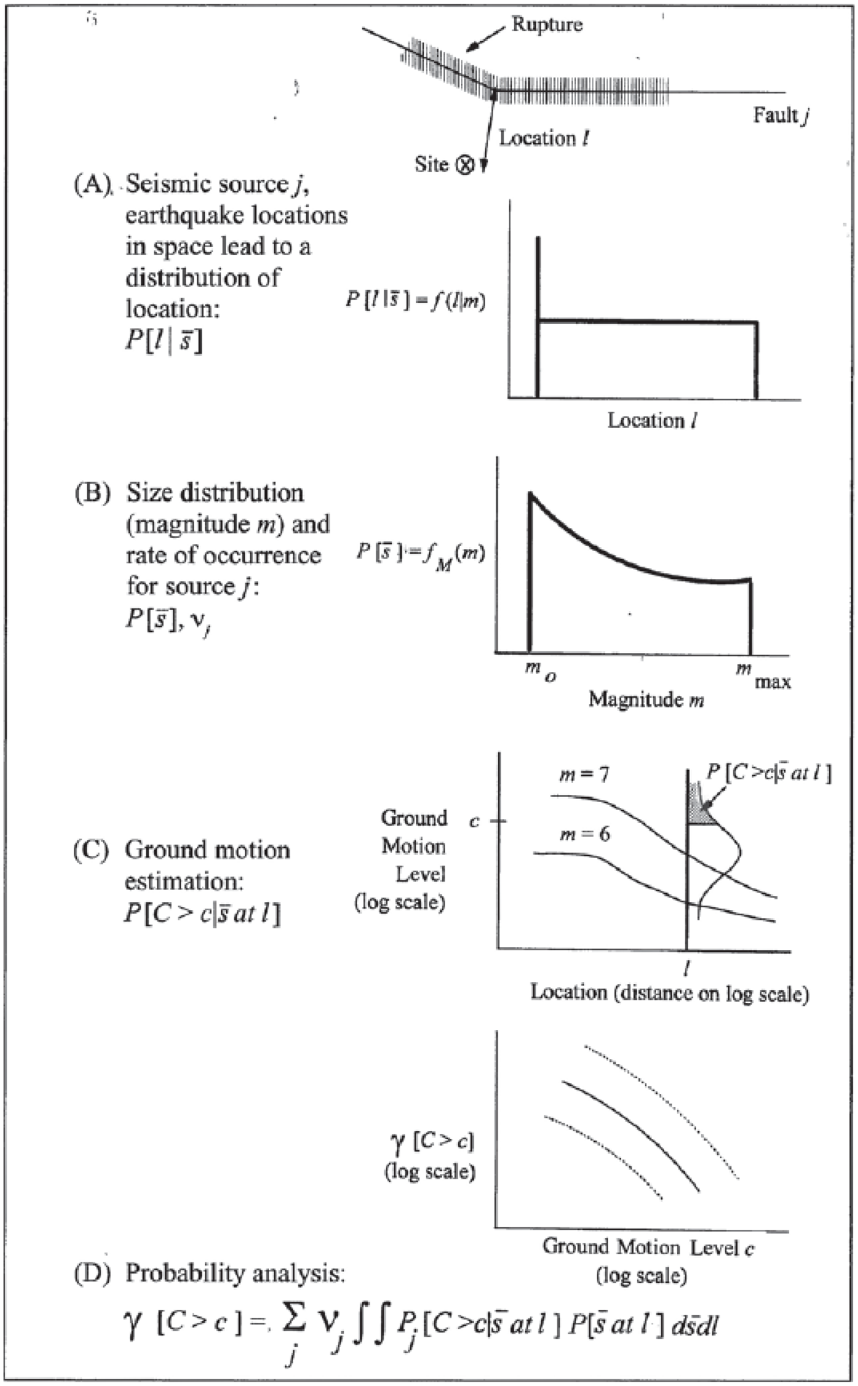

Figure 2.1-1: Steps in a PSHA (McGuire, 2004)

3.0 SEISMIC SOURCE CHARACTERIZATION

This section describes the methodology used for characterizing seismic sources in the PSHA. It summarizes the SSC evaluation process, fundamental aspects of the SSC such as the definition of seismic source types (e.g., source zones, fault sources), modelling earthquake recurrence, etc.

3.1 Overview

The objective of the SSC is to use available earth science information (data, evaluations and interpretations of these data, including evaluations of others not directly involved in the SSC) and integrate them into a composite temporal and spatial (aleatory) model of the future rate of earthquake occurrences. Due to the limitations of available data and the uncertainties associated with understanding the current stress regime and ongoing seismogenic processes, there are epistemic uncertainties that must be identified and quantitatively evaluated to produce a distribution on the SSC inputs to the PSHA model.

As described by SSHAC (Budnitz et al, 1997): "A seismic source is a construct developed for seismic hazard analysis as a means of approximating the locations of earthquake occurrences. A seismic source is defined as a region of the earth’s crust that has relatively uniform seismicity characteristics, and is distinct from those of neighbouring sources."

In fundamental terms, a seismic source is a volume of the earth's crust that has the same earthquake potential as defined by the size of events that may occur. Another seismic source in an adjacent part of the crust will, by this definition, have a different potential, the basis for which is the character of the tectonic features and/or observational evidence (historic or paleoseismic). The purpose of the SSC is to estimate the rate (events per year), location (spatial distribution) and size of future earthquake occurrences within a seismic source.

3.2 SSC EVALUATION AND INTEGRATION PROCESS

Due to the extent and tectonic diversity of the study region, the organization and coordination of the SSC Team effort was an early topic of discussion. Further, the TI believed it was important the entire SSC Team have a role in and responsibility for the evaluations that were performed.

3.2.1 SSC Team Organization

An early decision that was made by the SSC TI at the outset of the project concerned the organization of the SSC Team. Based on discussions at the first SSC workshop, it was concluded that the most effective approach would be to distribute the SSC evaluation among a group of sub-teams that were responsible for different geographic/tectonic regions[3]. The regions identified were the:

- Plate Boundary region;
- Coastal region; and
- Interior region.

The plate boundary region included the Cascadia subduction zone, the subducting Juan de Fuca plate and the Queen Charlotte fault (Figure 3.2-1). The coastal region was defined generally from the plate margin in the west to the volcanic arc in the east, while the Interior was the region east of the volcanic arc.

Sub-teams were formed to conduct the SSC evaluation in these regions. To facilitate joint ownership, and early dissemination of ideas throughout the entire team, the sub-teams comprised overlapping members of the TI and other SSC Team members.

In addition to the SSC evaluation sub-teams, a Conceptual Tectonic Framework (CTF) sub-team was formed to develop a CTF model for the study region and a

[3] Strict geographic boundaries for these areas were not defined. Initially the SSC in each area is being carried out on the basis of tectonic features (structure) within each area. However, as the evaluation proceeded, the groups interacted to address issues associated with the characterization in their areas.

Recurrence sub-team was formed to evaluate the potential use of a geodetic-based recurrence approach.

3.2.2 Workshops, Team Working Meetings, and Sub-team Meetings

A key element of a SSHAC Level 3 PSHA is the effort that goes into the gathering of information about the study region and the extent of the evaluations that are conducted. As part of this process, various meetings were held, including:

- Project workshops
- Sub-team meetings
- SSC Team meetings
- TI – sub-team elicitation meetings

The project workshops and meetings in which experts who were model proponents and/or resource experts were invited to present datasets and their assessments to the SSC Team were key elements of the process of understanding the state-of-knowledge of the technical community and the evaluation process itself. Engaging these experts allowed the SSC Team to identify the breadth and depth of scientific understanding and uncertainty of the broader technical community.

Table 3.2-1 summarizes the workshops and meetings that were held as part of the SSC.

3.2.3 PSHA Feedback

As part of the SSC evaluation, seismic hazard calculations were performed for a number of BC Hydro dam sites. The calculations included estimates of the total hazard and uncertainty as well as the sensitivity of the results for individual seismic sources. PSHA feedback was a key component of the SSC evaluation because it provided insight to SSC modelling alternatives that integrated the effect of recurrence modelling and models for the spatial distribution of earthquake occurrences.

Three rounds of PSHA calculations and results were provided to the SSC Team during the evaluation process. The feedback proved particularly beneficial as part of the development and finalization of the seismic source-embedded fault modelling approach.

3.3 MODELING SSC EPISTEMIC UNCERTAINTY

The SSC logic trees are used to portray the sources of model and parametric uncertainty in each element of the characterization (i.e., seismic source boundaries, earthquake recurrence, maximum magnitude, etc.). There were two components to the SSC logic tree modeling; the first was the logic trees for individual seismic sources. The second part was a master logic tree that modelled the sources of dependence between seismic sources and mapped how the sources were combined to define the complete, SSC global logic tree. The master logic tree was used to guide the construction of the SSC global logic tree which was used in the PSHA implementation.

3.3.1 Seismic Source Logic Trees

Logic trees for individual seismic sources model the uncertain elements (alternative models and uncertainty in model parameters) in the characterization of a seismic source (which are identified across the top of the logic tree). Figure 3.3-1 presents an illustration of a seismic source logic tree. For each uncertain element of the characterization of a seismic source, there is a node and a series of branches emanating from the node that represent the alternative credible models or parameter values that are considered. Associated with each branch (alternative model or parameter value) is a weight that reflects the scientific evaluation of the SSC Team and is a measure of the likelihood that an interpretation (i.e., model, parameter value, etc.) represents the true state-of-nature. The branch weights sum to unity at each node, reflecting the complete (discrete representation) distribution that is being modelled.

A path through the logic tree corresponds to a complete (all features of a seismic source are defined along a path) alternative interpretation (model) for a seismic source. The product of the weights along a path determines the weight or degree-of-belief that the model, as defined by that path, is the true state-of-nature. Many of the weights along a path are conditional on the models and parameters in upstream branches. In aggregate, the complete set of paths through the logic tree and their corresponding weights define a probability mass function on alternative models and interpretations for a seismic source. This probability mass function of alternative models captures the current state-of-knowledge and, as defined by the goal of the PSHA, represents the range and distribution of technically defensible interpretations for a seismic source.

3.3.2 SSC Global Logic Tree

The seismic hazard at a site is an aggregation (the sum) of the hazard contributed by all seismic sources in the vicinity. To estimate the hazard and model the epistemic uncertainty associated with all the relevant seismic sources, a master SSC logic tree was developed. The master logic tree modelled:

- the sources of epistemic uncertainty that are a source of dependence between seismic sources, and
- the manner in which the seismic sources were combined.

Sources of dependence were associated physical or parametric factors that were derived from the conceptual tectonic framework or from regional (location of the Cascadia subduction zone interface) or local factors associated with individual seismic sources (i.e., alternative seismic source boundaries).

The master logic tree was implemented (i.e., combination of the individual seismic source logic trees as defined in the master logic tree) to develop the global SSC logic tree, which was implemented in the PSHA calculations. The global SSC logic tree included the combination of seismic sources that were used to estimate the ground motion hazard at a site.

Once constructed, the global SSC logic tree provided a complete characterization of seismic sources in the study area; including all sources, their dependence on other sources, and their epistemic uncertainty. A path through the global SSC logic tree represented a complete characterization of the entire study region with respect to the future occurrence of earthquakes – an aleatory model of earthquake occurrences; their temporal and spatial rate of occurrence. The enumerated set of paths through the global SSC logic tree, which included all the seismic sources in the model, defined the full epistemic probability distribution on the rate of earthquake occurrences in the study region.

Section 6 of Volume 2 describes the SSC master logic tree and the construction of the global logic tree.

3.4 SEISMIC SOURCE TYPES

The characterization of a seismic source included the following:

- location and geometry in the crust or uppermost mantle;
- limits of seismogenic crust (i.e. minimum and maximum depths);
- orientation and geometry of faulting (i.e. strike, dip, length);
- style of faulting (i.e. whether dominantly strike-slip, thrust or normal or some other combination);
- probability of activity;
- deformation rates, derived from seismicity, and/or geologic data and models;
- maximum magnitudes; and
- model of earthquake recurrence.

These elements of the SSC were also the parameters that were defined in a seismic source logic tree.

A number of source types were used to define the location and rate of future earthquake occurrences. These were:

- fault sources, including fault zones,
- seismic source zones, and

- seismic source zone and embedded fault modeling concept.

Figure 3.4-1 presents a diagram that illustrates the modeling space for seismic sources and earthquake recurrence models (discussed in Section 3.5). The introduction of the seismic source and embedded fault concept and the alternative characteristic earthquake model filled a gap in the traditional SSC modelling alternatives (Figure 3.4-2). The seismic source-embedded fault approach provided the opportunity for greater specificity (as guided by available geologic information) in terms of the location of possible future earthquakes than the seismic source zone alone. As discussed in Section 3.5, the alternative characteristic earthquake model allowed the characteristic-like behaviour of embedded faults to be modelled.

The highest level of specificity of a seismic source and thus the location of future earthquakes in the SSC model was achieved through the use of fault sources (and fault zones) (Figure 3.4-3). A fault source was used to model a specific geologic feature for which there was evidence to characterize and estimate future earthquake occurrences, its location and rate of occurrence. The next highest level of specificity of the characteristics of future earthquake occurrence was achieved through the use of embedded faults (Figure 3.4-3). The zone and embedded fault approach was a concept developed as part of this study. It provided a modeling alternative to utilize geologic information to characterize the spatial distribution of future earthquake occurrences in a seismic source zone. The zone and embedded fault approach was an alternative to modeling the spatial location of earthquakes that relaxed the assumption of uniform seismicity or spatial smoothed seismicity that was often used in seismic source zones.

Embedded faults are a network of tectonic features which, in aggregate, represent an alternative model for the spatial location of future earthquake occurrences within a seismic source zone. The embedded fault concept was developed as part of this study. Embedded faults are an integral part of the characterization of the seismic source zone. The location and some geometry-related characteristics of embedded faults are defined based on specific geologic features within the source zone, but other aspects of the seismic source characterization, such as deformation rates and maximum magnitudes, are derived from the attributes of the source zone in which they are located and modeled. As such a network of embedded faults is integral to the seismic source zone and not an independent source of earthquake occurrences.

Seismic source zones represent the lowest level of specificity for source modeling. A source zone is a volume of the earth's crust, which in plain view, is defined by a polygon that is defined by regional geologic and tectonic characteristics, and the estimated seismogenic depth of the crust.

The same characteristics were used to define a seismic source zone as for fault sources; faulting style, strike, dip, etc. These characteristics were defined with ranges (that account for aleatory uncertainty, or as appropriate epistemic uncertainty) of parameters, including faulting geometry (strike and dip), faulting style, and seismogenic thickness.

Boundaries of seismic source zones define changes in the characteristics of expected future earthquake occurrence. Epistemic uncertainties in the data used to characterize the source zones for some sources can result in:

- boundary location uncertainties,
- alternative geometries, and/or
- alternative characterizations of the expected rate and size of future earthquake occurrences.

3.5 EARTHQUAKE RECURRENCE MODELS

Earthquake recurrence models estimate the temporal rate per year of earthquake occurrences in a seismic source. In the PSHA, the approach to estimating earthquake recurrence followed well-established approaches, but included the investigation of the use of geodetic strain data and the development of a new recurrence model.

The Cascadia subduction zone represented a special case for modelling earthquake recurrence. For one, the Cascadia subduction zone s capable of generating mega-earthquakes of **M** 9+/-. In addition, there were very different datasets available to estimate the recurrence of earthquakes within different magnitude ranges.

3.5.1 Recurrence Model Types

Four earthquake recurrence models were used in the SSC: 1) the truncated exponential model, 2) the characteristic earthquake model, 3) the maximum magnitude (or maximum moment) model, and 4) the alternative characteristic model. The alternative characteristic model was developed in this project. The role of the alternative characteristic model in the SSC is illustrated in Figure 3.4-1.

The shape of the different recurrence models in terms of the cumulative relative frequency of earthquakes as a function of magnitude are compared in Figure 3.5-1. The recurrence curves shown in the figure are normalized to represent the same seismic moment rate.

Truncated Exponential Model - The truncated exponential model of Youngs and Coppersmith (1985), which was first proposed by Cornell and Van Marke (1969) describes the number of events exceeding a given magnitude by an exponential distribution (similar to the Gutenberg-Richter relationship), that is truncated at a lower (m_o) and upper-bound (or maximum magnitude), M_{max}. The truncated exponential model is used extensively in PSHAs and is considered generally applicable for seismic source zones where there are potentially a large number of unknown faults capable of generating earthquakes in a region. Although as described below, the SSC Team did use the truncated exponential recurrence model for fault sources as well.

Characteristic Model - The characteristic earthquake model is used to model the recurrence of earthquakes on faults that rupture with a specific "characteristic" magnitude on individual segments. This model was described by Aki (1983) and Schwartz and Coppersmith (1984) and numerically modeled by Youngs and Coppersmith (1985) (Figure 3.5-1). For the characteristic model, the number of earthquakes exceeding a given magnitude is the sum of the characteristic events and the non-characteristic events. The characteristic events are typically distributed uniformly over a 0.5 magnitude unit range around the characteristic magnitude (M_{char}) and the remainder of the earthquakes are distributed exponentially with an upper bound magnitude one half magnitude unit lower than the upper bound of the characteristic magnitude range (Figure 3.5-1; Youngs and Coppersmith, 1985).

