Susitna-Watana Hydroelectric Project
(FERC No. 14241)

Site-Specific Seismic Hazard Study Plan Section 16.6

Study Completion Report

Prepared for

Alaska Energy Authority

SUSITNA-WATANA HYDRO

Clean, reliable energy for the next 100 years.

Prepared by

MWH

October 2015

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ATTACHMENTS

List of Acronyms, Abbreviations, and Definitions

Abbreviation	Definition
AEA	Alaska Energy Authority
AEC	Alaska Earthquake Center
BOC	Board of Consultants
CFR	Code of Federal Regulations
COSMOS	Consortium of Strong Motion Observations Systems
DSHA	Deterministic Seismic Hazard Assessment
FERC	Federal Energy Regulatory Commission
ft	feet
GMPE	Ground Motion Prediction Equations
INSAR	Interferometric Synthetic Aperture Radar
ILP	Integrated Licensing Process
IMASW	Interferometric Multichannel Analysis of Surface Waves
ISR	Initial Study Report
km	kilometer
K-NET	Kyoshin Network
LiDAR	Light Detection and Ranging
M	Magnitude
Mmax	Maximum Magnitude
M_L	Local Magnitude
m	meter
mi	miles
MCE	Maximum Credible Earthquake
MDE	Maximum Design Earthquake
NGA	Next Generation Attenuation
OBE	Operating Basis Earthquake
PEER	Pacific Earthquake Engineering Research Center
PGA	Peak Ground Acceleration
PHA	Peak Horizontal Acceleration
PSHA	Probabilistic Seismic Hazard Assessment
RSP	Revised Study Plan
RTS	Reservoir Triggered Seismicity
SCR	Study Plan Completion Report
SPD	Study Plan Determination
SSSHA	Site Specific Seismic Hazard Assessment
USGS	United States Geological Survey
V_s30	Shear Wave Velocity

1. INTRODUCTION

The Site Specific Seismic Hazard Study, Section 16.6 of the Revised Study Plan (RSP) approved by the Federal Energy Regulatory Commission (FERC) for the Susitna-Watana Hydroelectric Project, FERC Project No. 14241, focuses on conducting deterministic and probabilistic seismic hazard evaluations to estimate earthquake ground motion parameters at the Project site, assessing the risk at the site and the loads that the Project facilities would be subject to during and following seismic events, and proposing design criteria for Project facilities and structures considering the risk level.

A summary of the development of this study, together with the Alaska Energy Authority's (AEA) implementation of it through the 2013 study season, appears in Part A, Section 1 of the Initial Study Report (ISR) filed with FERC in June 2014. As required under FERC's regulations for the Integrated Licensing Process (ILP), the ISR describes AEA's "overall progress in implementing the study plan and schedule and the data collected, including an explanation of any variance from the study plan and schedule." (18 CFR 5.15(c)(1)).

Since filing the ISR in June 2014, AEA has continued to implement the FERC-approved plan for the Site-Specific Seismic Hazard Study, Section 16.6. For example:

- Evaluate crustal seismic sources through review of newly acquired LiDAR imagery and based on geomorphic characteristics in the field and geologic relationships around the lineament feature in the Project area with an emphasis in the dam site area,
- Perform Interferometric Multichannel Analysis of Surface Wave measurements to estimate shear wave velocity in the Project area,
- Evaluate the surface fault rupture hazard in the dam site area, focusing in the possibility of displacement along existing planes of weakness in the bedrock,
- Perform field geologic transects to access geologic relationships and styles and patterns of structural deformation
- Review of site-specific surface and subsurface investigations at the dam site
- Establish a geologic datum for evaluating tectonic (fault) activity during the late Quaternary; develop understanding of Quaternary geologic history
- Monitor earthquake activity in the Project area to refine the intraslab model, check the source characterization of background sources, define focal mechanisms for larger detected earthquakes and document the background level of seismicity to monitor reservoir triggered seismicity,
- Update ground motion prediction equations and utilize updated source models for seismic hazard analysis, and

- Development of preliminary seismic design criteria for the finite element analysis for the dam.

In furtherance of the next round of ISR meetings and FERC's Study Plan Determination (SPD) expected in 2016, this report contains a comprehensive discussion of results of the Site Specific Seismic Hazard Study from the beginning of the AEA's study program in 2012, through the June of 2015. It describes the methods of the SSSHS, and explains how all Study Objectives set forth in the Commission-approved Study Plan have been met. Accordingly, with this report, AEA has now completed all field work, data collection, data analysis, and reporting for this study.

Various technical memoranda and reports prepared for the Site Specific Seismic Hazard Study, attached to this report, include:

Attachment	Reference
1	MWH, (2015a), Site-Specific Seismic Hazard Study for the Susitna-Watana Dam, prepared for Alaska Energy Authority, October 2015, 153 p.
2	Fugro Consultants, Inc., (2012), Seismic Hazard Characterization and Ground Motion Analyses for the Susitna-Watana Dam Site Area, prepared for Alaska Energy Authority, Technical Memorandum No. 4, February 24, 2012, 146 p and appendices.
3	Fugro Consultants, Inc., (2013), Lineament Mapping and Analysis for the Susitna-Watana Dam Site, prepared for Alaska Energy Authority, Technical Memorandum No. 8, March 27, 2013, 61p. and appendix.
4	Fugro Consultants, Inc. (2014a), Watana Seismic Network Station Vs30 Measurements for the Susitna-Watana Dam Site, prepared for Alaska Energy Authority, Technical Memorandum No. 14-12-TM, March 20, 2014, 51p. and appendix.
5	Fugro Consultants, Inc., (2015a), Crustal Seismic Source Evaluation for the Susitna-Watana Dam Site, prepared for Alaska Energy Authority, Report No. 14-33-REP, May 2015, 141p and appendices.
6	Fugro Consultants, Inc., (2014b), Revised Intraslab Model and PSHA Sensitivity Results for the Susitna-Watana Dam Site Area., prepared for Alaska Energy Authority, Technical Memorandum No. 14-11-TM, April 2014, 31 p.
7	MWH, (2014a), Briefing Document – Discussion of MCE and OBE, prepared for Alaska Energy Authority, Technical Memorandum No. 14-13-BD, April 30, 2014, 6 p.
8	Fugro Consultants, Inc., (2014c), Seismic Network 2013 Annual Seismicity Report for the Susitna-Watana Dam Site Area prepared for Alaska Energy Authority, Report No. 14-06-REP, March 2015, 40p.
9	Fugro Consultants, Inc., (2015b), Seismic Network 2014 Annual Seismicity Report for the Susitna-Watana Dam Site Area prepared for Alaska Energy Authority, Report No. 14-32-REP, March 2015, 55p.
10	Alaska Earthquake Information Center, (AEC), (2015). Susitna-Watana Seismic Monitoring Project: January –June 2015 Report. Prepared for the Alaska Energy Authority, September 2015.
11	MWH, (2013), Preliminary Reservoir Triggered Seismicity, prepared for Alaska Energy Authority, Technical Memorandum No. 10 v3.0, March 29, 2013, 95 p.

The details of the site-specific seismic hazard study have been summarized and are presented in the report titled *Site-Specific Seismic Hazard Study Summary Report* (MWH 2015a; Attachment 1). In addition, the details of the engineering aspects of the project including seismic design as presented in the *Engineering Feasibility Report* (MWH 2014b).

2. STUDY OBJECTIVES

The goals of this study are to conduct deterministic and probabilistic seismic hazard evaluations to estimate earthquake ground motion parameters at the Project site, assess the risk at the site and the loads that the Project facilities would be subject to during and following seismic events, and propose design criteria for Project facilities and structures considering the risk level. The intent of the study is to fulfill specific objectives including, but not limited to the following:

1. Identify the seismic sources along which future earthquakes are likely to occur, including the potential for reservoir-triggered seismicity;
2. Characterization of the degree of activity, style of faulting, maximum magnitudes, and recurrence information of each seismic source;
3. Develop maps and tables depicting the spatial and geometric relations of the faults and seismic source zones together with specific distance parameters to evaluate ground motion parameters from each source;
4. Assemble available historical and instrumental seismicity data for the region, including maximum and minimum depth of events;
5. Determine the distance and orientation of each fault with respect to the site;
6. Estimate the earthquake ground motions at the proposed dam site, updating previous studies to include changes in practice and methodology since the 1980s;
7. Propose the seismic design criteria for the site;
8. Prepare supporting design report that includes the seismic criteria and results of dam stability analysis under seismic loading (this will be addressed as part of the dam analysis, not as part of the initial seismic characterization); and,
9. Use of Board of Consultants for independent technical review and guidance during development of site-specific studies.

3. STUDY AREA

The study area for the seismic hazard evaluation was necessarily large in order to include potentially significant seismic sources throughout the region. The study area encompassed subduction-related sources (i.e. plate interface between the North American and Pacific Plates, which was the source of the 1964 earthquake, the epicenter of which is a significant distance south of the Project, and intraslab sources within the down-going Pacific Plate) and all applicable Quaternary crustal seismic sources within about 62 miles (100 kilometers) of the site (Figure 3.1-1). Crustal seismic sources beyond these distances are not expected to provide significant ground motion contributions at the dam site relative to nearby sources. A more focused study area included the dam site and reservoir areas. The study area thus included much of the Talkeetna block and surrounding fault zones such as the Denali; Castle Mountain; Northern Foothills fold and thrust fault zone; inferred Talkeetna fault; and Broad Pass Fault.

4. METHODS AND VARIANCES

The study methods proceeded in accordance with Chapter 13 of the FERC Engineering Guidelines for the Evaluation of Hydropower Projects (FERC 2011). The site-specific seismic hazard evaluation for assessing the seismic risks and developing the seismic design criteria in support of licensing and detailed design included the following tasks:

- Update the understanding of geologic conditions and seismo-tectonic setting for the dam site area;
- Identify and characterize the seismic sources, including detailed geologic studies and lineament analyses;
- Identify whether a fault may be encountered beneath or adjacent to the dam and assess the activity of the feature and, if active, the likelihood for potential fault displacement or ground offset;
- Perform a deterministic and probabilistic seismic hazard assessment in order to define earthquake ground motions for structural analyses;
- Evaluate the potential for Reservoir Triggered Seismicity (RTS);
- Assess risks to Project structures and operation associated with seismic loading conditions; and
- Propose appropriate seismic design criteria.

These tasks were completed per methods described in the ISR Study 16.6 Section 4 in assessing the seismic risks for the Project.