Maximum Magnitude Model - A modified form of the maximum-moment model proposed by Wesnousky et al. (1983)[4] is used which is similar in concept to the characteristic model in that a seismic source produces a preferred or characteristic earthquake. The primary difference is that this 'characteristic earthquake' is the only size earthquake produced by the seismic source, there is no exponential portion of the recurrence curve, i.e., no events occur between the minimum magnitude of **M** 5.0 and the distribution about the maximum magnitude (Figure 3.5-1). As applied in this study, the maximum magnitude distribution is defined by a uniform distribution of width 0.5 magnitude units.

Alternative Characteristic Model - As part of the SSC evaluation a new recurrence model, referred to as the alternative characteristic recurrence model was developed. The model accounts for the "characteristic" earthquake behaviour of earthquakes as described above. However, the premise for the development of this model is different:

- In many of the BC Hydro SSC seismic source zones there are identified faults (though they are not known to be seismically active). Whereas faults are generally modeled to behave in a "characteristic" fashion, earthquake occurrence on them has a

[4] Wesnousky et al (1983) use a truncated Normal distribution to define the maximum moment model. In this analysis, a boxcar (uniform distribution) is used. Seismic hazard sensitivity calculations using the boxcar alternative indicate hazard results are insensitive to the distribution.

higher rate than an extrapolation of the Gutenberg-Richter fit to the historic seismicity indicates.

- The rate of earthquakes are so low that it is very unlikely they exist in the historic record (i.e., the project earthquake catalogue) where completeness periods range from about 50 to 150 years for **M** 5+ earthquakes in western Canada, depending on the region (Adams and Halchuk, 2003).
- Rates determined from a Gutenberg-Richter fit to the observed seismicity may be too low, due to incomplete detection of earthquakes and short duration of the observation period.
- The extrapolated rate of larger events may be too low, for the same reasons.

The alternative characteristic model developed in this work is similar to the Youngs and Coppersmith (1985) characteristic recurrence model, but resulted from more experimentation applied to the characteristic part.

The relative frequency of earthquakes in the characteristic magnitude range also follows a truncated exponential distribution.

1) The *b*-value for the Gutenberg-Richter part is set to that determined from the Gutenberg-Richter fit to the observed seismicity.
2) M_{max} is set to a value halfway between the mean M_{max} for faults in the zone and the highest value in the M_{max} logic trees of faults within the zone.
3) The level of the Gutenberg-Richter part of the model (i.e., position on the vertical axis) was set to be equivalent to the level from the Gutenberg-Richter fit to observed seismicity. In other words, the *a*-values (seismic activity rates) were constrained to be equal.

Given these constraints, the remaining free parameters that can be varied in order to fit the observations are the total seismic moment given to the model, and the proportion of this value assigned to the characteristic part. The remaining portion is assigned to the Gutenberg-Richter part. Based on the empirical evaluations that were performed, the proportion of the moment that is assigned to the characteristic magnitude range is 0.96 (see Appendix I in Volume 2).

3.5.2 Recurrence Model Weights and Seismic Source Types

For a given seismic source, the SSC Team evaluated the alternative recurrence models and individually weighted them to represent the evaluation of their applicability to a seismic source. Table 3.5-1 lists the alternative recurrence models and their weights that were used for different seismic source types.

3.5.3 Spatial Smoothing of Seismicity

In some source zones, non-uniform spatial density models were used to define the relative likelihood of the location of future seismicity. These spatial density functions were derived using kernel density estimation (e.g. Silverman, 1986; Frankel et al., 1996). A Gaussian density function is used as the kernel with relative shape parameters The magnitude range used to develop the kernel density estimates also varies, depending upon the amount of seismicity data available in each source. Selection of the kernel size parameter, h (i.e., the smoothing distance) controls the balance between accurately portraying the areas of high seismicity without introducing areas of unrealistically low seismicity in areas of sparse seismicity. Stock and Smith (2002) recommended that an improved approach is to use adaptive kernel smoothing (Silverman, 1986) in which the kernel size is adjusted throughout the study region, decreasing in size in areas of higher data (earthquake) density and increasing in size in areas of sparse data. The adaptive kernel density approach was applied in developing spatial density models.

3.6 MAXIMUM MAGNITUDE

For each seismic source in the SSC model, an estimate is made of the maximum magnitude that can be generated. The estimate is a probability distribution that depends on the characteristics of the source and the style of faulting. Section 5 of Volume 2 describes the methodology used to estimate the maximum magnitude for seismic sources in the SSC model.

3.6.1 Fault Sources

In general, the empirical relationships of Wells and Coppersmith (1994) (normal and reverse faulting),Hanks and Bakun (2002) and WGCEP (2003) are used for strike-slip faulting. Depending on the available data, the SSC Team used relations for estimating **M** based on rupture area (RA), surface rupture length (SRL), and average displacement (AD). For most faults, displacement per event data is lacking and so only the relations for RA and SRL are used. The SSC Team equally weighted the relations used unless noted otherwise in the description of the characterization of each seismic source.

3.6.2 Crustal Seismic Source Zones

Developing estimates of the maximum magnitude distribution for seismic source zones in BC was not as straightforward as for fault sources given the short historical seismicity record and the lack of paleoseismic data. It was particularly challenging in the Interior region where deformation rates were low (i.e., at or just above that of a stable continental region). Wheeler (2009) discussed at length the various approaches used for the Central and Eastern US. He compared each method and concluded that all approaches had pros and cons, depending on the available data and characteristics of the seismic source zone. Furthermore, none of the approaches yielded maximum magnitude estimates that fitted the available paleoseismic data very well, although some approaches fit better than others.

Based on the available data for this project, the SSC Team generally used a combination of historical observations and global analogs to constrain the range of maximum magnitudes for crustal seismic source zones. The largest observed historical earthquake in a region was used to generally constrain the lower bound of the maximum magnitude distribution, whereas global analogs were used to constrain the upper bound and provide guidance on intermediate values and their weights, which were also chosen based on zone-specific characteristics such as seismogenic thickness, pre-existing structures, and dominant style of faulting.

Table 3.2-1: Summary of the SSC Team Workshops, Meetings and Key Activiities

No.	Workshop/Meetings/Activities	Data Gathering	Evaluation	Integration	Team Ownership	Documentation
1	Gathering of geologic, seismologic and geophysical information and the development of uniform datasets.	■				
2	SSC Workshop 1 – Presentation of available information and discussion of SSC evaluation approach	■				
3	SSC Workshop 2 – Presentation by proponent and resource experts; identification of information needs, and modeling issues	■				
4	Development of a Conceptual Tectonic Framework		■	■		
5	SSC Workshop 3 - Conceptual Tectonic Framework presentation; Discussion of SSC Evaluation Guidance; SSC sub-team summaries; PSHA Modeling Issues		■	■	■	
6	SSC Sub-Team Evaluations		■			
7	Feedback and interactions within CTF, SSC, BC Hydro, and Peer Review Panel		■			
8	PSHA Sensitivity Analysis/Feedback		■			
9	Interface with Ground Motion Modeling Evaluation team		■			
10	SSC Workshop 4 – Presentation of Initial SSC Model to SSC team and Peer Review Panel; Discussion, debate and feedback on the initial sub-team SSC model		■	■	■	
11	SSC TI-SSC Sub-team Elicitation and Feedback Meetings		■	■	■	
12	Preliminary SSC Model Documentation					■
13	Peer Review of Preliminary and Final SSC Documentation		■	■		
14	Joint SSC-GMC Feedback Workshop				■	
15	SSC Team Feedback Meeting			■	■	
16	SSC Model Final Evaluation and Revision			■	■	
17	Final SSC Report					■

Table 3.5-1: Summary of the Earthquake Recurrence Models and Weights for Different Seismic Source Types

Source Type	Recurrence Modes	Weights	Basis Summary
Fault	Characteristic Maximum Moment Truncated Exponential	0.6 0.3 0.1	Preference is given to the characteristic model over the others (Youngs and Coppersmith, 1985). The truncated exponential is assigned low weight because of its limited use by the informed technical community in PSHAs.
Fault Zones	Characteristic Maximum Moment Truncated Exponential	0.6 0.3 0.1	Same as for fault sources.
Seismic Source Zone – General Seismic Source Zone – Large Area	Alternative Characteristic Truncated Exponential Truncated Exponential	0.1 – 0.6 0.4 – 0.9 1.0	The weight given to the alternative characteristic model varies depending on the features of the (see Section 5 of Volume 2) seismic source and seismicity data. For large area sources the truncated exponential is given a weight of 1.0.
Background Source Zone (with Active or Embedded Faults)	Truncated Exponential Alternative Characteristic	Varies with source zoned and modeling Alternative (see Section 5 in Volume 2)	For a seismic source in which it is judged the major active faults or a complete network of embedded faults has been identified, the source zone recurrence is defined by the truncated exponential. This is to say there are no tectonic features that have not been modeled that behave in a characteristic manner.
Embedded Faults	Truncated Exponential Alternative Characteristic	Varies with source zoned and modeling Alternative (see Tables 5.5-4 and 5.11-2)	The embedded faults are one part of the zone-embedded fault modeling alternative. Depending on the modeling alternative, different recurrence models for the embedded faults.

Source Type	Recurrence Modes	Weights	Basis Summary
CSZ Megathrust Earthquakes (**M** ~9)	Maximum Magnitude	1.0	The data available for the megathrust and intermediate events provides a basis to estimate earthquake rates in defined magnitude bins. The maximum magnitude (box car distribution centered on the maximum magnitude) model only is used to set the rate for the earthquakes in each bin.
Intermediate Earthquakes (8 < **M** < 8.8)	Maximum Magnitude	1.0	
Small Magnitude Earthquakes (**M** < 8)	Truncated Exponential	1.0	The small CSZ events (M<8) are assumed to be defined by a truncated exponential distribution. For these events, the CSZ is essentially a large seismic source zone in which the characteristic events have been modeled separately.

Note: The Plate Boundary Region includes the Cascadia subduction zone which in part underlies the Coastal Region.

Base map created by AMEC Geomatrix (2011)

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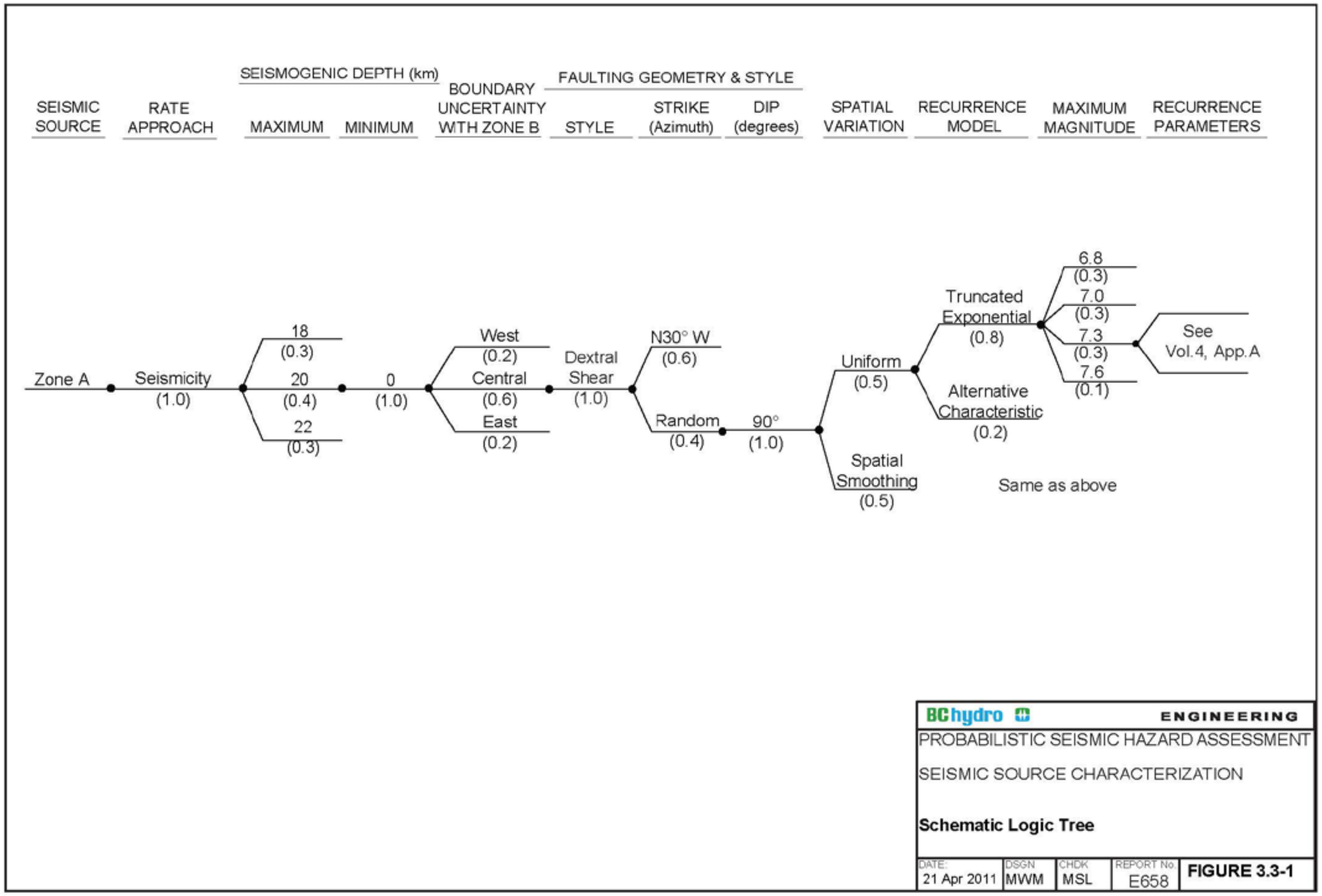
PROBABILISTIC SEISMIC HAZARD ASSESSMENT

SEISMIC SOURCE CHARACTERIZATION

SSC Study Area and Regions

DATE	DSGN	CHKD	REPORT No.	
9 May 2011	MSL	MWM	E658	**FIG. 3.2-1**


SEISMIC SOURCE
RATE APPROACH
SEISMOGENIC DEPTH (km)
MAXIMUM
MINIMUM
BOUNDARY UNCERTAINTY WITH ZONE B
FAULTING GEOMETRY & STYLE
STYLE
STRIKE (Azimuth)
DIP (degrees)
SPATIAL VARIATION
RECURRENCE MODEL
MAXIMUM MAGNITUDE
RECURRENCE PARAMETERS
Zone A
Seismicity (1.0)
18 (0.3)
20 (0.4)
22 (0.3)
0 (1.0)
West (0.2)
Central (0.6)
East (0.2)
Dextral Shear (1.0)
N30° W (0.6)
Random (0.4)
90° (1.0)
Uniform (0.5)
Spatial Smoothing (0.5)
Truncated Exponential (0.8)
Alternative Characteristic (0.2)
Same as above
6.8 (0.3)
7.0 (0.3)
7.3 (0.3)
7.6 (0.1)
See Vol.4, App.A
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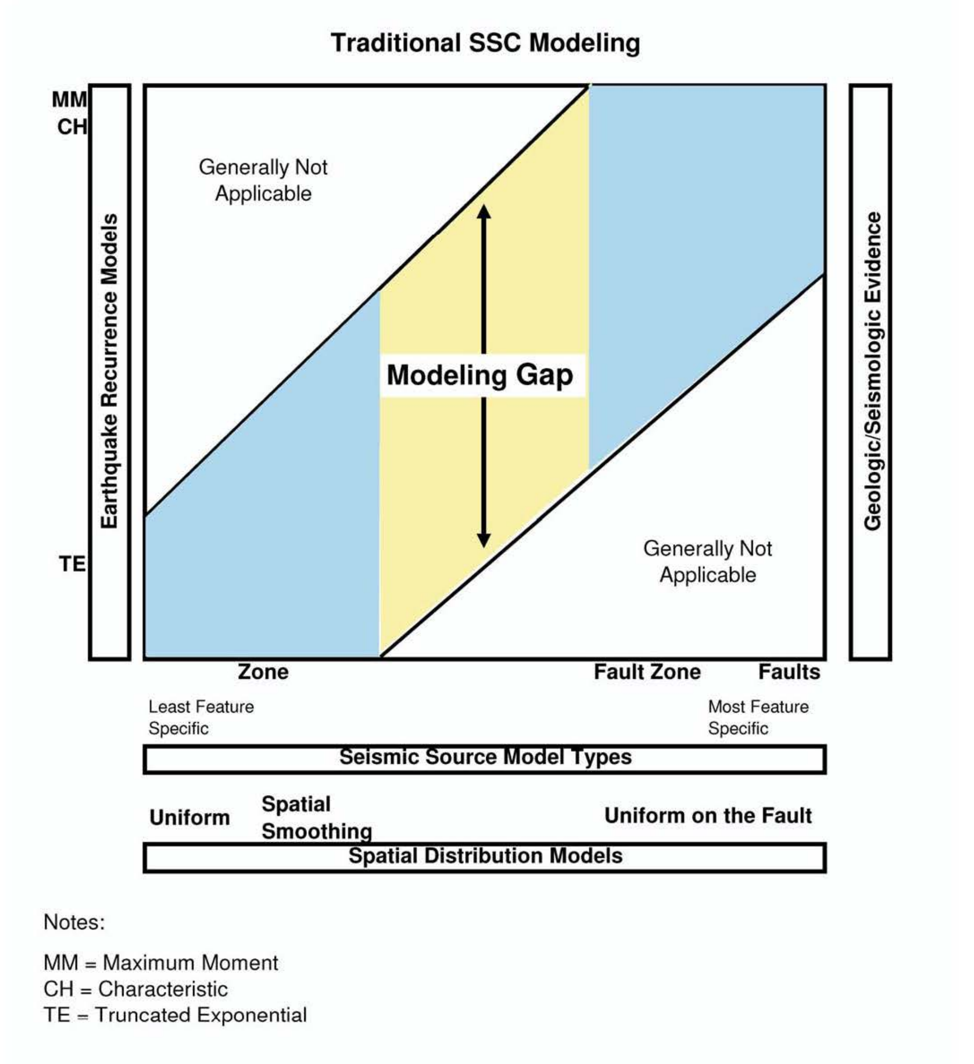
PROBABILISTIC SEISMIC HAZARD ASSESSMENT
SEISMIC SOURCE CHARACTERIZATION
Schematic Logic Tree
DATE: 21 Apr 2011
DSGN MWM
CHDK MSL
REPORT No E658
FIGURE 3.3-1



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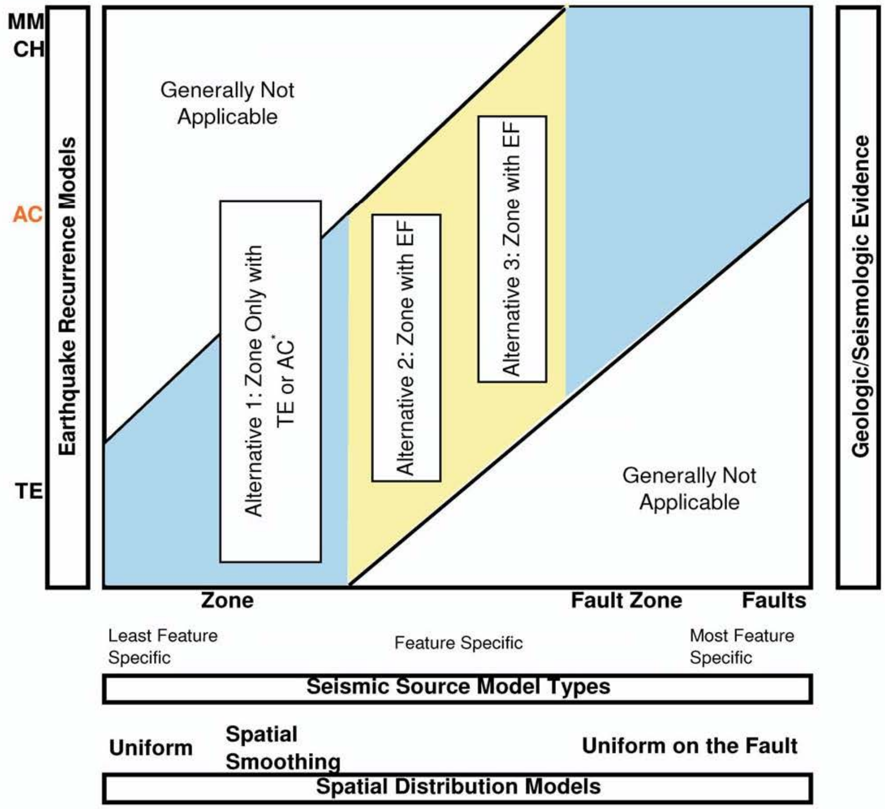
PROBABILISTIC SEISMIC HAZARD ASSESSMENT

SEISMIC SOURCE CHARACTERIZATION

Spatial Model-Earthquake Recurrence Modeling Space Diagram

DATE	DSGN	CHKD	REPORT No.	
26 Apr 2011	MWM	MSL	E658	**FIGURE 3.4-1**



Notes:

MM = Maximum Moment
CH = Characteristic
TE = Truncated Exponential

EF = Embedded Faults

*See the text in Section 5.5 for a description of the alternative spatial distribution models (Alternatives 1, 2 and 3)

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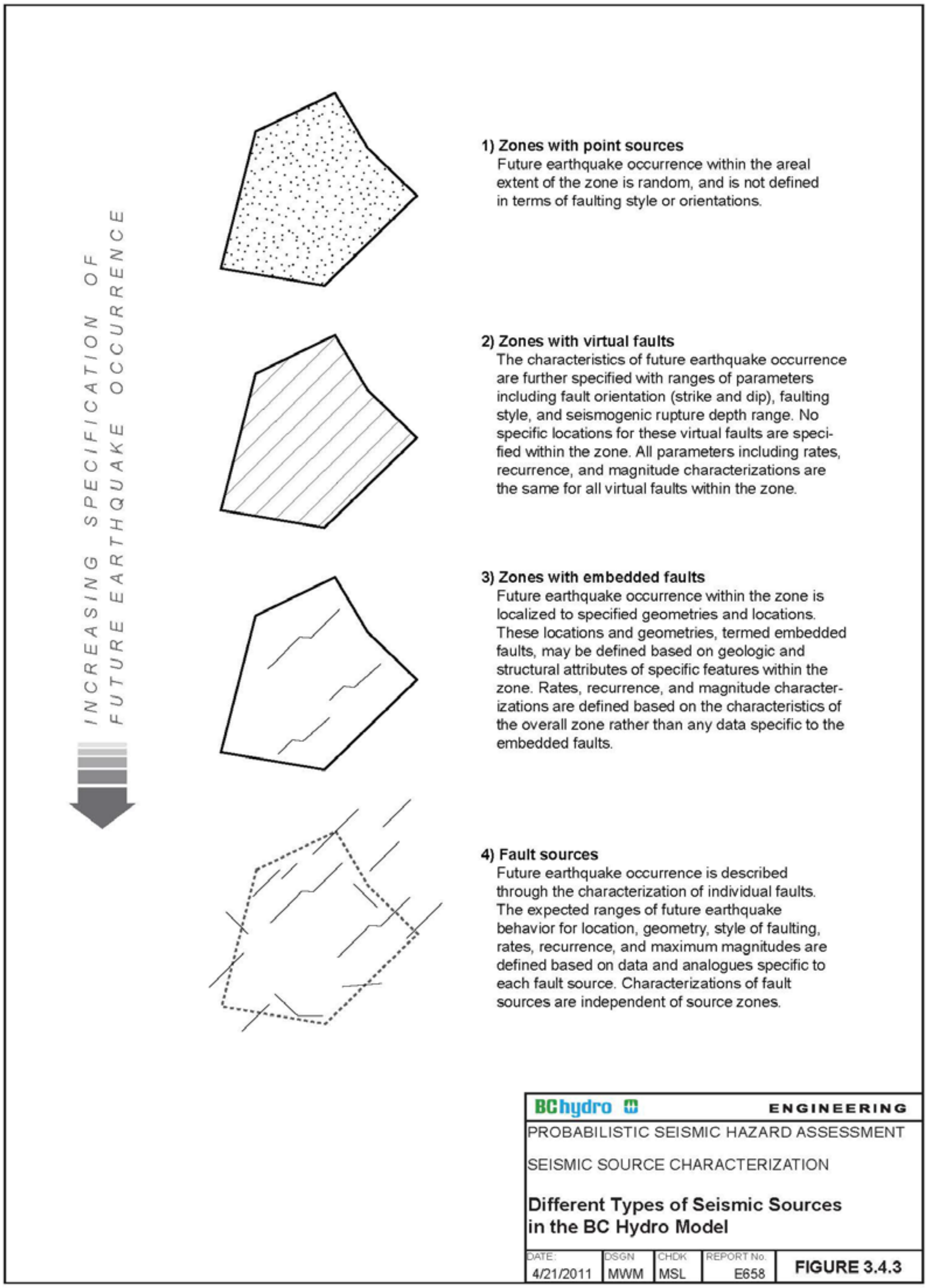
PROBABILISTIC SEISMIC HAZARD ASSESSMENT				
SEISMIC SOURCE CHARACTERIZATION				
Modeling Space Diagram with Three Alternative Models				
DATE 26 Apr 2011	DSGN MWM	CHKD MSL	REPORT No. E658	**FIGURE 3.4-2**


INCREASING SPECIFICATION OF FUTURE EARTHQUAKE OCCURRENCE
1) Zones with point sources
Future earthquake occurrence within the areal extent of the zone is random, and is not defined in terms of faulting style or orientations.
2) Zones with virtual faults
The characteristics of future earthquake occurrence are further specified with ranges of parameters including fault orientation (strike and dip), faulting style, and seismogenic rupture depth range. No specific locations for these virtual faults are specified within the zone. All parameters including rates, recurrence, and magnitude characterizations are the same for all virtual faults within the zone.
3) Zones with embedded faults
Future earthquake occurrence within the zone is localized to specified geometries and locations. These locations and geometries, termed embedded faults, may be defined based on geologic and structural attributes of specific features within the zone. Rates, recurrence, and magnitude characterizations are defined based on the characteristics of the overall zone rather than any data specific to the embedded faults.
4) Fault sources
Future earthquake occurrence is described through the characterization of individual faults. The expected ranges of future earthquake behavior for location, geometry, style of faulting, rates, recurrence, and maximum magnitudes are defined based on data and analogues specific to each fault source. Characterizations of fault sources are independent of source zones.
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SEISMIC SOURCE CHARACTERIZATION
Different Types of Seismic Sources in the BC Hydro Model
DATE: 4/21/2011
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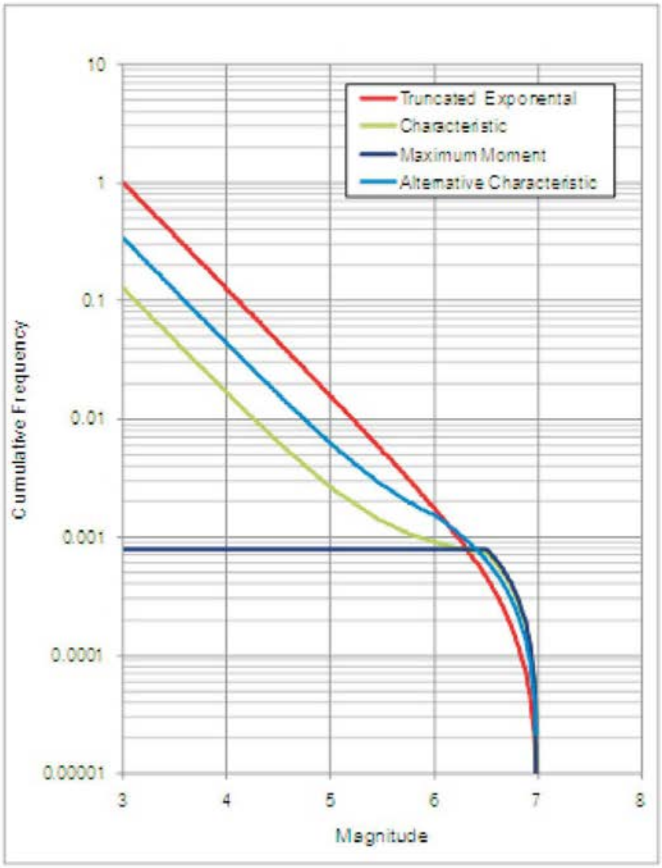
CHDK MSL
REPORT No. E658
FIGURE 3.4.3



BChydro ENGINEERING

PROBABILISTIC SEISMIC HAZARD ASSESSMENT

SEISMIC SOURCE CHARACTERIZATION

Earthquake Recurrence Models

DATE	DSGN	CHKD	REPORT No.	
21 Apr 2011	MWM	MSL	E658	**FIGURE 3.5-1**

4.0 GROUND MOTION CHARACTERIZATION

As described in Section 1, the study region is tectonically diverse. This fact adds a level of complexity to both the SSC and the GMC parts of the PSHA. With respect to estimating earthquake ground motions, three sets of GMPEs are required; for the Cascadia subduction zone (interface and intraslab), crustal earthquakes east of the plate margin, and the stable continental interior of eastern BC and Alberta. During the first GMC workshop, the TI concluded that available ground motion prediction models could be used to estimate ground motions associated with crustal earthquakes. However, for purposes of estimating ground motions associated with subduction zone earthquakes the GMC TI concluded that simply using existing models and assigning weights to them was not appropriate. The TI noted the range in existing subduction ground motion models estimates is significant and many of the models had not been updated as new ground motion data became available. Consequently, the GMC TI and the project sponsor concluded that an effort would be undertaken to develop a new subduction ground motion prediction equation. Volume 3 of the PSHA report describes the development of the subduction zone ground motion prediction model and the crustal ground motion prediction equations that were used. This section summarizes the features of the ground motion characterization component of the PSHA.

4.1 APPROACH

In general and in the study region specifically, there are four broad types of tectonic regions for predicting ground motions:

1. Active crustal regions;
2. Stable continental regions;
3. Volcanic regions; and
4. Subduction zones.

The first three regions are related to crustal earthquakes while the fourth deals with subduction zone interface and deeper intraslab earthquakes. Figure 4.1-1 shows the tectonic regions in the study area. Ground motion prediction equations are developed/evaluated for these different tectonic regions, reflecting the differences in magnitude and distance scaling due to different source and propagation characteristics.

The study region contained seismic sources in all four tectonic regimes. Figure 4.1-1 shows a division of the study region into the four 'ground motion' zones - Western North America (WNA), Eastern North America (CENA), Volcanic Arc and Cascadia subduction zone.

The purpose of the GMC component of the PSHA was to predict ground motions that could occur as a result of earthquakes that are identified in the SSC model, taking into account the tectonic diversity of the region, crustal attenuation, characteristics of earthquake occurrences (magnitude, style of faulting, depth, etc.), and near-surface geologic conditions.

At the first ground motion workshop, the general approach taken to develop the ground model inputs to the PSHA involved the following steps:

- Identify the classes of ground motion models required for the different tectonic regions;
- For each class of models, identify available credible models, evaluate them and determine their applicability to the study region;
- If no existing models are deemed appropriate or applicable to the study region, develop a new model;
- For each class of ground motion models, assign relative weights to the selected models that reflect the defensible interpretations of the technical community;
- Identify the range of v_{s30} (shear wave velocity of the top 30 m of the underlying rock) for BC Hydro facility sites;
- Account for the differences in site conditions (v_{s30}) between the study region and the reference condition used in the selected ground motion models.

The conclusion of the first workshop was that existing subduction zone attenuation models were not adequate for use in the PSHA. A primary reason for this was that many of the models had not taken advantage of ground motion data from subduction earthquakes from Japan, Taiwan and South America. As a result, it was concluded that these data should be obtained and included in a subduction ground motion database, and used to develop a new model that was better constrained in magnitude and distance ranges where data had been previously limited.

4.2 GROUND MOTION CHARACTERIZATION

The prediction and characterization of earthquake ground motions are defined in terms of:

- A reference ground condition with a v_{s30} = 760 m/s;
- Model of the median horizontal spectral acceleration that includes an estimate of the epistemic uncertainty in the median for a defined set of structure frequencies as predicted as a function of earthquake magnitude, source-site distance, faulting style, site location with respect to fault rupture (hanging-wall versus footwall);
- Aleatory uncertainty model (i.e., logarithmic standard deviation) that estimates the variability in ground motions not explained by the ground motion prediction model parameters including an estimate of the uncertainty in the aleatory model;
- Vertical ground motion model; and
- Maximum ground motions.

Horizontal ground motions are defined in terms of the geometric mean of the two horizontal components of ground motion. Given the tectonic diversity of the study region, three sets of ground motion prediction models are developed that embody these five elements. The active crustal region and the volcanic arc use the same set of GMPEs

4.2.1 Crustal Ground Motion Prediction Equations

Crustal prediction models were required for the active crustal and the stable continental regions. In both cases the TI identified existing ground motion models that could be considered for use in the PSHA.

4.2.2 Active Crustal Regions

Most of the study region is located in an active crustal region. The Next Generation Attenuation (NGA) models were the most current GMPEs for active crustal regions. There were five GMPEs in the NGA model package. However, these models were developed primarily with California strong-motion data and did not include data from BC. To assess the viability of the NGA models to estimate ground motion hazards in BC, an assessment was conducted to evaluate whether predicted motions are consistent with available strong-motion records in BC.

The results of the evaluation concluded that the NGA models were not inconsistent with recorded ground motions and therefore there was no reason that these could not be used in the PSHA. The description of the evaluation that was performed is provided in Section 4 in Volume 3.

In addition to the conclusion that the NGA models could be used to predict ground motions in BC, the GMC TI determined the NGA models as originally published should be amended to address the epistemic uncertainty in the estimate of the median of the individual ground motion models. This additional uncertainty was attributable in part to the lack-of-fit of a model to the ground motion data. An estimate of the epistemic uncertainty in the median of the individual NGA models was made (in terms of a logarithmic standard deviation), and this uncertainty was included in the logic tree for the NGA models. The estimate of uncertainty is described in Section 4 of Volume 3. As described in Section 4.5, a single–station sigma (aleatory uncertainty) model was used in the analysis. The single-station sigma model was derived for the NGA models. No epistemic uncertainty in the single-station sigma model was considered given the variability between the models wass on the same order as the standard error in their estimate (see Section 4.7 in Volume 3). The uncertainty in the ground motion models for the active crustal attenuation was modelled in a logic tree.