4.1. Board of Consultants Review

As requested by FERC (FERC 2012), the Board of Consultants (BOC) has been engaged for technical review of the dam analysis and engineering feasibility. AEA convened a Board of Consultants comprising Joseph Ehasz; Alfred J. Hendron; Yusof Ghanaat; and Brian Forbes, George Taylor and Ellen Faulkner, supplemented by William Lettis for some meetings monitoring progress on seismic hazard study and analysis. The Board of Consultants reviewed the interim SSSHS report and the sections of the Engineering Feasibility Report for the Susitna-

Watana Hydroelectric Project relating to the dam analysis and derivation of the ground motions. Their comments were taken into account in the finalization of the document. Norm Abrahamson, an independent technical reviewer to the engineering consultant also has reviewed the Site Specific Seismic Hazard Assessment (SSSHA) Summary Report and his comments have been addressed in the document. Technical review has included review of the site specific seismic hazard studies, seismic design criteria, dam finite element analysis and the engineering feasibility report.

4.1.1. Variances

There were no variances to this study component of the Study Plan.

4.2. Review of Project Documentation

The review was conducted of the existing documentation and included additional Light Detection and Ranging (LiDAR) imagery data set coverage for the upper Watana Creek and Fog Lakes / Stephan Lake areas, earthquake event data from the Project seismic monitoring network, and recently published scientific results by others within the Project area. The available data and reporting on studies were used to characterize the geologic, seismic and tectonic framework within the Project area.

4.2.1. Variances

There were no variances to this study component of the Study Plan.

4.3. Seismic Hazard Analysis

Preliminary deterministic and probabilistic seismic hazard evaluations were undertaken previously to update the seismic hazard studies from the 1980s that included an update of the site-specific seismic source model as presented in the technical memorandum *Seismic Hazard Characterization and Ground Motion Analyses for the Susitna-Watana Dam Site Area* (Fugro, 2012; Attachment 2). The methods follow the recommendations of Chapter 13 of the Federal Energy Regulatory Commission's Engineering Guidelines (FERC 2011). Subtasks for the seismic hazard analysis included:

- Update evaluations of geologic, seismologic, and seismotectonic literature for the Project study area to identify data gaps and uncertainties that may require further evaluations.
- Update the seismicity catalogue for evaluation of seismicity rates, depths, magnitudes, and focal mechanisms.
- Develop a seismotectonic model that identifies and characterizes seismic sources of engineering significance to the Project.
- Conduct geologic studies using newly acquired LiDAR and Interferometric Synthetic Aperture Radar (INSAR) datasets to aid in the identification and evaluation of potential

seismic sources and geohazards. Criteria were established for determining significant crustal seismic source potential (e.g., rupture length and earthquake magnitude, length – distance screening criteria).

- Collect field geologic data for characterization of potential crustal seismic sources and surface displacement hazards.
- Perform fault displacement hazard analysis to evaluate the significance (likelihood and amount) of potential ground surface displacement from faulting in the area of the Project, including beneath the dam.
- Perform sensitivity studies on selected surface tectonic features, faults and lineaments, identified and being considered as potential crustal seismic sources of engineering significance on the design of the Project.
- Determined preliminary ground motion parameters by conducting a Probabilistic Seismic Hazard Analysis (PSHA) and a Deterministic Seismic Hazard Analysis (DSHA) for the Project area.
- Detect and monitor local earthquakes to understand the seismic hazards in the Project area.

The methods employed to complete the crustal seismic source evaluation since the ISR included geologic reconnaissance and mapping, evaluation of seismic sources, shear wave velocity measurements at multiple locations in the Project area, collection of soil samples for age dating, and a dam site area fault rupture evaluation. The detailed results are presented in technical memoranda and a report titled *Lineament Mapping and Analysis for the Susitna-Watana Dam Site* (Fugro 2013; Attachment 3), *Watana Seismic Network Station Vs30 Measurements for the Susitna-Watana Dam Site* (Fugro 2014a, Attachment 4), and *Crustal Seismic Source Evaluation for the Susitna-Watana Dam Site* (Fugro 2015a; Attachment 5).

Furthermore the data collected during these studies, various components of the initial PSHA relative to the controlling source at the Watana site, the intraslab source, were updated and revised. A PSHA sensitivity study was performed to better understand the refinements to the slab position, variance of maximum magnitude (Mmax), and the correlation distance or the width of the spatial smoothing kernel used for smoothed seismicity. The detailed results of this study component are presented in the technical memorandum titled *Revised Intraslab Model and PSHA Sensitivity Results for the Susitna-Watana Dam Site Area* (Fugro, 2014b; Attachment 6).

The seismic design criteria were developed following FERC guidelines using a DSHA, while the maximum design earthquake (MDE) was defined based on the 5,000-year return frequency ground motions from a PSHA. The operating basis earthquake (OBE) was selected to be the 500 year return period from the PSHA. It should be noted that the maximum credible earthquake (MCE) is represented by four different response spectra from three different sources: the subduction zone events – interface and intraslab and crustal events. The intraslab is represented by a M7.5 and M8.0. The results of this study component are presented in the briefing document titled *Discussion of MCE and OBE* (MWH 2014a; Attachment 7) and the report filed in November 2015 titled *Engineering Feasibility Report* (MWH 2014b).