4.2.3 Stable Continental Region

To estimate ground motions in the stable continental region, the GMC TI reviewed available ground motion models for CENA. From these, the TI selected four models for use in the PSHA.

As in the case for the prediction equations used for seismic sources in the active crustal region, additional epistemic uncertainty in the median CENA models was included. This additional uncertainty was developed as part of the candidate models that were selected.

The selection of the CENA models and the single-station sigma is described in Section 5 of Volume 3. A logic tree was used to model the uncertainty in the GMPE for the stable continental region. For the stable continental ground motion, a single-station sigma model was derived from the NGA models. The epistemic uncertainty in the single-station sigma was modelled by a three-point distribution, based on its standard error.

4.2.4 Subduction Ground Motion Prediction Equations

As noted above, the GMC TI concluded that a new subduction zone ground motion prediction equation should be developed for the PSHA. The model development started with the compilation of an up-to-date, world-wide database of strong-motion data recorded during subduction earthquakes. The database was compiled by convening a workshop of resource experts who contributed and helped identify subduction data sources world-wide.

The subduction GMPE was defined in terms of:

- Earthquake magnitude,
- Source-site distance,
- Subduction event type; interface or intraslab,

- Recording site location (with respect to the volcanic arc; forearc or backarc),
- Earthquake depth, and
- Site conditions (i.e., v_{s30})

The development of the subduction GMPE included analysis to estimate the median model for horizontal spectral acceleration at selected structural frequencies, an evaluation of the epistemic uncertainty in the median, and an estimate of the aleatory, single-station sigma (see Section 4.5).

The model also included an estimate of the uncertainty in the aleatory standard deviation. The uncertainty in the subduction model was also modelled using a logic tree.

Section 3 of Volume 3 describes the development of the BC Hydro subduction model.

4.3 SINGLE-STATION SIGMA MODEL

The aleatory variability of ground motions (the aleatory logarithmic standard deviation) is generally determined from residuals of ground motions as derived from the statistical analysis of the GMPE. The logarithm of ground motion residuals is normally-distributed and range over +/- three standard deviations. Typically, these are used to estimate the total aleatory ground motion variability; the variability that is not explained by the GMPE. There are a number of factors that contribute to this variability, including the random differences between earthquakes of the same magnitude (i.e., dynamic stress drop, fault rupture characteristics), differences in propagation path between the earthquake source and strong-motion recording stations (even for recordings from the same earthquake), and variations in near-surface geologic conditions between strong-motion recording stations.

Recent studies of ground motion variability have estimated a component of the total variability that is attributable to the variation in site-response (Chen and

Tsai, 2002; Atkinson, 2006; and Morikawa et al., 2008). These studies, which have examined strong-motion datasets where individual recording sites have multiple ground motion recordings, have shown that the variability at individual sites, referred to as the single-station sigma is lower than the traditional or total aleatory standard deviation that is estimated in ground motion regression analysis.

In this project, the single-station sigma was used in the PSHA calculations. A key advantage of using the single-station sigma was that it provided a framework for using site-specific information in the evaluation of seismic ground motions at a site. For individual sites, it offered the flexibility to incorporate into the hazard results, the effects of site-specific amplification, variability, and as the case may be epistemic uncertainties associated with the site response effects. The effect of site-specific response was incorporated into the PSHA results in a post-processing step whereby the seismic hazard results (seismic hazard curves) and the site-response factors were probabilistically combined to determine the site-specific hazard. This process is described in Volume 4.

4.4 VERTICAL GROUND MOTIONS

As part of the input to engineering evaluations, vertical and/or horizontal ground motions may be required. To estimate vertical ground motions the GMC TI elected to use an approach in which the horizontal ground motions estimated in the PSHA are scaled by a vertical-to-horizontal (V/H) ratio. This approach has the advantage that it allows the vertical ground motions to be correlated to the level of horizontal shaking, as opposed to an alternative approach where vertical motions are estimated independent of the level of horizontal motion as would be the case if the PSHA calculations were performed with vertical ground motion prediction equations.

In this project, vertical response spectra were estimated as a function of the horizontal motion, the dependence on earthquake magnitude and distance, and the correlation of vertical amplitudes between structural frequencies. Thus, the vertical motions were estimated conditionally on the horizontal motions. This approach was similar to the approach Baker and Cornell (2006) used to develop the conditional mean spectrum (CMS) for horizontal ground motions.

There is epistemic uncertainty in the V/H ratio, however, this uncertainty was not explicitly modelled in the PSHA. The argument for not including this uncertainty was the potential for overestimating the epistemic uncertainty given the uncertainty in the estimate of the horizontal ground motions (see Section 6.4 in Volume 3).

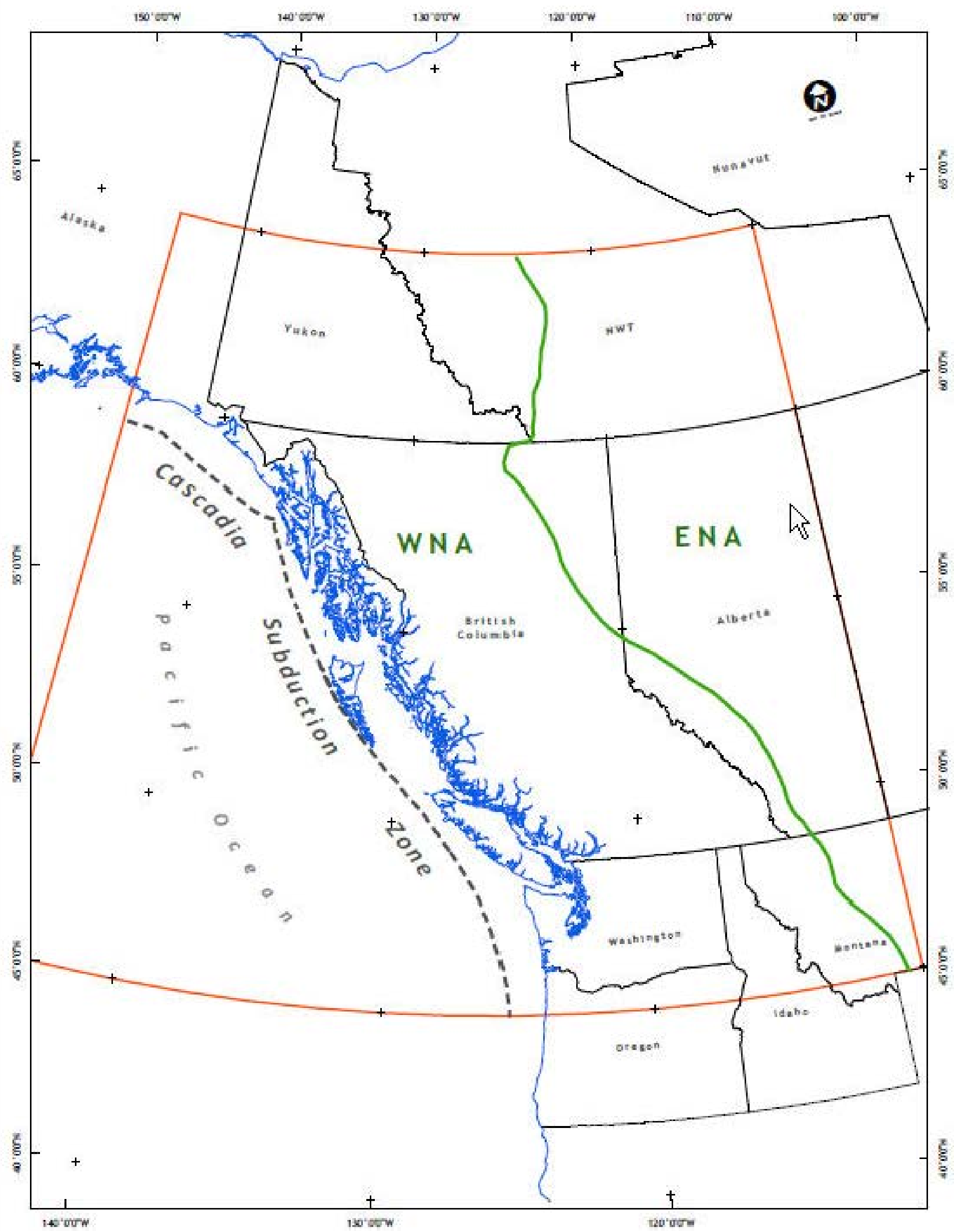
4.5 MAXIMUM GROUND MOTIONS

In the past, alternative approaches have been used to impose limits on earthquake ground motions that could occur. These approaches included,

- Upper-tail truncation by defining a truncation of the aleatory distribution in terms of a specified number of standard deviations above the median, or
- In terms of an absolute limit on the ground motions that could occur (e.g., 2.5g).

A recent study by EPRI (2006) that attempted to establish a basis to truncate the distribution on ground motions concluded no such basis could be developed.

As a result, the distribution on ground motions is not truncated in the PSHA. However, a truncation is applied at the numerical limit of the normal distribution algorithm that was used in the PSHA software.



BChydro PSHA07DS
Ground Motion Characterization (GMC) Model
DSGN. JJC CHKD. KOA DATE. Nov 2010

'Ground Motion Model' Zones

Fig. 4.1-1
REPORT No. E658-3

5.0 PSHA IMPLEMENTATION

This section summarizes the implementation of the PSHA model. Topics discussed include the implementation of the SSC and GMC models, the PSHA software and its verification, the BC Hydro dam sites that were evaluated and the results that were produced for each site.

5.1 Implementation Process

The implementation of the PSHA model involved entering the SSC and GMC models into data files that were used by the PSHA software package; linking the SSC and GMC models (assigning the appropriate GMC models to seismic sources), and carrying out the calculations to estimate the ground motion hazard at each dam site. The implementation involved the following steps:

1. Constructed an overall logic tree model that combines (links) the ground motion and the SSC global logic trees.
2. Implemented the SSC models in the PSHA software such that the aleatory and epistemic uncertainty in the seismic sources models were accurately represented and correctly defined in the input files. This included the linking of the ground motion models with the seismic sources and the SSC master logic tree and the individual seismic source logic trees (see Volume 2, Section 6).
3. Implemented (coded) the subduction GMPEs developed as part of this project, the CENA GMPEs that were used with seismic sources located in the stable continental region, and the NGA models for seismic source located in the active continental crust.
4. Verified the PSHA software
5. Reviewed and verified that the PSHA software reflected the SSC and GMC models as described in Volumes 2 and 3.
6. Performed the PSHA calculations for the dam sites.
7. Conducted sensitivity analyses to illustrate the effect of different elements of the SSC and GMC model that were important to the hazard at dam sites in various parts of the study region.

The following sections describe the primary features of the implementation process.

5.2 PSHA SOFTWARE

The PSHA was implemented using the software package developed and maintained by AMEC Geomatrix (AMEC). The AMEC PSHA software package consisted of a set of three programs:

- XCD53BC (special BC Hydro version),
- HAZ51, and
- TREE50.

A summary of each of the codes is provided below and described in more detail in the software user documentation (AMEC, 2011).

Program XCD53BC - XCD53BC computes the conditional (on earthquake magnitude) probability of exceedance of ground motions for a single source geometry and ground motion measure. This corresponds to the bracketed summation, $P(Z>z \mid m, r)$ in Equation (2-3) in which the spatial integration over the future occurrence of earthquakes on a fault source or in a seismic source zone, as a function of earthquake magnitude, is carried out. Due to the uncertainty in ground motion attenuation models and seismic source characteristics (geometry, fault dip, fault strike, etc.), XCD53BC evaluates the combinations of ground motion attenuation models and seismic source parameters for each seismic source.

Program HAZ51 - HAZ51 combines the output from program XCD53BC with the estimates of the frequency of earthquake occurrences as a function of magnitude to complete the summation of Equation (2-3). The program can accept multiple levels of nested alternative recurrence parameters (alternative earthquake recurrence models and model parameters) in a logic tree and computes the mean hazard as well as hazard distribution and variance components. The program can combine the hazard from up to 100 sources. It computes the combined hazard distribution assuming the distributions for the individual sources are independent.

Program TREE50 – Program TREE30 combines the output files from HAZ51 according to linked GMC and SSC logic trees. The program accepts multiple levels of nested logic tree branches of HAZ51 output files with assigned probabilities. These levels include those in seismic source logic tree that combines the distributions of the hazard from multiple seismic sources, assuming they are independent as well as multiple levels that combines the distributions of the hazard from multiple sources assuming they are independent.

The programs are run in sequence to carry out different parts of the PSHA quantification. Program XCD53BC convolves the distance and ground motion distributions to produce conditional probabilities of exceedance for a given magnitude and source geometry. These are input into program HAZ51 which computes the earthquake frequencies, convolves them with the conditional probabilities of exceedance output from XCD53BC to obtain frequencies of exceedance for a specific set of input parameters, and computes the hazard distribution and statistics for an a level logic tree for an individual source and the combined distributions of multiple sources. For larger logic trees, program TREE50 is used to combine the results of multiple outputs of HAZ51, providing a total of 33 levels of epistemic uncertainty that can be modelled.

The AMEC PSHA software has been subjected to quality assurance reviews, including those carried out for this project (AMEC, 2011).

As part of the PSHA project, BC Hydro acquired rights to use the proprietary software developed and maintained by AMEC Geomatrix. This provides BC Hydro the flexibility to make PSHA calculations for other sites, conduct sensitivity studies and generate additional results for dam sites that have not been produced specifically as part of this project (see Section 5.4).

5.3 SEISMIC HAZARD RESULTS FOR BC HYDRO DAM SITES

PSHA calculations were performed for 42 BC Hydro dam sites (including the proposed Site C). For purposes of organizing the PSHA calculations, the sites were assigned to three groups (A, B and C). A different set of PSHA results was generated for each group. Table 5.4-1 lists the three groups and the PSHA results that are generated for each group.

As needed in the future, BC Hydro will be able to re-run the PSHA calculations if additional results are required; results for more ground motion measures, magnitude-distance deaggregation results, or if seismic hazard input is required at other facility locations.

5.4 SITE-SPECIFIC APPLICATIONS

The PSHA calculations reported in Volume 4 are carried out using the single-station sigma aleatory model. The single-station sigma model (described in Volume 3, Appendix 6) corresponds to the ground motion aleatory variability in which the site-to-site variability has been removed from the total aleatory variability associated with the GMPEs used in the PSHA calculations.

The results presented in Volume 4, Section 3 for a site cannot be used directly unless two conditions are met:

1. The site in question must have a v_{s30} of 760 m/s and,
2. There must be strong evidence that the average response at the site is equal to the average response of the population of sites with of v_{s30} 760 m/s used to develop the GMPEs used in the hazard analysis.

If these conditions are not met, then the results in Volume 4, Section 3 must be modified based on the information and conditions that are applicable for the site. To demonstrate that these conditions are met, certain site-specific information is required (see Volume 4, Section 5).

The first type of data required is information on the dynamic properties, particularly shear wave velocity to determine the v_{s30} at a given dam site. Data is also required to define other relevant parameters (see Volume 4, Section 5) in order that a comparison can be made between the characteristics of a specific site and those of the recording stations used to develop the GMPEs utilized in the PSHA.

The second type of data required consists of sufficient recordings of earthquake ground motions at the site being considered that would allow a comparison of the motion at the site, to the average motion that would be predicted for the site for the given earthquake using the GMPEs. This allows the analyst to define the average response of the site relative to the population of sites with the same site conditions (i.e. same v_{s30}) (see the discussion in Volume 4, Section 5).

If it cannot be demonstrated that the characteristics of a site are consistent with the sites used to develop the GMPEs, modifications must be made to the PSHA results in Volume 4, Section 3. The modifications must take into account the average site response, as compared to the average response that would be predicted and the additional aleatory and epistemic uncertainty that is applicable.

These calculations are carried out using a computation package developed as part of the PSHA project. The code, SITEMOD, is a post processor that can be used to adjust the mean hazard results presented in Volume 4, Section 3 to account for the information available at a given site. SITEMOD allows for the application of an average difference in ground motions at the site in question compared to the reference v_{s30} of 760 m/s and for the uncertainty in the response at that site relative to the population of sites with similar characteristics.

Table 5.4-1: BC Hydro Dam Sites and PSHA Results

Sites	PSHA Results
Group A 1. Site C 2. John Hart 3. Ruskin Dam 4. La Joie 5. Jordan Diversion 6. Kootenay Canal 7. Peace Canyon	1. Seismic hazard curves with uncertainty distribution for all spectral periods. 2. Uniform hazard response spectra for vertical and horizontal ground motions for return periods of 100, 475, 1,000, 2,475, 10,000, 100,000, and 1,000,000 years. 3. Magnitude-distance deaggregation results (plots) for PGA and S_a at 0.2 and 1.0 seconds.
Group B 8. Mica Dam 9. Alouette 10. Duncan 11. Hugh Keenleyside 12. Terzaghi Dam 13. WAC Bennett	1. Seismic hazard curves with uncertainty distribution for PGA and S_a at 0.2 and 1.0 seconds. 2. Uniform hazard response spectra for vertical and horizontal ground motions for return periods of 100, 475, 1,000, 2,475, 10,000, 100,000, and 1,000,000 years. 3. Magnitude-distance deaggregation results (plots) for PGA and S_a at 0.2 and 1.0 seconds.
Group C 14. Revelstoke 15. Coquitlam 16. Elsie 17. Strathcona 18. Seven Mile 19. Stave Falls 20. Ladore 21. Buntzen 22. Cheakamus 23. Aberfeldie 24. Clowhom 25. Comox 26. Seton 27. Elko 28. Elliott 29. Heber Diversion 30. Sugar Lake 31. Puntledge Diversion 32. Quinsam Diversion 33. Quinsam Storage 34. Clayton Falls 35. Salmon River Diversion 36. Bear Creek 37. Spillimacheen 38. Falls River 39. Wahleach 40. Walter Hardman	1. Seismic hazard curves with uncertainty distribution for PGA. 2. Magnitude-distance deaggregation results (plots) for PGA.