The seismic hazard at the dam site encompasses contributions from three different sources: the subduction zone events – interface and intraslab (also referred to as the slab), and crustal events. Response Spectra and time histories were developed for each type of event to evaluate the difference in frequency content. The time histories were selected from the COSMOS, PEER, K-NET (Japanese Earthquake Database), and a database run by the University of Chile and the Chile Ministry of the Interior and Public Safety for ground motions that had magnitude, distance and record properties similar to the controlling events. Once a time history record was selected it was synthetically modified to match the target spectra. The time history details are presented in the *Engineering Feasibility Report Appendix B6* (MWH 2014b).

4.3.1. Variances

There were no variances to this study component of the Study Plan.

4.4. Long-Term Earthquake Monitoring System

The long-term earthquake monitoring system established in 2012 to monitor and document earthquake events in the Project area continued to be operated through June 2015. Following expansion of the initial monitoring system in 2013, the network consisted of seven instrumented locations (WAT-1 through WAT-7) within about 30 mi (48 km) of the dam site. The network was comprised of four 6 component strong motion and broadband seismograph station, and three 3-component broadband seismograph stations. At seismic station WAT-1, located at the dam site, a high resolution GPS station was co-located to track crustal motion relative to the North American Plate during August 2013. The monitoring system is linked and integrated into the Alaska Seismographic Network operated by the Alaska Earthquake Information Center (AEC) for real-time data acquisition, processing, and analysis.

During the 2014 field season, maintenance was performed on a number of the monitoring stations. The seismic monitoring network continued to detect and provide event data on the earthquakes in the Project area through June 2015. In June 2015, the number of seismograph stations comprising the monitoring network was reduced with equipment removal and restoration of the sites at WAT2, WAT3, WAT4, and WAT5 (AEC 2015, Attachment 10). A summary of the seismic activity recorded by the Susitna-Watana Seismic Network are presented in the reports titled *Susitna-Watana Hydroelectric Project Seismic Network 2013 Annual Seismicity Report* (Fugro 2014c; Attachment 8) and *Susitna-Watana Hydroelectric Project Seismic Network 2014 Annual Seismicity Report* (Fugro 2015b; Attachment 9). The seismic event data obtained during the first six months of 2015 are presented in the report titled *Susitna-Watana Seismic Monitoring Project: January – June 2015 Report* (AEC 2015, Attachment 10).

This study component is complete.

4.4.1. Variances

There were no variances to this study component of the Study Plan.

4.5. Preliminary Reservoir Triggered Seismicity

The preliminary reservoir triggered seismicity (RTS) study component methods were discussed in the ISR, Section 16.6.4.6 (AEA 2014). No additional effort was undertaken since this task was reported out in the ISR. The results of the preliminary study are presented in the technical memorandum titled *Preliminary Reservoir Triggered Seismicity* (MWH 2013; Attachment 11).

This study component is complete.

4.5.1. Variances

There were no variances to this study component of the Study Plan.

5. RESULTS

5.1. Crustal Seismic Source Evaluation

As discussed in the ISR (AEA, 2014), an initial assessment was made of existing and additional crustal seismic sources utilizing two high-resolution elevation datasets, a coarser resolution INSAR dataset and a high resolution LiDAR dataset recently made available for the Project site area. These datasets were used to identify lineaments and faults in the Project area, within 62 mi (100 km) from the Watana dam site.

A total of 22 lineament groups and 3 boarder lineaments were identified for evaluation through field reconnaissance and on the ground inspection (Fugro 2013; Attachment 3). These lineaments groups were evaluated for signs of recent activity such as deflected streams, offsets in Quaternary deposits, faceted ridges, uphill facing scarps, etc. many of the lineament groups investigated are judged to be dominantly erosional in origin, or to a lesser extent, related to rock bedding or jointing, are not associated with tectonic faults.

Of the 25 lineament groups or lineaments, two groups, associated with the Sonona Creek and Castle Mountain faults, were found to have defensible justification for consideration or inclusion as a crustal seismic source. However since the Sonona Creek fault was included in the preliminary PSHA and did not result in significant contributions to the seismic hazard at Watana due to slip rate and distance (42 mi, 70 km), no additional field investigation is required. For the lineaments associated with a northeast extension of the Castle Mountain, while Quaternary deposits are lacking, there is a sharpness of the geomorphic expression in bedrock, it would be prudent to include this Holocene active fault system in alternatives considered for an updated crustal seismic source model.

Previous mapping conducted in the Watana dam site area depicted or inferred several nearby potential fault structures of crustal scale (Figure 5.1-1). The Talkeetna fault was recognized as a major northeast-southwest trending tectonic feature near the dam site (Kachadoorian and Moore 1979; WCC 1982). Based on lineament mapping, field reconnaissance and the paleoseismic trenching of a scarp, geomorphic evidence supports that interpretation that the scarp is likely an ice-marginal feature that was not formed by surface fault rupture. Furthermore, recent geophysical surveys and mapping by Twelker et al. (2014) concluded that the Talkeetna fault is not expressed in bedrock geology as a single, continuous fault but is interpreted to be a series of complex, high angle, northeast-trending fault strands, which strands appear to be cross-cut and truncated by north-northwest trending bedrock faults. This evidence suggests that the Talkeetna fault is not active in the contemporary stress regime.