Sites	**PSHA Results**
41. Whatshan 42. Wilsey	

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APPENDIX A:

GLOSSARY OF ACRONYMS AND DETAILED DEFINITIONS

APPENDIX A: GLOSSARY OF ACRONYMS AND DETAILED DEFINITIONS

A.1 LIST OF ACRONYMS

A.1.1 General

AD: Anno Domini

BP: before present

BCGS: British Columbia Geological Survey

CTZ: coseismic transition zone

CENA: Central and Eastern North America

DOE: U.S. Department of Energy

EPRI: Electric Power Research Institute

ETS: episodic tremor and slip

ETZ: effective transition zone

EXP: Explorer Plate

FWLA: Fugro William Lettis Associates Inc.

Ga: giga or billion years old or ago

Gy: giga or billion years

GIS: geographic information system

GMC: ground motion characterization

GPS: global positioning system

GSC: Geological Survey of Canada

ISC: International Seismological Center

JdF: Juan de Fuca Plate

LiDAR: light detection and ranging

ka: kilo or thousand years old or ago

ky: kilo or thousand years

M: magnitude

m_{bLg}: Lg body wave magnitude

M_L: Richter local magnitude

M_{max}: maximum magnitude

M_{min}: minimum magnitude

M_o: seismic moment

M_s: surface wave magnitude

MMI: modified Mercalli intensity

Ma: mega or million years old or ago

MS: Microsoft

M_w: moment magnitude

My: mega or million years

NA: North America Plate

NCal: Northern California

NEHRP: National Earthquake Hazard Reduction Program

NoVI: northern Vancouver Island

NSHM: National Seismic Hazard Maps

PA: Pacific Plate

P_A; probability of activity

PEER: Pacific Earthquake Engineering Research Center

PGC: Pacific Geoscience Centre

PGV: peak ground velocity

PSHA: probabilistic seismic hazard analysis

RA: rupture area

SCal: Southern California

SoVI: southern Vancouver Island

SRL: surface rupture length

SSC: seismic source characterization

SSHAC: Senior Seismic Hazard Analysis Committee

SSZ: seismic source zone

S-wave: shear-wave

SSRL: subsurface rupture length

SVG: Spatial Vision Group

T_e: elastic thickness

USGS: United States Geological Survey

USNRC: United States Nuclear Regulatory Commission

UTC: Coordinated Universal Time

WNA: Western North America

A.1.2 Seismic Sources

(a) Areal Source Zones

ESZ: Explorer Shear Zone

IP: Interior Plains

ISB: Intermountain Seismic Belt

JdFPSD: Juan de Fuca Puget Sound Deep

JdFPSS: Juan de Fuca Puget Sound Shallow

JdFVI: Juan de Fuca Vancouver Island

NCB: Northern Columbia Basin

NCM: Northern Coastal Margin

NFB: Northern Foreland Belt

NIM: Northern Intermontane

NRMT: Northern Rocky Mountain Trench

NTZ: Nootka Transform Zone

NTZC: Nootka Transform Zone – Continental

NVA: Northern Volcanic Arc

OLY: Olympic Peninsula

OMI: Omineca

PL: Puget Lowland

PRA: Peace River Arch

QCT-N: Queen Charlotte Transform - North

QCT-S: Queen Charlotte Transform - South

RDW: Revere-Dellwood-Wilson

SCM: Southern Coastal Margin

SFB: Southern Foreland Belt

SIM: Southern Intermontane

SVA: Southern Volcanic Arc

WEM: Winona Explorer Margin

(b) Fault Sources

BCF: Boulder Creek Fault

BLF: Bull Lake Fault

CF: Calawah Fault

CSZ: Cascadia Subduction Zone

DMF: Devils Mountain Fault

EOFZ: Eastern Olympic Mountain Fault Zone

FF: Flathead Fault

HCF: Hell Creek Fault

LC-BC-LRF: Lake Creek-Boundary Creek-Little River Fault

LRF: Leech River Fault

MF: Mission Fault

NF: Nyack Fault

OCF: O'Brien Creek Fault

QCF: Queen Charlotte Fault

RF: Roosevelt Fault

SF: Swan Fault

SFF: South Fork Flathead Fault

SFZ: Seattle Fault Zone

SJF: Skipjack Fault

SLF: Savage Lake Fault

SPF: Strawberry Point Fault

SJFFZ: Strait of Juan de Fuca Fault Zone

SWIF: Southern Whidbey Island Fault Zone

TC: Tacoma Fault

UPF: Utsalady Point Fault

WF: Whitefish Fault

A.1.3 Ground Motion

ACR: active crustal region

AEF: annual exceedence frequency

AS: aftershock

CMS: conditional mean spectrum

CMT: centroid moment tensor

GMM: ground motion modeling

GMPE: ground motion prediction equation

IF: interface

IS: intraslab

MS: mainshock

NGA: Next Generation of Attenuation

PGA: peak ground acceleration

PGV: peak ground velocity

psa: pseudo spectral acceleration

R_{EPI}: epicentral distance

R_{HYP}: hypocentral distance

R_{RUP}: rupture distance

R_{JB}: Joyner-Boore distance

R_{X}: strike-perpendicular coordinate

SCR: stable continental region

SMM: small to moderate earthquake

UHS: uniform hazard spectrum

V/H: vertical-to-horizontal ground motion ratio

Z_{TOR}: depth to top of fault rupture

A.2 LIST OF DEFINITIONS

Active Fault (Quaternary): A fault that has slipped in geologically recent time, has an association with earthquakes and is likely to slip again in the future (i.e., can be considered to have a probability or potential for slip and earthquake recurrence). There are different definitions of recent geological time. Faults are commonly considered to be active if they have moved in the last 10 or 12 ky (i.e., Holocene). In this study, faults that have or may have slipped in Quaternary time (i.e., the last 1.6-1.7 My) are considered to be active or potentially active.

Aftershocks: Smaller earthquakes that occur immediately after a large earthquake (mainshock) in a restricted volume around the mainshock. Aftershocks represent the adjustment of the mainshock rupture zone and adjacent area to the new stress state. The largest aftershock is usually more than a magnitude unit smaller than the mainshock. The frequency of occurrence of aftershocks decays rapidly with time after the mainshock.

Aleatory Uncertainty: The variability inherent in a nondeterministic (i.e., stochastic, random) phenomenon. Aleatory variability is accounted for by modeling the phenomenon in terms of a probability model. In principle, aleatory uncertainty cannot be reduced by the accumulation of more data or additional information, but the detailed characteristics of the probability model can be improved. Aleatory variability is sometimes called "randomness" (American Nuclear Society, 2008a).

Alternative Boundary: An alternative boundary is defined where the presently available data and its interpretation does not define a single boundary location. An alternative location for a zone boundary is thus chosen on the basis of specific geologic, geophysical, seismological, or tectonic data that generally exclude intermediate locations.

Anelastic Attenuation: Attenuation caused by intrinsic anelasticity of the Earth. Anelasticity is associated with small-scale crystal dislocations, friction, and movement of interstitial fluids. (Lay and Wallace, 1995)

Areal Source Zone: An area or region of the Earth's crust (actually a volumetric source zone because there is a seismogenic depth component) that is assumed to have relatively uniform earthquake source characteristics. Areal source zones are used in PSHA to model background seismicity or regions where there is an absence of information on active faulting. See also "Background Source Zone" and "Volumetric Source Zone" (American Nuclear Society, 2008a).

Aseismic: Pertaining to not having or not being subject to earthquakes.

Attenuation: The gradual decrease in the amplitude of seismic waves as they propagate through the earth's crust. Attenuation results from geometric spreading of propagating waves, energy absorption (anelasticity), and scattering of waves. Attenuation is commonly modeled in a GMPE by one or more decreasing functions of source-to-site distance.

Backarc: In the classic setting, an isolated marine basin behind an island arc subduction zone, formed either by backarc spreading or by a step-back in the location of underthrusting adding oceanic lithosphere to the leading edge of the overriding plate. In the Cordillera (continental-oceanic convergence) subduction setting the backarc is inland of the "volcanic arc" and is generally elongated parallel to the convergent plate margin (Keary, 1996). See also "Forearc".

Background Seismicity: Background (floating or random) earthquakes are events in a PSHA that are not associated with known or mapped faults. They are modeled in PSHAs using areal source zones. The combination of the background seismicity plus the seismicity associated with any fault(s) constitutes the seismicity as a whole for the source zone. See also "Areal Source Zone".

Background Source Zone: A part of the earth's crust, usually of large areal dimension, within which potentially damaging earthquakes could occur that are not associated either with known fault sources or even with the uniform pattern, rate, or style of deformation or seismicity commonly identified with volumetric seismic source zones. In PSHAs, earthquakes that cannot be associated with other sources default to a background source zone (American Nuclear Society, 2008a).

Bar: A widely used metric unit of measurement for pressure. 1 bar = 0.1 MPa = 10^6 dyne/cm^2.

Between-Earthquake Residual: Same as "Inter-Event Residual".

Blind Fault: A fault that does not rupture all the way up to the Earth's surface and consequently has no surface trace. These features are usually associated with thrust faults, which are formed by compressive stresses. Blind thrust faults do not penetrate the uppermost layers of crust, but they cause the surface layers to fold over them as they deform, often forming an anticline or fold expressed as a small hill or ridge at the ground surface (American Nuclear Society, 2008a).

Cascadia Subduction Zone Dislocation Model: The Cascadia subduction zone has been kinematically and thermally modelled by the Geological Survey of Canada based on surface interseismic deformation (GPS) and heat flow data (Wang et al, 2003). An elastic dislocation model delineates the subduction zone into a number of zones (from updip to downdip):

Shallow free-slip zone

Locked zone

Effective transition zone (ETZ)

Coseismic transition zone (CTZ)

Interseismic transition zone (ITZ)

Deep free-slip zone

Locked Zone:

This zone represents the zone of unstable stick-slip behaviour on the subduction interface, with an updip limit defined by the 100-150°C isotherm and a downdip limit in part modelled on the 350°C isotherm. This zone occurs between the Cascadia deformation front and the west coast of Vancouver Island and Olympic Peninsula. Together with the coseismic transition zone this represents the portion of the subduction interface that ruptures during a megathrust earthquake. The total seismogenic width of the locked and coseismic transition zones perpendicular to the margin has an important influence on the maximum size of great earthquakes (Natural Resources Canada, 2008).

Effective Transition Zone:

This zone is the transition between the fully locked and deep free-slip zones. It comprises two zones; a shallower coseismic transition zone and a deeper interseismic transition zone. The downdip limit of this zone is in part modelled on the 450°C isotherm. In the dislocation model, this zone is a mathematical expression in a static elastic model that accommodates the transition from zero fault slip to full plate convergence rate.

Coseismic Transition Zone:

This zone is the shallower portion of the effective transition zone that is assumed to rupture during a megathrust earthquake. The amount of coseismic slip in this zone decreases linearly downdip away from the locked zone. Together with the locked zone this represents the portion of the subduction interface that ruptures during a megathrust earthquake.

Interseismic Transition Zone:

This zone is the deeper portion of the effective transition zone that is not involved in coseismic rupture. The downdip limit of this zone is in part modelled on the 450°C isotherm. The zone is characterised by episodic tremor and slip events.

Free-Slip Zones:

There are two free slip zones where the subduction interface moves freely and PA-NA convergence is accommodated aseismically by steady slip motion at the full plate convergence rate:

Shallow Free Slip Zone: A shallow zone of aseismic stable slip extending seaward of the Cascadia deformation front and up-dip of the locked zone.

Deep Free Slip Zone: A deep creep (plastic deformation) zone of stable sliding behaviour extending landward and down-dip of the effective transition zone.

Censoring: An observation x_i is said to be censored if it is known only that $x_i \leq L_i$ (righer-censored) or $x_i \geq U_i$ (left-censored), where L_i and U_i are fixed values (Everitt, 1998).

Characteristic Earthquake: Individual faults and fault segments tend to generate essentially the same size, or characteristic, earthquakes having a relatively narrow range of magnitudes at or near the maximum and at a frequency higher than would be estimated from the Gutenberg-Richter relationship (Chen and Scawthorn, 2003; Schwartz and Coppersmith, 1984).

Characteristic Magnitude: Magnitude of the characteristic earthquake on an individual fault. Generally, this is a relatively narrow range of magnitudes at or near the maximum governed by the geometry, mechanical properties, and state of stress of a particular fault (Chen and Scawthorn, 2003).

Characteristic Magnitude Recurrence Model: See "Recurrence Models".

Completeness: Describes the completeness (down to some specified magnitude) of a record of historical earthquakes. Completeness is a function of the characteristics of population/urban growth and distribution and the development of seismic monitoring through a seismograph network. Completeness varies spatially and temporally with the spacing and development over time of the seismograph network.

Concealed Fault: See "Blind Fault".

Conditional Mean Spectrum: The expected (i.e. mean) response spectrum, conditional on the occurrence of a target spectral acceleration value at the period of interest. (Baker, 2011)

Continuum Deformation Model: See "Distributed Shear Deformation Model".

Corner Frequency of a Filter: Corner frequency is a boundary in a filter's frequency response at which the amplitude of input time series begins to be reduced rather than passing through. In PEER’s record processing procedure, filter corner is defined by a 3 dB corner, a frequency for which the filter response is −3 dB of the nominal passband value.

Coseismic: Refers to the geological phenomena, such as slip or movement along a fault, crustal deformation, subsidence or uplift that occurs simultaneously with an earthquake.

Coseismic Transition Zone: See "Cascadia Subduction Zone Dislocation Model".

Critical Damping: The least amount of damping that will prevent free oscillatory vibration in a one-degree-of-freedom system.

Crust: The outermost solid layer of the Earth, distinguished chemically from the underlying mantle beneath the "Mohorovičić Discontinuity". The crust comprises of the markedly dissimilar "oceanic" crust and "continential" crust (Keary, 1996).

Oceanic Crust:
Thin (~7 km), young (<200 Ma) crust consisting of three layers: an uppermost layer of sediments, a mid-layer of basaltic pillow lavas underlain by dykes and gabbroic intrusions, and an underlying layer of ultrabasic rocks (Keary, 1996). The oceanic crust represents material, which has been emplaced at the Earth's surface directly by magmatism from the Earth's mantle. As the most common type of magma to be derived from the Earth's mantle, it has a basaltic composition (USGS, 2008a).

Continental Crust:
The upper layer of continent-bearing lithosphere, bounded at the base by the **"**Mohorovičić discontinuity" at a depth of ~20-80 km, at which there is a downward increase in density from ~3.0 to ~3.3 Mg/m^3. Its average composition is between granodiorite and quartz diorite (Keary, 1996). The continental crust represents material that has been recycled numerous times by igneous activity, metamorphism, sedimentation, deformation and mountain building (USGS, 2008a).

Damping Ratio: The ratio of the actual damping to the critical damping.

Deaggregation: Process used to determine the fractional contribution of each magnitude-distance (M-D) pair or of each seismic source zone, to the total seismic hazard. To accomplish the M-D deaggregation, a set of magnitude and distance bins are selected and the annual probability of exceeding selected ground acceleration parameters from each M-D pair is computed and divided by the total probability of exceedence for all modeled earthquakes (American Nuclear Society, 2008).

Deep Free Slip Zone: See "Cascadia Subduction Zone Dislocation Model".

Dextral (Right-Lateral): The sense of movement across a boundary, such as a fault, in which the side opposite to the observer moves to the right (Keary, 1996).

Distributed Shear Deformation Model: A deformation model that assumes that the deforming upper crust behaves as a deforming continuum and contains no discrete (elastic) blocks. Though gradients in the residual velocity field potentially reveal localized deformation strain, none are explicitly resolved on any crustal faults. Such a model was developed by Mazzotti et al. (2008) for southwest BC and includes removal of the elastic strain accumulation on the Cascadia subduction zone. Compare with "Rigid Block Deformation Model".

Dip: The angle by which a fault plane deviates from the horizontal. Dip angle is measured in a plane perpendicular to the strike.

Earthquake Collection Area: The concept of an expanded earthquake collection area is used to account for uncertainty in earthquake catalogue locations near certain seismic source zone boundaries.

Effective Transition Zone (ETZ): See "Cascadia Subduction Zone Dislocation Model".

E-Layer: A low velocity, electrically conductive band of seismic reflectors beneath Vancouver Island (Zhao et al, 2001). The preferred interpretation is that the E-layer represents a region where oceanic sediments have been accreted at depth beneath an overriding subduction complex (Yorath et al., 1985; Clowes et al., 1987). It delimits a region of active decoupling between the overriding continental plate and the subducting oceanic plate. Other researchers (Nicholson et al., 2005; Audet et al., 2008) have interpreted the E-layer to represent the dehydrating oceanic crust of the subducting Juan de Fuca Plate. See also "F-Layer".

Elastic Deformation Model: See "Rigid Block Deformation Model".

Elastic Thickness (T_e): For a simple lithospheric rheology–depth function, T_e corresponds approximately to the depth of the brittle–ductile transition, or the base of the mechanical lithosphere. T_e is reduced for a more complex rheology especially if a weak layer in the lower crust decouples the crust and the mantle. It is related to flexural rigidity of the lithosphere, and the characteristic flexural wavelength and is calculated using the coherence between gravity and topography and is related to the thermal regime (Hyndman et al., 2005).

Embedded Fault: An embedded fault is a characteristic of the source zone model that provides a mechanism to localize future earthquake occurrences on a known geological fault feature within a source zone. An embedded fault or suite of embedded faults is (are) defined based on mapped fault(s) within a seismic source zone that has (have) some potential for future earthquake occurrence in the present tectonic environment that is greater than that which a uniform or smoothed rate across the zone would depict.

Epicentre: The point on the Earth's surface directly above the focus (i.e. hypocentre) of the earthquake source (American Nuclear Society, 2008a).

Epistemic Uncertainty: Uncertainty attributable to incomplete knowledge about a phenomenon that affects the ability to model it. Epistemic uncertainty is captured by considering a range of model parameters for a given expert interpretation or multiple expert interpretations each of which is assigned an associated weight representing statistical confidence in the alternatives. In principle, epistemic uncertainty can be reduced by the accumulation of additional information associated with the phenomenon. The uncertainty in the parameters of the probability distribution of a random phenomenon is epistemic (American Nuclear Society, 2008a).

Epsilon: The number of logarithmic standard deviations by which the logarithmic ground motion deviates from the predicted median (McGuire, 1995).

Ergodic Assumption: A random process in which the distribution of a random variable (e.g., spectral acceleration) in space is the same as its distribution at a single location when sampled in multiple experiments (earthquakes) over time. The ergodic assumption in a site-specific PSHA (i.e. for a single location) refers to the use of a ground-motion standard deviation derived from data recorded at multiple locations (such as the case of most GMPEs), rather than from data recorded at the site of interests.

Event Term: An earthquake-specific effect to represent the influence of the random earthquake-specific source characteristics on ground motions. In the mixed-effects model setting, the event term is the random earthquake effect η_i. (see "Mixed-Effects Model"). Without resorting to a rigour and complicated statistical inference procedure, the event term of an earthquake can be estimated by the average (total) residual of data from that earthquake, if the count of data is sufficiently large.

Fault: A planar or gently curved dislocation surface or zone in the Earth’s crust along which there has been relative displacement.

Fault Source: A fault, or zone of faults, which have been identified to be seismogenic and capable of generating earthquakes.

Finite Fault Simulation: Simulation of ground acceleration from a large earthquake using a finite-fault model as the earthquake source. There are important characteristics in a finite fault model that influence the simulated ground motion of large earthquakes that are not included in a point-source model, such as the fault geometry, rupture direction and rupture velocity, and distribution of asperities (areas of larger-than-average amount of slip).

Fixed Effects: Fixed effects are parameters (or coefficients) of a regression model associated with the entire population or with certain repeatable levels of experimental factors (Pinheiro and Bates, 2000). See also "Random Effects".

F-Layer: An intermittently imaged weakly reflecting layer beneath the "E-Layer" (Nicholson et al., 2005). It is interpreted by most geoscientists to be the top surface of the subducted Juan de Fuca slab beneath Vancouver Island. See also "E-Layer".

Floating Earthquake: See "Background Seismicity".

Focal Mechanism Solution (Fault Plane Solution): The identification of the faulting style, or mechanism responsible for an earthquake and the orientation of the nodal planes. A stereographic plot is used to analyse the seismic wave forms generated by an earthquake to define two nodal planes, one of which is the fault plane, in terms of strike, dip, rake, and style of faulting (Cronin, 2004).
Footwall: Pertaining to a fault (see "Hanging Wall").

Forearc: An elongate basin between the trench and volcanic arc of a subduction zone (Keary, 1996). The basin is elongated parallel to the plate margin. See also "Backarc".

Free Slip Zone: See "Cascadia Subduction Zone Dislocation Model", "Deep Free Slip Zone" and "Shallow Free Slip Zone".

Ga: The SI unit representing one giga-annum = 10^9 (billion) years, where one year is equal to 365.25 days, used to quantify geological time scales, specifically age in terms of billions of years old, or billions of years ago. See also "ka" and "Ma".

Gaussian Smoothing: Also sometimes referred to as "Spatial Smoothing". A numerical approach to spatially smooth historical seismicity in PSHA by using a Gaussian function with a correlation distance or standard deviation. A region of seismicity is gridded and a moving cell systematically samples the data points, in this case earthquake events within the specified are of the cell. The number of earthquakes above a specified magnitude in each cell on the grid are converted from cumulative values to incremental values and the grid is smoothed spatially.

Geographic Information System (GIS): A computer system capable of capturing, storing, analyzing, and displaying geographically referenced information (USGS, 2007).

Geodetic Rate: The calculation of crustal deformation rates using information gathered from geodetic methods such as GPS measurements, but also including very long base lines, and other survey methods. (Compare with "Seismicity Rate", "Geological Rate" and "Plate Rate".)

Geological Rate: The estimation of crustal deformation rates using information gathered from geological evidence such as paleoseismic displacements for dated rupture events on active faults. (Compare with "Geodetic Rate", "Seismicity Rate" and "Plate Rate".)

Geomatrix 3rd Letter: A discrete scheme for characterizing the soil condition of an instrument based on its geotechnical subsurface characteristics (Chiou et al., 2008):

A = Rock. Instrument on rock (V_S > 600 m/s) or < 5 m of soil over rock.
B = Shallow (stiff) soil. Instrument on/in soil profile up to 20 m thick overlying rock.
C = Deep narrow soil. Instrument on/in soil profile at least 20 m thick overlying rock, in a narrow canyon or valley no more than several km wide.
D = Deep broad soil. Instrument on/in soil profile at least 20 m thick overlying rock, in a broad valley.

E = Soft deep soil. Instrument on/in deep soil profile with average V_S <150 m/s.

Geometric Attenuation (Geometric Spreading): The attenuation of wave amplitude caused by distribution of the seismic energy to greater volumes.

Geometric Mean (Geometric Average): The geometric mean of a set of numbers is the *n*th root of the product of these numbers, where *n* is the count of numbers in the set. If the numbers are x_1, x_2,..., x_n, their geometric mean is $\sqrt[n]{x_1 x_2 \ldots x_n}$.

Global Positioning System (GPS): A constellation of artificial satellites which allows accurate three-dimensional positioning by radio interferometry using radio receiver stations positioned on the Earth's surface (Keary, 1996).

GMRotI50: A measure of horizontal ground motion computed as the geometric-mean response spectra of the two horizontal components of ground motions rotated to a prescribed orientation. This prescribed orientation for GMRotI50 is the rotation angle whose geometric-mean spectra best fit the median of those geometric-mean spectra from the ground motions rotated in small increments (typically at 1°) over the nonredundant rotational range of 0° to 90° (Boore et al., 2006). GMRotI50 was adopted for use in the PEER-NGA ground motion prediction equations published in 2008.

Gutenberg-Richter Recurrence Model: See "Recurrence Models".

Gy: The unit that represents one giga-years = 10^9 (billion) years where one year = 365.25 days, used to represent the duration of a remote interval of geologic time, or period. See also "ka" and "Ma".

Hanging Wall: The two opposing sides of a non-vertical fault are known as the hanging wall and footwall. The hanging wall occurs above the inclined fault plane and the footwall occurs below the fault.

Holocene (Recent): The geologic epoch referring to a period of time between the present day and approximately 10,000-11,000 years ago.

Hypocentre: The point in the earth's crust where a rupture initiates, creating an earthquake (American Nuclear Society, 2008a).

Hypocentral Depth: The depth of the hypocentre below the surface of the earth.

Hypocentral Distance: Distance from a recording site to the hypocentre.

Interface: The contact or boundary between the subducted plate (oceanic crust) and the overlying plate (continental crust) and mantle wedge.

Inter-plate: Pertains to the seismo-tectonic processes, such as earthquakes, at the interface between the plates (American Nuclear Society, 2008a). (See also "Interface".)

Intraplate: Pertains to the seismotectonic processes that occur within the interior of the Earth's crustal plates.

Interseismic Transition Zone: See "Cascadia Subduction Zone Dislocation Model".

Inversion: The procedure of converting observed measurements into information about a physical object or system that one is interested in but is not directly observable. Inversion is used in many branches of science and mathematics, including medical imaging, geophysics, remote sensing, and non-destructive testing.

Inter-Event Error: Same as "Inter-Event Residual".

Intra-Event Error: Same as "Intra-Event Residual".

Inter-Event Residual: See "Mixed-Effects Model (and its Residuals)".

Intra-Event Residual: See "Mixed-Effects Model (and its Residuals)".

Joyner-Boore Distance: The shortest distance from the recording station to the surface projection of the ruptured surface.

ka: The SI unit representing 1 kilo-annum = 10^3 (thousand) years, where one year is equal to 365.25 days, used to quantify geological time scales, specifically age in terms of thousands of years old, or thousands of years ago. See also "Ga", "Ma", and "Radiocarbon C14 Dating".

Kappa: A shallow crustal damping parameter often used for firm to hard rock sites. At rock sites, this shallow crustal damping is generally considered to occur over the top 1 to 2 km of the crust possibly due to a frictional mechanism in these somewhat softer materials before the increase in confining pressure with depth completely closes the fractures. Kappa could be a controlling factor of rock spectra shape at high frequency (> 5 hz). See also Volume 3, Appendix 4.

ky: Represents the duration of a remote interval of geologic time as a number of years. One ky represents 10^3, or a thousand years, where one year = 365.25 days. See also "Gy" and "My".

Light Detection and Radar (LiDAR): The technology that determines distance to an object or surface using laser pulses. Like the similar radar technology, which uses radio waves instead of light, the range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal. Data are usually collected with aircraft-mounted lasers capable of recording elevation measurements at a rate of 2,000 to 5,000 pulses per seconds and have a vertical precision of about 15 cm (6 in). After a baseline data set has been created, follow-up flights can be used to detect elevational changes.

Likelihood Function: The probability of a set of observations as a function of the model parameter values. This function is the basis of the maximum likelihood estimation. See also "Maximum Likelihood Method".

Locked Zone: See also "Cascadia Subduction Zone Dislocation Model".

Ma: The SI unit representing 1 mega-annum = 10^6 (million) years, where one year is equal to 365.25 days, used to quantify geological time scales, specifically age in terms of millions of years old, or millions of years ago. See also "ka" and "Ga".

Magnitude: A number that characterizes the size of an earthquake. It is related to the energy released in the form of seismic waves. Early estimates of magnitude were based on the measurement of the maximum motion recorded by a seismograph. Several scales have been defined, but the most commonly used are;
Local magnitude (M_L), commonly referred to as "Richter magnitude"
Surface-wave magnitude (M_S)
Body-wave magnitude (m_b)
Moment magnitude (M_w or **M**)
Body-wave magnitude using the Lg wave (m_{bLg}), where the Lg wave is a surface wave that travels through the continental crust (USGS, 2008a).

Scales M_L, M_s and m_b have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes but is more difficult to compute than the other types. All magnitude scales yield approximately the same value for earthquakes of up to about magnitude 5, but for larger events, m_b, then M_L, and finally M_S progressively diverge and increasingly underestimate the size of the earthquake compared to M_w. It is important, therefore, to specify the magnitude scale being referenced, especially for larger earthquakes (American Nuclear Society, 2008a).

Mainshock: See "Aftershocks".

Maximum Likelihood Method: An estimation method involving maximization of the likelihood or the logarithm of likelihood with respect to the unknown model parameters.

Maximum Magnitude: The magnitude of the largest earthquake estimated for a fault source or areal source zone.

Maximum Magnitude Recurrence Model: See "Recurrence Models".

Maximum Moment Recurrence Model: See "Recurrence Models".

Metadata: Data about data. For a strong-motion database, metadata are the supporting information about the earthquake sources (such as their magnitude, type of faulting, etc), recording instruments (such as their location, soil condition, and housing), and other attributes of the ground-motion data (such as the source-to-site distance, filter corner, instrument orientation, etc.)

Mixed-Effects Model (and its Residuals): A statistical model with both fixed effects and random effects is called a mixed-effects model. Mixed-effects model has been a popular choice for the regression analysis of ground-motion data. In GMPE development, one often uses the simple mixed-effect model proposed by Abrahamson and Youngs (1992), in which only the intercept is modeled as a random effect of earthquake, while the other coefficients are treated as fixed effects. Their regression model has the form;

$$\ln y_{ij} = f(M_{wi}, R_{RUP_{ij}}, \theta) + \eta_i + \varepsilon_{ij}$$

, where θ is the vector of fixed effects, η_i is the sole random (earthquake) effect associated with the *ith* earthquake, ε_{ij} is the intra-earthquake (or intra-event) residual. When one views η_i as a part of the modeling error, it is also called the inter-event residual (error). The term η_i represents the event-to-event variability and its standard deviation is called the inter-event standard deviation.

Mohorovičić Discontinuity (Moho): The seismic discontinuity between the crust and the mantle (Keary, 1996).

Moment Magnitude Recurrence Model: See "Recurrence Models".

My: Represents the duration of a remote interval of geologic time as a number of years. One My represents 10^6, or a million years, where one year = 365.25 days. See also "ky" and "My".

Nanostrain: An engineering unit measuring strain. An object under strain is typically deformed (extended or compressed), and the strain is measured by the amount of this deformation relative to the same object in an undeformed state. One nanostrain is the strain producing a deformation of one part per billion (i.e., 10^{-9}). Strains in geological formations are often measured in this unit (Rowlett, 2000).

NEHRP Classes: A site classification scheme based on the average shear-wave velocity to a depth of 30 m:
A > 1500 m/s
B = 760 m/s to 1500 m/s
C = 360 m/s to 760 m/s
D = 180 m/s to 360 m/s
E < 180 m/s
(BSSC, 1994)

Null Hypothesis: The 'no difference' or 'no association' hypothesis to be tested (usually by means of a significance test) against an alternative hypothesis that postulates non-zero difference or association (Everitt, 1998).

Paleoseismic: Refers to the science of evaluating past earthquakes through the geological analyses of the surficial strata and landforms that have been created, deformed and/or offset by earthquakes.

Partial Rupture: A rupture which does not occur over the entire fault length.

Peak Ground Acceleration: The largest ground acceleration, usually the maximum absolute value of acceleration displayed on an accelerogram, produced by an earthquake at a site (American Nuclear Society, 2008b).

Peak Ground Velocity: The largest ground velocity produced by an earthquake at a site (American Nuclear Society, 2008b).

Peninsular Range (Soil) Model: A model of nonlinear dynamic soil properties that includes a set of modulus reduction curves and hysteretic damping curves for the generic deep soil sites of the Peninsular Range in California (Silva et al, 1997).

Plate Rate: The estimation of crustal deformation rate based on relative plate motions on specific and/or between adjacent tectonic plates, usually obtained from paleo-magnetic studies (Compare with "Geodetic Rate", "Geological Rate" and "Seismicity Rate".)

Plate Rate Model(s): A model(s) that is based usually on magnetic anomaly patterns and geodetic surveys that simulates the relative surface motion of the tectonic plates that comprise the Earth’s crust. The UNAVCO Plate Motion Calculator is an Internet accessible on-line tool for the calculation of tectonic plate motions at any location on the Earth using one or more of 11 available models. The calculator and plate rate models are accessible on-line at http://sps.unavco.org/crustal_motion/dxdt/model/. Three of the models used in this PHSA study include;

Nuvel-1A:

A revision to the original Nuvel-1 model, recalibrated to remedy the errors in angular velocities present in the previous model**.** The angular velocities are generally the same as Nuvel-1, except that the rate of rotations are, on average, about 4.4% slower due to an adjustment to the magnetic anomaly time scale (DeMets et al., 1994).

HS2 Nuvel-1A:

This model represents the plate motions relative to fixed "hotspot" frames. HS2-Nuvel-1A was determined from the hotspot data and errors used to determine AM1-2 (Gripp and Gordon, 1990).

REVEL 2000:

REVEL 2000 is a global plate motion model with plate velocities based on space geodesy. The model is derived from publicly available space geodetic (primarily GPS) data for the period 199 to the present. Three plate pairs including the North American-Pacific exhibit significant differences between the geodetic and geologic model that may reflect systematic errors in Nuvel-1A due to the use of seafloor magnetic rate data that do not reflect the full plate rate because of tectonic complexities (Sella et al., 2002).

pP**:** Selected seismic phases corresponding to P-wave propagated upward from the hypocentre, turned into downward propagating P-waves by the reflection at the free surface, and observed at teleseismic distances (Aki and Richards, 1980).

Probabilistic Seismic Hazard Analysis (PSHA): A procedure first developed by Cornell (1968) to calculate the annual exceedance frequency (or return period) of a specified level of ground motions at a site. A typical PSHA outputs seismic hazard curves, deaggregated hazard and uniform hazard spectra for use in site specific seismic design. Aleatory variability and epistemic uncertainty are captured in a PSHA. Criteria and guidance for conducting a PSHA are provided in ANSI0ANS-2.29- 2008 (American Nuclear Society, 2008a).