In addition several topographic lineaments (e.g., Susitna feature, Watana lineament) were observed using Landsat imagery (Gedney and Shapiro 1975). The Susitna feature is described as a northeast-southwest structural grain in the Talkeetna Mountains that begins at Tsusena Creek at the Susitna River that extends to the northeast to the Susitna Glacier in the Alaska Range, approximately 70-mi long (110 km). WCC (1982) evaluated geomorphic features along the lineament including excavation of a prominent scarp (S-1) but concluded the scarp is not related to faulting but rather is of glacial origin. In this study, it was observed that there are a number of scarps of similar morphology in the vicinity of the paleoseismic trench suggesting that it is not an anomalous feature on the landscape. Moreover, a number of lineament groups were mapped as cross-cutting the feature (e.g., LG-16, LG-21b, LG-22); the lineaments mapped trend sub-perpendicular to the Susitna feature, and are not displaced where they overlie the projection. Thus, based on the lineament mapping and analysis, coupled with field investigations and in light of previous investigation findings, the data do not support evidence for the existence of a Susitna fault or feature and therefore it is discarded as a tectonic lineament or fault-related feature near the dam site.

It had been postulated that a significant geologic feature, known as the Watana lineament, corresponding to a series of east-west trending, relatively linear segments of the Susitna River, could potentially be present below the Susitna River at the location of the dam. If present, such a feature would present a significant engineering challenge to the project. A number of lineaments are located both on the north and south sides of the Susitna River; however, these lineaments and their orientations are attributed to glacial ice flow or erosion and do not line up with the proposed Watana lineament. In addition, two angled borings, DH14-9b and DH14-10, were drilled across the width of the river in opposing directions with the intent of intersecting any significant geologic structure, if present. In general, the rock encountered slightly weathered, strong to very strong diorite with occasional zones of alteration. While small shears with one to two inches of clay gouge were encountered, no significant geologic structures were observed in either hole. This provides subsurface evidence in support of interpretations made from geologic mapping that the existence of a through-going fault in the thalweg of the river channel at the dam site is improbable.

Recent dam site mapping as part of the dam site fault rupture evaluation was performed and considered regional geologic history, sub-regional deformation patterns, observed in Mesozoic and Cenozoic rocks around the site, emplacement of intrusions, volcanics, crustal stress orientations from earthquake focal mechanisms, known active faulting, plate motions and GPS data, geomorphic landform evaluations, and current understanding of geologic features at the dam site. Based on geologic mapping and drilling, bedrock at the dam site is pervasively fractured with thin shear zones present as high-angle features. Furthermore, these investigations imply that there is less continuity of dam foundation geologic structures (i.e., geologic features) than has previously been depicted, therefore reducing the potential significance of potential surface fault rupture. The lines of evidence that support this conclusion are:

- The apparent lack of continuity and small scale of structural geologic features (shear zones) at the dam site;
- The dominant northwest-southeast trend of geologic features is unfavorably oriented with respect to the contemporary tectonic stress regime;
- The absence of nearby crustal scale fault structures and any neotectonic or paleoseismic evidence of Quaternary faulting; and
- The absence of Quaternary faults mapped within about 15 mi (25 km) of the site.

Additional discussion of the geologic conditions at the Watana dam site is presented in the study implementation report for Geology and Soils Resource Characterization (AEA 2015).

5.2. Long-Term Seismic Monitoring

Since initiation of the Susitna-Watana Seismic Network on November 16, 2012 through December 2014 a total of 2,523 earthquakes have been recorded. In 2014 a daily average of 3.8 events was recorded (1.8 crustal events per day and 2.0 intraslab events per day). The largest event in 2014, M_L 4.6, occurred on November 29, 2014 at a depth of 37.9 mi (62.1 km), with an epicenter 24.5 mi (40 km) southeast of the proposed Watana dam site (Fugro 2014c, 2015b; Attachments 8 and 9).

The spatial pattern of both crustal and intraslab seismicity is variable over the Project Area, but much more dense in the western half of the Project Area. There is a notable lack of seismicity to the east and southeast of the dam site from both crustal and intraslab sources.

Focal mechanisms calculated by the AEC based on the larger earthquake event data detected by the Susitna-Watana Seismic Monitoring Network indicate that the shallow crust within the Talkeetna Block, a region the includes the Watana dam site is undergoing north-northwest south-southeast compression, consistent with the relative Pacific-North America plate motion, with the maximum horizontal stress rotating progressively in a counterclockwise direction from east to west (Figure 5.2-1). For the intraslab events, the majority of focal mechanisms indicate strike-parallel horizontal compression within the down-going Pacific Plate (which also show the same counterclockwise rotation of horizontal maximum stress axes seen in the crustal mechanisms), and three focal mechanisms indicate normal faulting with inconsistently oriented stress axes.

Based on recurrence calculations for the period of December 1, 2012 through December 31, 2014 (from combined crustal and intraslab events), about two M_L 4 events per year would be anticipated within the Project Area, a M_L 5 event would be anticipated about every three years, and a M_L 6 event about every 20 years. Due to the low fraction of crustal earthquakes compared to the total, and low upper magnitudes of the crustal seismicity, the intraslab seismicity forms the preponderance of events contributing to these recurrence statistics and thus drives the results.

5.3. Seismic Hazard Analysis

5.3.1. Preliminary Probabilistic Seismic Hazard Analysis

Based on the review of the literature and the previous studies, an updated site-specific seismic source model was developed and preliminary ground motion parameters (based on FERC guidelines) were developed for the Project for use in initial dam analyses. As part of the hazard update, a new seismic source characterization model of the dam region and site was developed. At the time of the SSSHA report preparation current ground motion prediction equations (GMPEs) including next generation attenuation (NGA) relationships for shallow crustal sources, and a recently developed GMPE for the Cascadia subduction zone, were used in the PSHA and DSHA for the proposed Watana Dam.

5.3.2. PSHA Sensitivity Analysis - Intraslab

The intraslab earthquake source of the Alaska Subduction Zone lies directly beneath the proposed Watana dam site, and was found to be the dominant contributor to the seismic hazard to the Project. The existing United States Geological Survey (USGS) model was updated using data from newly obtained seismic event monitoring. This data enabled the development of a 3D intraslab model (dipping planes) defined by seismicity clouds within the down going slab. The data was also used to develop 2D earthquake occurrence rate grids (Fugro 2014b; Attachment 6).

A PSHA sensitivity evaluation was conducted to determine the effect of varying key parameters of the new intraslab model. The sensitivity of smoothing (correlation distance), Mmax, distance to the slab, and averaged seismic shear wave velocity (Vs30) were evaluated. The results of this study indicated that the PSHA was relatively insensitive to correlation distance and Vs30; however, significant variations were observed with changes to Mmax (Fugro 2014b; Attachment 6).

5.3.3. DSHA for Intraslab Events

A DSHA was conducted to evaluate seismic events associated with intraslab rupture. This analysis was conducted to aid in the selection of design criteria at the Watana Dam. Values for distance, magnitude, and epsilon (a statistical value) were evaluated and selected based on a review of available data. The parameters were then used in a GMPE to determine preliminary seismic design parameters (MWH 2014b).

The following determinations were made base on the findings of this DSHA:

- GMPEs for the DSHA should be selected based on hypocentral distance and hypocentral depth rather than distance to the rupture plane.
- A postulated Mmax 8.0 was recommended for the PSHA. Previous models had considered a maximum magnitude of 7.5 (Fugro 2012; Attachment 2).
- An epsilon value of 0.5 (corresponding to the 69th percentile value) was recommended for the site if a large (magnitude 8) event is used for the MCE.
- An epsilon value corresponding to the 84th percentile should be used if a smaller (magnitude 7.5) is used for the MCE.
- Peak ground acceleration (PGA) of 0.81g was calculated using the recommended epsilon value of 0.5.

5.3.4. Seismic Shear Wave Velocity

The average seismic shear wave velocity (Vs30) of the upper 100 ft. (30 meters) was determined at the location of each of the recently installed seismic monitoring stations. The Vs30 values were determined using IMASW (interferometric multichannel analysis of surface waves) and resulted in velocities ranging from 2415 ft/s to 10345 ft/s (737 to 3154 m/s) predominantly in rock (Fugro 2014a; Attachment 4, Table 3). High on the north abutment above the Watana dam site, a V_S30 value was calculated to be 3,556 ft/s (1,084 m/s). The calculated shear wave velocities were all determined to be higher than the value used in the initial PSHA (2,635 ft/s; 800 m/s) (Fugro 2012; Attachment 2 Subsection 5.2).

5.4. Seismic Design Criteria

Table 5-1 summarizes the PGA resulting from the MCE, MDE and OBE for Watana Dam. It should be noted that the MCE is represented by four different response spectra from three different sources: the subduction zone events – interface and intraslab and crustal events. The intraslab is represented by a M7.5 and M8.0. Additional details regarding the PGA and deterministic percentile selected for these events are presented in Table 5-2. The results are summarized in the report titled Site-Specific Seismic Hazard Study (16.6) Summary Report (MWH 2015a; Attachment 1).

Based on the initial PSHA for the Watana Dam site area, (Fugro, 2012; Attachment 2), the seismic hazard at the dam site encompasses contributions from three different sources: the subduction zone events – interface and intraslab (also referred to as the slab), and crustal events. Response Spectra and time histories were developed for each type of event to evaluate the difference in frequency content.

Prior to the completion of the crustal seismic source evaluation, the crustal event was selected to be a M 7.0 event on the Fog Lake graben located at a distance of 4.4 mi (7 km). In the Crustal

Seismic Source Evaluation (Fugro, 2015a; Attachment 5) the evaluation of potential crustal seismic sources has not identified any specific features with evidence of late Quaternary faulting within at least 25 mi (40 km) of the Watana dam site; however, this event is a conservative representation of the background crustal event from the PSHA.

Guidance furnished by FERC, Evaluation of Earthquake Ground Motions, was followed and a deterministic spectrum was used (Idriss & Archuleta, 2007). Figure 5.4-1 illustrates the response spectrum. The 2,500, 5,000, and 10,000 year return period uniform hazard spectra are also included on Figure 5.4-1; this data is from the seismic hazard analysis report (MWH 2015a, Attachment 1, Section 11.1). It should be noted that the V_S30 used in the initial probabilistic seismic hazard assessment was 2,625 ft. (800 m/s).

The 84^{th} percentile or above was used for all of the events, except the M 8.0 event for the slab, where the 69th percentile is used. The interface event was scaled up at the fundamental period of the dam (0.55 seconds) to match the 5,000 year return period, resulting in the 88^{th} percentile, see Figure 5.4-1.

In total, four sets of time histories containing three records each have been developed for the slab, interface and crustal events using spectral matching techniques. All of the ground motions are based on the deterministic analyses using a V_S30 of 1,100 m/s. The intraslab event utilized two different earthquake records, one was from the El Salvador M_W7.6 and the other was from the Japan M_W7.0.

For the MCE, the time histories used are shown in Table 5-3.