Processed Time Series: See "Record Processing Procedure"

***p*-value:** The probability of the observed data when the null hypothesis is true (Everitt, 1998).

Quaternary: The geologic period comprising the past 1.6 to 7.1 ky (American Nuclear Society, 2008a).

Radiocarbon C14 Dating: Method of determining the age of once-living material, developed by US physicist Willard Libby in 1947. It depends on the decay of the radioactive isotope carbon-14 (radiocarbon) to nitrogen. The method is a useful technique for dating fossils and archaeological specimens from 500 to 50,000 years old and is widely used by geologists, anthropologists, and archaeologists. Use of the term "ka" after the age value follows the convention established in the field of C-14 dating where the ‘‘present’’ refers to 1950 AD (USGS, 2005).

Rake: The angle from the strike direction to the slip direction, measured counter clockwise within the fault plane.

Random Effects: Random effects are parameters (or coefficients) of a regression model associated with individual experimental units drawn at random from a population (Pinheiro and Bates, 2000). Random effects vary from unit to unit, whereas fixed effects are constant across all units. For strong-motion data, one usually chooses earthquake as the experimental unit. In the studies of single-station sigma, recording station is also considered an experimental unit.

Record Processing Procedure: Procedure routinely performed to turn raw recordings of ground acceleration into processed time series that are suitable for use in engineering application. The procedure typically includes correction of instrument response, baseline correction to remove baseline drift, and (low-pass or high-pass) filtering to remove noise.

Recurrence: The period of the loading cycle. Recurrence is the expression of the frequency of occurrence of earthquakes of a given magnitude, or the time between rupture events on a given fault or fault segment (Trepman, 2002).

Recurrence Interval: The time interval, or return period, between earthquakes of a given magnitude for a seismic source, such as a given fault or fault segment (American Nuclear Society, 2008a).

Recurrence Model: A model to express the relative number of earthquakes of different magnitudes as function of time. Three common models are in use:

Characteristic Magnitude Recurrence Model:
Part of the moment rate is apportioned to the characteristic events, typically associated with fault sources, that are distributed uniformly around the characteristic magnitude, and the remainder of the moment rate is distributed exponentially with a maximum magnitude generally one unit lower than the characteristic magnitude (Youngs and Coppersmith, 1985).

Maximum Magnitude or Maximum Moment Recurrence Model:
The maximum magnitude, or maximum moment, model can be regarded as an extreme version of the characteristic model. In the maximum magnitude model, there is no exponential portion of the recurrence curve, i.e., no events can occur between the minimum magnitude of **M** 5.0 and the distribution about the maximum magnitude. This model is typically used for individual faults and fault segments that tend to repeatedly generate earthquakes of comparable magnitudes.

Truncated Exponential (Gutenberg-Richter) Recurrence Model:
A recurrence model typically used for "areal source zones" whereby the magnitude-frequency of relationship can be described by an exponential distribution. Observations of historical seismicity over a region can be modeled by an exponential recurrence model. Also known as the Gutenberg-Richter

recurrence model, the model is truncated to reflect a decreased recurrence of very large earthquakes and a maximum earthquake magnitude for the distribution.

Residual: The difference between the observed value of a response variable and the value predicted by some model of interest. For a GMPE, the residual is computed in the logarithm domain.

Response Spectra: The maximum values of acceleration, velocity, or displacement experienced by single-degree-of-freedom systems spanning a selected range of natural periods when subjected to a given time history of earthquake ground motion. For a given damping ratio, the spectrum of maximum response values is presented as a function of the undamped natural period of single-degree-of-freedom systems. The response spectrum of acceleration and velocity may be calculated from the spectrum of displacement as a function of the natural period by assuming that the motions are harmonic and undamped. When calculated in this manner, these are sometimes referred to as pseudo acceleration and pseudo velocity response spectrum values.

Rigid Block Deformation Model: A deformation model that assumes that all measurable strain, within a resolution of about 1 mm/yr, occurs at the boundaries and not in the interior of a block. Such a model was developed by McCaffrey et al. (2007) to characterise modern-day deformation (from GPS station data) for the Vancouver Island, southwest BC and northwest Washington region. Their model included a number of rigid blocks, or zones, where non-recoverable permanent deformation is assumed to occur as relative motions of the blocks along the block boundaries. Compare with "Distributed Shear Deformation Model".

Rupture Distance: The shortest distance from the recording station to the ruptured surface.

Rupture Model: A fault rupture model uses a weighted combination of the rupture scenarios for each fault, each combination representing one possibility for the long-term behaviour of the fault (WGCEP, 2003).

Rupture Scenario: A combination of one or more adjacent rupture sources that describes a possible mode of failure of the entire fault during one earthquake cycle (WGCEP, 2003).

Rupture Source: An individual fault or fault segment that can rupture independently and be the source of an earthquake

R_x: The strike-perpendicular coordinates in a fault coordinate system. The fault coordinate system uses the fault strike direction as the Y-axis and the strike-perpendicular direction (the fault dip direction) as the X-axis. The origin of the coordinate system is arbitrary, usually located at the first endpoint of the fault trace or at the midpoint of the fault trace.

Saturation: For a GMPE**,** saturation refers to the diminishing increase of high-frequency spectral acceleration (including PGA) as earthquake magnitude increases. The degree of saturation varies with distance and spectral period. In some GMPEs, full saturation occurs at zero distance to large-magnitude faults, where the high-frequency spectral acceleration will not increase even though the magnitude increases.

Segmentation: The division of an active (seismogenic) fault into discrete sections, separated by recognizable geometrical boundaries that tend to rupture independently of each other. Longer faults especially tend to be segmented, e.g., San Andreas fault, Cascadia megathrust, Queen Charlotte fault.

Seismicity: The distribution of earthquakes in space, time, and size (magnitude).

Seismicity Rate: The estimation of the rate of crustal deformation based on the seismic moment, or energy, released from a collection of earthquakes over time. (Compare with "Geodetic Rate", "Geological Rate" and "Plate Rate".)

Seismic Moment: The measure of the size of an earthquake based on the area of fault rupture, the average amount of slip and the force required to overcome the friction along the ruptured fault plane. The scalar seismic moment M_0 is defined by the equation;

$M_0 = \mu AD$,

where;

μ is the shear modulus of the rocks involved in the earthquake (in dyne / cm^2),

A is the area of the rupture along the geologic fault where the earthquake occurred (in cm^2), and

D is the average displacement on A (in cm).

M_0 thus has dimensions of energy, measured in dyne centimetres.

Seismic Source: Faults or volumes within the Earth where future earthquakes are expected to occur. In a PSHA, all seismic sources with a potential to contribute significantly to the hazard are considered (American Nuclear Society, 2008a).

Seismic Source Characteristics: The parameters that characterize a seismic source for PSHA, including source geometry, probability of activity, maximum magnitude and earthquake recurrence (American Nuclear Society, 2008a).

Seismic Source Zone: Seismic sources are regions or features of the earth's crust that are assumed to have relatively uniform seismic source characteristics, but are distinct from adjacent regions or features. See also "Areal Source Zone", "Fault Source Zone" and "Volumetric Source Zone".

Seismic Source Zone Boundary: A source zone boundary separates adjacent seismic source zones with differences in recurrence rate, orientation and style of faulting, seismogenic depth, maximum magnitude, and/or the spatial distribution of seismicity.

Seismogenic: Pertaining to having the capability of producing earthquakes.

Seismogenic Crust: The brittle portion of the Earth’s crust capable of generating earthquakes through the temperature-controlled mechanism of stick-slip behaviour. T_S is the thickness of the seismogenic crust, it is typically measured from the base of the upper aseismic portion of the crust (2-5 km thick) down to the maximum depth of earthquakes (Nazareth and Hauksson, 2004).

Seismogenic Depth: The maximum depth of seismicity within the Earth’s crust or lithosphere.

Seismogenic Thickness (T_s): See "Seismogenic Crust".

Seismotectonic: The rock-deforming processes, resulting in tectonic structures and seismicity that occur over large sections of the Earth’s crust and upper mantle (American Nuclear Society, 2008a).

Senior Seismic Hazard Analysis Committee (SSHAC): A committee sponsored by the NRC, DOE, and EPRI to review the state-of-the-art and improve the overall stability of the PSHA process. SSHAC concluded that most of the differences in individual PSHA results were consequences of differences in the process of elicitation of the information from experts. SSHAC made recommendations on the process, which are now almost uniformly adopted by analysts worldwide (American Nuclear Society, 2008b).

ShakeMap: ShakeMap is a product of the US Geological Survey Earthquake Hazards Program in conjunction with regional seismic network operators. ShakeMap sites provide near-real-time maps of ground motion and shaking intensity following significant earthquakes. These maps are used by federal, state, and local organizations, both public and private, for post-earthquake response and recovery, public and scientific information, as well as for preparedness exercises and disaster planning.

Shallow Free Slip Zone: See "Cascadia Subduction Zone Dislocation Model".

Shear (S) Wave Splitting: The phenomenon whereby pervasive fluid filled cracks of common alignment within a rock cause S-waves to be split into two orthogonal components; a fast wave polarised parallel to the cracks and parallel to the direction of the regional compressive stress (the fast direction), and a slow wave polarised at right angles to the orientation of the cracks (Keary, 1996).

Sigma: The Greek letter typically used to denote a standard deviation.

Single-Degree-of-Freedom System: A structure that responds to seismic excitation in only one vibration mode.

Single-Station Sigma: Standard deviation of ground motions at a single site. It is estimated by removing the variability in site-specific site responses from the reported standard deviation of a GMPE assuming ergodic condition (Lin et al., 2011). See also "Ergodic Assumption" and Volume 3, Appendix 6.

Sinistral (Left-Lateral): The sense of movement across a geological boundary, such as a fault, in which the side opposite the observer moves to the left (Keary, 1996).

Site Response (Amplification): The amplification (i.e., increase or decrease) of earthquake ground motion by rock and soil near the earth's surface in the vicinity of the site of interest. Topographic effects, the effect of the water table, and basin edge wave propagation effects are sometimes included under site response (American Nuclear Society, 2008a).

Site Term: Site term is the difference of a site's own site-specific response (amplification) from the average response of sites in the same site class or having the same V_{S30} value. The site term for a specific site is often estimated by the average intra-event residuals observed at that site, relative to some GMPE.

SKS Waveform: Selected seismic shear-wave phases corresponding to: S (shear wave refracted through the mantle), K (converted to P-energy compressional wave through the outer core), and S (shear wave refracted through the mantle). Generally, the anisotropy that causes the SKS splitting occurs in the olivine-rich upper mantle beneath the recording seismic station. The fast direction is parallel to the a-axis of olivine crystals aligned to the direction of dislocation creep extension in the mantle.

Slab: The oceanic plate that underthrusts the overriding continental plate in a subduction zone and is consumed by the earth's mantle (USGS, 2008a; 2008c).

Spatial Smoothing: See "Gaussian Smoothing".

Spectral Period: The natural period of a single-degree-of-freedom system. It is the abscissa of a response spectrum.

Spectral Shape: Response spectrum normalized to its PGA.

Standard Error: The standard deviation of the sampling distribution of a statistics. The sampling distribution is the probability distribution of a statistics calculated from a random sample of a particular size. For example, the sampling distribution of the arithmetic mean (sample mean) of samples of size *n* taken from a normal distribution with mean μ and standard deviation σ, is a normal distribution also with mean μ but with standard deviation $\sigma / \sqrt{n}$ (Everitt, 1998). The standard error of the sample mean is therefore $\sigma / \sqrt{n}$ and an estimate of this standard error is $s / \sqrt{n}$, where *s* is the sample standard deviation.

Stress Drop: The sudden reduction of stress across the fault plane during rupture. It is the initial shear stress acting across a fault plane minus shear stress across the same fault plane after the occurrence of rupture. Stress drop is commonly measured in units of bar. See also "Bar".

Strike: The direction in which fault runs. Strike is measured clockwise round from the north, with the fault dipping down to the right of the strike direction.

Tectonic/Structural Fabric: The complete macroscopic to megascopic spatial and geometrical configuration of all the components that make up a body of rock. This includes the texture, structure and preferred orientation of elements within the rock such as faults and folds.

Time-Dependent Model: A time-dependent analysis used in earthquake forecasts and PSHAs incorporate the timing of past earthquakes on seismic sources. Thus earthquake probabilities and hazard exceedance probabilities change with time.

Time-Independent Model: A time-independent analysis used in earthquake forecasts and PSHAs is the traditional approach which assumes the earthquake occurrence is a Poissonian process and there is no dependence on the timing of past earthquakes on seismic sources. Thus earthquake probabilities and hazard exceedance probabilities do not change with time.

Total Residual: The sum of inter-event residual and intra-event residual. See also "Mixed-Effects Model (and its Residuals)".

Transcurrent: Extending or running transversely, especially perpendicular to an expected direction or flow.

Transpression: The stress regime associated with movement along a curved strike-slip fault, with components of convergence and strike-slip motion (Keary, 1996).

Transtension: The stress regime associated with movement along a curved strike-slip fault, with components of extension and strike-slip motion (Keary, 1996).

***t*-test (Student's t-test):** Significant test for assessing hypothesis about population means (Everitt, 1998)

Truncated-Exponential Recurrence Model: See "Recurrence Models".

Uncertainty: See "Epistemic Uncertainty" and "Aleatory Uncertainty" (American Nuclear Society, 2008a).

Uncertain Boundaries: When the data used to define a source zone boundary lacks spatial resolution or definition, a range of boundaries is delineated to represent alternative interpretations of the boundary between adjacent source zones. This may result from limited resolution of available data at regional map scales, or limitations in the data.

Uniform Hazard Response Spectrum: A response spectrum derived such that the annual probability of exceeding the spectral quantity (i.e., spectra acceleration, spectral displacement, etc.) is the same for all oscillator frequencies (American Nuclear Society, 2008a).

Usable Spectral Period Range: Range of spectral period in which spectral value is not significantly affected by the filtering applied during record processing. Determination of the usable period range is based on the corner frequency of the filter, the rate of decay of the filter response, and the number of passes of filter. The longest usable spectral period adopted in NGA project corresponds to the Fourier frequency at which the filter response is about -1/2 db down from the nominal passband value. With this criteria, for a causal 5-pole Butterworth filter typically used in PEER's processing procedure, the longest useable period is 1/(1.25 * corner frequency) (Chiou et al., 2008). See also "Corner Frequency of a Filter" and "Record Processing Procedure".

Variability: See "Epistemic Uncertainty" and "Aleatory Uncertainty" (American Nuclear Society, 2008a).

Virtual Fault: A virtual fault represents a seismic source zone used for performing the numerical integration over the seismic source volume (spatial integration possible future earthquake locations) and to take into account the style of faulting and geometry of future earthquake ruptures.

Volcanic Arc: Occurs when the oceanic lithosphere subducts beneath an overriding plate of continental lithosphere. A belt of volcanoes is generated on continental crust.

Volcanic Front: A clear border between volcanic and non-volcanic zones. It often occurs in the trench side of a volcanic arc. The depth of a subducting plate underneath a volcanic front is usually 100 to 150 km.

Volumetric Source Zone: See "Areal Source Zone".

V_{S30} (or v_{s30})**:** The time-averaged shear-wave velocity to 30 m depth. $V_{S30} = 30/t$, where t is the shear-wave travel time (in units of second) from the surface to 30 m depth (Boore, 2004). V_{S30} has been used as an explanatory variable (predictor) for site response in a number of recent GMPE and as the basis for specifying site classes in building code.

Wadati-Benioff Zone (Benioff Zone): The zone of seismicity observed in the down-going oceanic crustal plate in subduction zones that originate from internal deformation of the slab. These events are also referred to as intraslab earthquakes. The depth extent of Wadati-Benioff zones is controlled by temperature and rock and water composition. The zone consists of two sub-zones of seismicity; a less pronounced upper zone delineating the top of the down-going slab, and a more pronounced lower zone at about 10 to 20 km within the upper mantle (Keary, 1996; USGS, 2008c).

Within-Earthquake Residual: See "Intra-Event Residual".

Zone with Embedded Fault: A seismic source modeling construct that allows for partitioning predicted earthquake occurrences between the background in the source zone and one or more embedded faults. A portion of the seismic moment (i.e. larger magnitude events) are localised on the embedded fault(s) compared to smaller magnitude events in the zone. See also "Embedded Fault".

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APPENDIX B:
FINAL PPRP LETTER

Dr. Kofi O. Addo
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Dear Dr. Addo:

Reference: *BC Hydro Probabilistic Seismic Hazard Assessment Project:* Participatory Peer Review Panel Final Report

This letter constitutes the final report of the Participatory Peer Review Panel (PPRP) for the *BC Hydro Probabilistic Seismic Hazard Assessment Project*. The three Panel members (J. Carl Stepp, Kenneth W. Campbell, and Kevin J. Coppersmith) participated in the Project in a manner fully consistent with the SSHAC Guidance. The Panel was actively engaged in all phases and activities of the Project implementation, including the evaluation and integration activities that are the core of the SSHAC Level 3 assessment process. The Panel's participation described more fully later in this letter, also included review of analyses performed by the Project to support the evaluation and integration processes, review of interim evaluation and integration products, and review of the draft project report and the final project report.