Based on review comments on the initial design response spectra from the Board of Consultants the design response spectra was increased for the interface event .The Chilean event, Table 5-4, was also used for the dam analysis (MWH 2014b).

6. DISCUSSION

Three critical seismic sources are identified: (1) crustal faults, (2) subduction interface, and (3) intraslab. For the crustal seismic sources, the principle sources considered in this study were the Denali fault and Fog Lake graben. Deterministic evaluations found that the intraslab source produces the largest PGA at the site. The deterministic evaluation indicates that the largest values of ground motions at the site are associated with the subduction interface and intraslab sources, because of their large magnitude, relatively short distance, and GMPEs used for these sources. The deterministic results for the crustal sources (e.g. Denali fault, Fog Lakes graben, Castle Mountain fault, and 10,000-year crustal seismicity) indicate that these sources are relatively less significant, as compared to subduction megathrust and intraslab seismic sources.

The results of the field investigations of potential crustal seismic sources did not identify any specific features with evidence of late Quaternary faulting within at least 25 mi (40 km) of the Watana dam site (Fugro 2015a; Attachment 5). For most of this area, the time and detection limits of the imagery and field investigations imply post-glacial limits of about 12,000 to 15,000 years and detection of surface offsets of more than three feet (about 1m) over several miles. At the Watana dam site where detailed LiDAR data is available, potential detection limits of surface fault displacements are much lower, about 18 inches (0.5m) over several hundreds of feet. The findings are consistent with the observations that the reservoir area is structurally coherent with a lack of pervasive penetrative deformation.

Moreover, geomorphic and geological data similarly suggest that potential “blind” sources, located at shallow crustal depths and capable of producing significant rates of long-term vertical deformation are also absent from the dam site area. Thus given the absence of primary seismogenic structures with appreciable rates of surface deformation in the immediate dam site area, it is inferred that the potential for secondary faulting on structures at the dam site is also absent or negligible.

Shallow crustal deformation in the nearby region of Watana dam site appears to be characterized by near-horizontal maximum compressive stresses oriented northwest-southeast, parallel to the geologic features at the site. Strain ellipse deformation concepts suggest that the likelihood of reactivating northwest-oriented features under the existing conditions is low because of their near parallelism with compressive stress.

With the installation of the Susitna-Watana Seismic Network, the seismic station density in the region was increased. This led to greater magnitude detection capabilities, a decrease in magnitude of completeness, and greater location accuracy. Focal mechanisms produced by the AEC in the Susitna-Watana project area indicate that the crust around the proposed dam site is undergoing north-northwest south-southeast horizontal compression, consistent with the relative Pacific – North America plate motion, with the maximum horizontal stress rotating in a counterclockwise direction from east to west in the network area (Fugro 2014c, 2015b).

Source deaggregation plots were developed, one for each of the four spectral response periods (PHA, 0.5 sec, 1.0 sec, and 3.0 sec). Only sources contributing 5% or more at any ground motion level are plotted on the deaggregations. The peak horizontal acceleration (PHA) hazard is dominated by the Alaskan subduction zone intraslab source at all return periods.

Sensitivity studies indicate hazard variations due to Mmax choices of 7.8 and 8.1 are significant. For the two response periods, at a 10,000 year return period, ground motion increases of about 25% and 50% are indicated, respectively. However, due to the paucity of ground motion records for magnitudes above 7.5, magnitude scaling of ground motions in the GMPEs above Mw 7.5 is highly uncertain, and warrants further investigation during final design.

Preliminary investigations into historical occurrence of the largest earthquake magnitudes for worldwide subduction zones indicate that an upper bound value for future slab Mmax distributions used in the final PSHA analysis is likely to lie above 7.5.

For the proposed Watana Dam, MCE ground motions were estimated following FERC guidelines using DSHA, while the MDE was defined based on the 5,000-year return period ground motions from a PSHA. The OBE was selected to be the 500 year return period from the

PSHA. For analyses performed for engineering feasibility, a deterministic approach was followed and design response spectra were recommended as follows:

MCE

- Interface 88th percentile, M9.2 at a rupture distance of 78 km, PGA=0.58g
- Intraslab 84th percentile, M7.5 at a hypocentral distance of 50km, PGA=0.69g
- Intraslab 69th percentile M8.0 at a hypocentral distance of 50km, PGA=0.81g
- Crustal 84th percentile M7.0 at a rupture distance of 3.5km, PGA=0.49g

OBE

The development of the OBE followed a probabilistic approach and was assigned a return period of 500 years, which has resulted in a projected PGA of 0.27g.

7. CONCLUSION

The overall objectives of the Site Specific Seismic Hazard Assessment included conducting deterministic and probabilistic seismic hazard evaluations to estimate earthquake ground motion parameters, assess seismic risks, determine seismic loads that the Project facilities would be subject to during and following seismic events, and propose seismic design criteria. These objectives have been met and the efforts undertaken for this study provides the basic requirements necessary for the license application. This study plan is complete.

The tasks conducted to-date demonstrates that the proposed Susitna-Watana Dam is feasible from a seismic risk standpoint. These studies are intended to meet the requirements of filing for a FERC license. Further evaluation will be required for detailed design and should include and update to the site specific seismic hazard assessment and update and/or confirmation of the seismic design criteria for final design.