In the remainder of this letter, we provide our observations and conclusions on key elements of the project implementation process, and we summarize our reviews of the draft and final project reports. We do this by responding to questions 1 through 5 of your letter of June 27, 2011 entitled *Re: PSHA07DS—Expectations of Final Peer Review.*

Q1: Has the PPRP been adequately involved in the Project and provided with sufficient information to allow the Panel to understand and comment on the technical and procedural approaches applied in the project?

Consistent with SSHAC Guidance, the Panel was fully engaged in peer-review interactions with the BC Hydro PSHA Project TI Teams and the Project Management throughout the entire project performance—from development of the Project Plan in early 2008 through production of the Final Project Report in early 2012. A requirement of the Panel is to provide both written and oral peer-review comments and recommendations on both technical and process aspects at many stages of the project implementation. The Panel is additionally required to provide written comments on draft interim project reports and on the draft final Project report. PPRP activities, leading up to this final letter report, have included:

- Review of the Project Plan.
- Participation in each of the eleven project workshops, including advising in the planning stage; participating collectively as a review panel during the workshop, providing comments daily on technical and process issues; and submitting a written consensus report of the Panel's observations and recommendations following the workshop.
- Interacting with the TI Teams and Project Management to document the resolution of recommendations made in PPRP formal communications.

- Providing review comments and recommendations on nine technical analysis reports prepared by the TI Team to support the evaluation and integration process.
- Providing review comments and recommendations on the TI Teams' intermediate work products, particularly early versions of the SSC and GMC Models and the hazard results at six dam sites
- Direct interaction with the TI Teams and Project Manager in more than 10 teleconferences.
- Extensive, critical peer-review of the preliminary SSC and GMC Models and the draft final project report communicated in PPRP consensus reports.

The PPRP, collectively and individually fully understood the SSHAC Guidance for a structured participatory peer review and the requirements for a Level 3 assessment project; had full and frequent access to information and interacted extensively with the TI Teams and Project Manager throughout the entire project; provided peer-review comments at numerous stages; and, as documented within the Final Project Report, was fully engaged to meet its peer-review obligations in an effective way.

Q2: Were the processes used in the selection and/or development of the seismic source and ground motion models compliant with the recommended SSHAC Level 3 approach?

Fundamentally, this question is answered by comparing the process used in the project with the process outlined generally in the original SSHAC Guidance[1] and more specifically, in the implementation guidance issued by the US Nuclear Regulatory Commission (USNRC)[2]. For example, USNRC (2012, Table 4-1) identifies the essential steps in SSHAC Level 3 and 4 studies that define the minimum required activities for a hazard study to comply with a SSHAC Level 3 or 4 process:

1. Select SSHAC Level
2. Develop Project Plan
3. Select project participants
4. Develop project database
5. Hold workshops (minimum of three, focused on available data, alternative models, and feedback)
6. Develop preliminary model(s) and Hazard Input Document (HID)
7. Perform preliminary hazard calculations and sensitivity analyses
8. Finalize models in light of feedback
9. Perform final hazard calculations and sensitivity analyses
10. Develop draft and final project report

[1] Budnitz, R.J., G, Apostolakis, D.M. Boore, L.S. Cluff, K.J. Coppersmith, C.A. Cornell and P.A. Morris, *Recommendations for probabilistic seismic hazard analysis: guidance on uncertainty and the use of experts*. NUREG/CR-6372, two volumes, US Nuclear Regulatory Commission, Washington, D.C., 1997, http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6372/

[2] NRC, *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazards Studies*. NUREG-2117, US Nuclear Regulatory Commission, Washington, D.C., 2012, http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2117/.

11. Participatory peer review of entire process

Review of the project documentation as well as ongoing participatory peer reviews throughout the project leads to the conclusion that the essential steps of a SSHAC Level 3 process have been followed in the BC Hydro PSHA Project. For example, the roles, responsibilities, and expertise of all project participants were given priority and documented[3]; a major effort was devoted to developing a project database that was accessible to the TI Teams; topical workshops were held to identify available data, discuss alternative models, and present feedback based on preliminary interpretations; preliminary models were developed and seismic hazard calculations conducted to provide additional feedback to the TI Teams; draft and final reports were developed that documented the process followed and the technical assessments made; and a peer review process was conducted that included both participatory aspects and late-stage reviews (e.g., review of the draft final report).

Given that the essential steps have been followed, every SSHAC Level 3 project also includes refinements and innovations that are best suited to the technical assessments being made for that particular project. In the case of the BC Hydro PSHA, innovative approaches were used to conduct the process in a highly complex tectonic environment. For example, the SSC TI Team was divided into sub-teams to focus on the different types of seismic sources that would need to be considered. These sub-teams then presented their evaluations to the entire TI Team in numerous working meetings to ensure that ownership of the final integrated model was fully supported by all members. As another unique approach, the SSC TI Team considered and evaluated the potential implications of geodetic data to their assessments of earthquake recurrence for certain seismic sources. They concluded that the geodetic data provide useful constraints on regional tectonic interpretations, but that they are not sufficient to directly estimate earthquake recurrence rates. The exploration of this concept is consistent with the SSHAC process of evaluation and is well documented in the project report. The GMC TI Team, after reviewing the available subduction tectonic plate interface and intraslab ground motion prediction equations (GMPEs) and discovering the large epistemic uncertainty associated with these equations, concluded that new subduction GMPEs using an updated subduction plate interface ground motion database were needed. The Team also concluded that the subduction plate interface model should be tested against the very large sets of new data obtained from the 2010 Maule, Chile (M 8.8) and the 2011 Tohoku, Japan (M 9.0) earthquakes. The results of these tests modified the magnitude scaling of the final GMC model at large magnitudes. The Team developed a reasonable, robust approach that will contribute to the long-term stability of the plate interface ground motion model.

In light of due consideration of the essential elements of a SSHAC process and the specific manner in which the BC Hydro PSHA was conducted, the Panel concludes that the SSC Model and GMC Model assessments were performed consistent with current state-of-practice guidance for a SSHAC Level 3 process.

[3] "*BC Hydro PSHA Project Seismic Source Characterization Evaluation Guidance*", BC Hydro PSHA Project Internal Guidance Document.

Q3: Do the recommended models adequately capture the body, centre and range of the current practices and published knowledge of the informed technical community?

We begin the response to this question by first considering the terminology that is given in the SSHAC Guidance The key statement in the SSHAC Guidance (Budnitz et al., 1997, Footnote #1) that encapsulates the SSHAC approach is as follows: "*Regardless of the scale of the PSHA study the goal remains the same: to represent the center, the body, and the range that the larger informed technical community would have if they were to conduct the study*". Detailed implementation guidance by the NRC (2012, Footnote #2) explains that the objective of the SSHAC Guidance is achieved through a two-stage process of *evaluation* followed by *integration*, as is defined below:

"Therefore, consistent with the original intent of the SSHAC Guidance, we recast the goals of the SSHAC process in terms of the two main activities (i.e., evaluation and integration) by the following statement:

> The fundamental goal of a SSHAC process is to carry out properly and document completely the activities of evaluation and integration, defined as:
> *Evaluation:* The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis.
> *Integration:* Representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods)."

Considering the definitions given in the SSHAC Guidance, we interpret the question to ask for the PPRP's conclusions regarding whether or not the evaluation and integration processes conducted for the BC Hydro PSHA were successful.

The *evaluation* process begins with a compilation and systematic evaluation of the data that have been developed by the larger technical community. The SSC and GMC TI Teams were successful in identifying the full range of relevant data that exists within the technical community and in placing those datasets within a project database that was accessible by all the project participants. Key examples are the extensive episodes of seismically-triggered submarine turbidity flows recently mapped in the offshore region that are evidence for large plate interface earthquakes on the Cascadia Subduction Zone, and the compilation of ground motion recordings from crustal and subduction zone earthquakes. These data were appropriately evaluated for their quality and relevance in seismic source characterization and ground motion characterization activities, respectively.

The evaluation process also included evaluating the models and methods that have been proposed by the larger technical community. Typically, these models and methods were advocated by proponent experts in a workshop setting in order to facilitate the TI Teams' understanding of uncertainty and implications of alternative technically defensible interpretations that constitute the SSC or GMC and model integration. The BC Hydro PSHA project was successful in conducting and documenting a comprehensive evaluation of alternative models and methods proposed by the technical community. For example, proponent experts regarding alternative tectonic modeling of the geodetic observations to map current earthquake strain rate data participated in the project and provided their alternative viewpoints in written form and in workshops for the evaluation by the SSC Team. Likewise, alternative viewpoints regarding the applicability of the current ground motion models developed using primarily strong ground motion recordings in California, called the NGA-West models, to active crustal seismic sources in British Columbia were evaluated by the GMC team, including the need to incorporate additional epistemic uncertainty to account for modeling uncertainties not fully represented in the suite of NGA-West models. In some cases, the evaluation process led to the conclusion that the existing models and methods were not appropriate for use in the project. A good example is the assessment by the SSC TI Team, after considerable evaluation of the technical community's viewpoints and models, that models of crustal strain rate derived from geodetic data are not sufficiently understood to be used as independent indicators of earthquake recurrence rate. Another example is the evaluation by the GMC Team that the published subduction ground motion models did not adequately account for the level of epistemic uncertainty as indicated by more recent ground motion recordings for these types of sources.

The *integration* process entails the building of models in the form of logic trees to capture current knowledge and uncertainties (i.e., the center, body, and range of technically defensible interpretations). A concerted effort was devoted in the BC Hydro PSHA to properly and completely account for uncertainties, as represented, for example, by the global and source-specific logic trees that portray the BC Hydro models. For example, the SSC global logic tree represents knowledge and uncertainty in aspects of the model that are common to all seismic sources. Appropriately, the global logic tree is related to the overall tectonic framework of the region within which the model-building integration process occurs. Care was given in the model-building process to appropriately distinguish between epistemic uncertainties and aleatory variability. This distinction is especially important in the ground motion modeling component of the hazard model. The GMC logic trees represent the epistemic uncertainty in ground motion models for the various seismic source types (subduction zone, active crustal, stable continental tectonic environments). In addition, the concept of single-station sigma was adopted as a means of removing the systematic site-to-site differences in aleatory variability in ground motion due to site-specific geology.

The tectonic complexity of the BC Hydro study region requires large and complex SSC and GMC models to completely and appropriately capture current knowledge and uncertainties. Efforts were made to simplify the models when it could be shown that detailed characterization would not lead to significant differences in the hazard results. For example, unless the data suggested otherwise, the simple Poisson earthquake recurrence model was used for most seismic sources, rather than introduce the complexities of real-time or renewal recurrence models. It is likely that the use of the BC Hydro PSHA model could be further simplified for any site-specific application. For example, the more distant parts of the SSC model could be removed or simplified because of their negligible contribution to the hazard at a particular site.

Based on our observation of the completeness and high professional standard in which the evaluation and integration activities were conducted, the Panel concludes that the data, models, and methods within the larger technical community have been properly evaluated, and that the center, body, and range of technically defensible interpretations have been appropriately represented in the SSC and GMC components of the PSHA Model.

Q4: Are the seismic source and ground motion models sufficiently well-founded, defensible and documented in the reports? In particular, are model elements that were developed specifically for this project (e.g., the embedded fault concept, alternative characteristic recurrence model, subduction zone geometry and prediction models) sufficiently justified and clearly documented?

Requirements for a successful *integration* or model-building phase of a SSHAC Level 3 process are that it is informed by a complete evaluation of all relevant data, models, and methods during the *evaluation* phase of the project, that all assessments are technically defensible, and that the developed models are thoroughly documented so as to be transparent to users. As discussed in the responses to Q2 and Q3, the evaluation and integration phases of the project were conducted in a manner that is consistent with current state-of-practice guidance for SSHAC Level 3 projects and, based on PPRP participatory interactions throughout the project, the Panel is able to conclude that the resulting SSC and GMC models capture the center, body, and range of technically defensible interpretations.

During the course of the integration process, the SSC and GMC TI Teams found that the available set of methods or model elements were not sufficient to properly and completely represent current knowledge and uncertainty in some components of the models. In those cases, the TI Teams developed a refined set of model elements or concepts that—although they are not radically different from current practice—provide approaches that the Teams concluded were more effective in modeling technical aspects than available tools. For example, the embedded fault concept was introduced as a means of allowing for more geologic information to be accounted for in the development of seismic source geometries and the future spatial distribution of earthquakes within a source zone. Likewise, the alternative characteristic recurrence model was introduced as a means of providing for recurrence behavior of a seismic source zone that is consistent with observed numbers of small-magnitude earthquakes as well as for allowing characteristic recurrence of earthquakes on mapped faults within the zone. Another extension of existing methods was the use of a master logic tree to model the independent and dependent parts of the SSC model. The GMC TI Team developed an entirely new subduction GMC model in order to accommodate new ground motion data and reduce the large epistemic uncertainty represented by the existing GMPEs and, then, modified the large-magnitude scaling of the new model late in the Project after the occurrence of the Maule, Chile and Tohoku, Japan earthquakes. The GMC Team also introduced the single-station sigma approach to eliminate site-to-site epistemic uncertainty from the aleatory standard deviation of the ground motion models.

A strong requirement of the SSHAC Guidance is that all elements of the SSC and GMC models must be completely documented and adequately justified technically. This is particularly true of new model elements that have not enjoyed the benefit of use on multiple projects or that have not been subjected to peer review within the larger technical community. Particularly in those cases, the PPRP must ensure that the model elements are sufficiently justified and adequately defended in the project documentation. This has been the case in the BC Hydro PSHA. For example, the PPRP was present as observers at workshops where these concepts were presented, provided written comments in response to those workshops, asked questions and provided feedback regarding the adequacy of the written descriptions in white papers and technical analysis reports, participated in briefings and conference calls related to the topics, and provided detailed written comments related to the draft project report. Based on this process of participatory review throughout the course of the project, the PPRP concludes that the bases for the SSC and GMC model elements are technically defensible, and that the technical assessments and process for arriving at the model elements are adequately documented.

Q5: Are the developed models expected to have reasonable stability/longevity that provides a defensible basis for making decisions about major capital investments for BC Hydro's long life assets?

The goals of stability and longevity have long been identified by both those responsible for conducting hazard assessments for purposes of seismic design and safety evaluations, as well as those responsible for ensuring public safety. Over the past few decades, this has led to the increased use of probabilistic seismic hazard analysis approaches that explicitly incorporate current knowledge and uncertainty. Furthermore, the formal structured SSHAC Level 3 and 4 approaches have been progressively better defined in evolving implementation guidance (e.g., USNRC, 2012; ANSI/ANS-2.29-2008[4]). These guidance documents were developed to take advantage of the experience gained in the application of PSHA over the past few decades. Explicit goals in the guidance are that their diligent and successful application will lead to great stability, longevity, and regulatory assurance. For example, as stated in USNRC (2012, p. 3):

> "It is recognized that innovative approaches to achieving the SSHAC goals will continue to be developed in the future and that project-specific refinements to the approaches discussed here may be appropriate. However, the application of the guidance given in this document will most likely lead to greater stability and longevity of the hazard assessment being made. Likewise, higher levels of regulatory assurance are likely to be gained with careful and conscientious application of this guidance."

With regard to those things that could lead to a loss of stability or longevity, the USNRC guidance (2012, p. 41) takes this position:

> "A desirable outcome of a Level 3 or 4 study is increased longevity and stability of the hazard assessment. This means that the numerical results of the hazard analysis can be expected to remain stable for a reasonable period of time after the completion of the hazard study. Of course, the appearance of significant new information—such as an earthquake larger than anticipated, the discovery of a previously unknown active fault, or a collection of ground-motion recordings that fundamentally contradict all current models—at any time can lead to the necessity to revisit the hazard analysis. However, such a re-visitation is far less likely to be required in a Level 3 or Level 4 study as a result of the significant efforts to identify all existing information and models."

[4] ANSI/ANS-2.29-2008. *Probabilistic Seismic Hazard Analysis*. American Nuclear Society and American National Standards Institute National Standard.

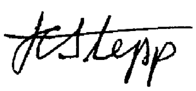
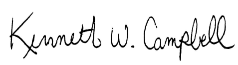
Given that a SSHAC Level 3 process has a high likelihood of achieving stability and longevity, the measure of success for any particular application—such as the BC Hydro PSHA—is the degree to which the SSHAC Level 3 process has been conducted in compliance with applicable guidance. As discussed in our response to Q2, we conclude that all of the essential steps in a SSHAC Level 3 process have been successfully implemented. Therefore, although there are no guarantees that new information will not create the need to revisit the SSC and GMC models given in the BC Hydro PSHA, we judge it to be unlikely that such new information will threaten the stability and longevity of the models or the calculated hazard results based on them.

Concluding Remarks

In addition to a participatory review of the project throughout its conduct, the Panel has made a thorough review of the draft project report to ensure a high-quality project report that fully meets SSHAC requirements for clear, complete, and transparent documentation of all aspects of the project. We are pleased to confirm that implementation of the *BC Hydro Probabilistic Seismic Hazard Assessment* fully conformed with the SSHAC Guidance and that the resulting SSC and GMC models properly meet the SSHAC goal of representing the center, body, and range of technically defensible interpretations.

This concludes our PPRP Final Report for the *BC Hydro Probabilistic Seismic Hazard Assessment* project.

Sincerely,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