8. LITERATURE CITED

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9. TABLES

Table 5-1. Peak Ground Acceleration Values for the MCE, MDE and OBE

CASE	DESIGN EVENT	PGA
MCE	Deterministic	0.81g
MDE	5,000-yr Return Period	0.66g
OBE	500-yr Return Period	0.27g

Table 5-2. Peak Ground Acceleration and Percentile for Deterministic Response Spectra

DESIGN EVENT	CASE	Crustal	Interface	Intraslab	
		Fog Lake	Alaskan Subduction Zone		
MCE - DSHA	Magnitude	7.0	9.2	7.5	8.0
	PGA(g) [percentile]	0.49 [84th]	0.58 [88th]	0.69 [84th]	0.81 [69th]

Table 5-3. Selected Time Histories for Feasibility Analysis– Intraslab and Crustal

EVENT	RECORDING STATION	TIME HISTORIES	SEISMIC SOURCE
El Salvador (M 7.6)	STTEC	M_w 7.5 – 84th percentile	Intraslab
Japan 2011 (M 7.0)	MYG 009	M_w 8.0 – 69th percentile	Intraslab
Loma Prieta, California (M 6.93)	GIL	M_w 7.0 – 84th percentile	Crustal

Table 5-4. Selected Time Histories for Feasibility Analysis – Interface

EVENT	RECORDING STATION	TIME HISTORY	SEISMIC SOURCE
Chile 2010	CURI	M_w 9.2 – 88th percentile	Interface

10. FIGURES

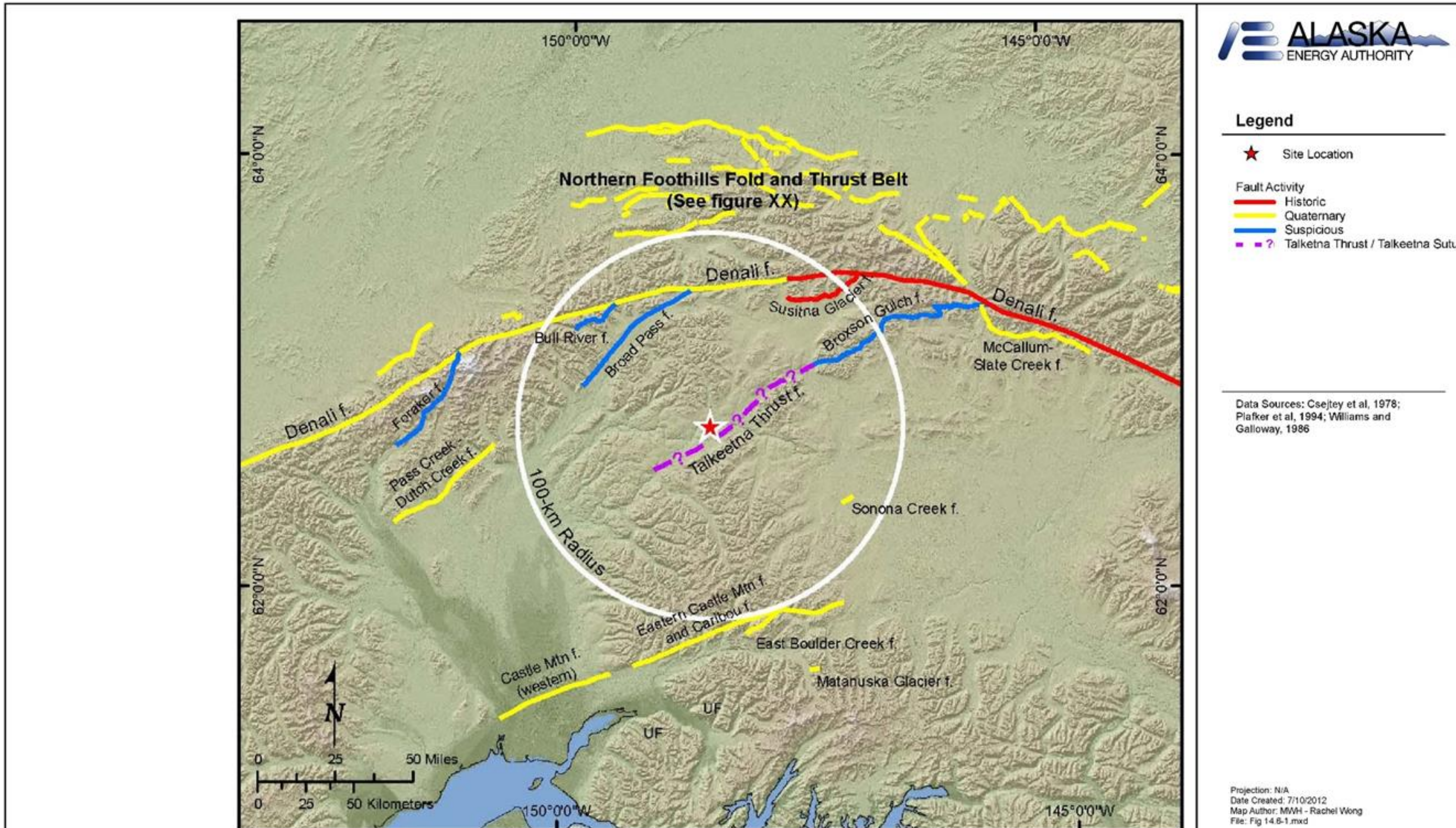

Figure 3.1-1. Regional Faults (Csejtey et. al. 1978; Williams and Galloway 1986; Plafker et. al. 1994)

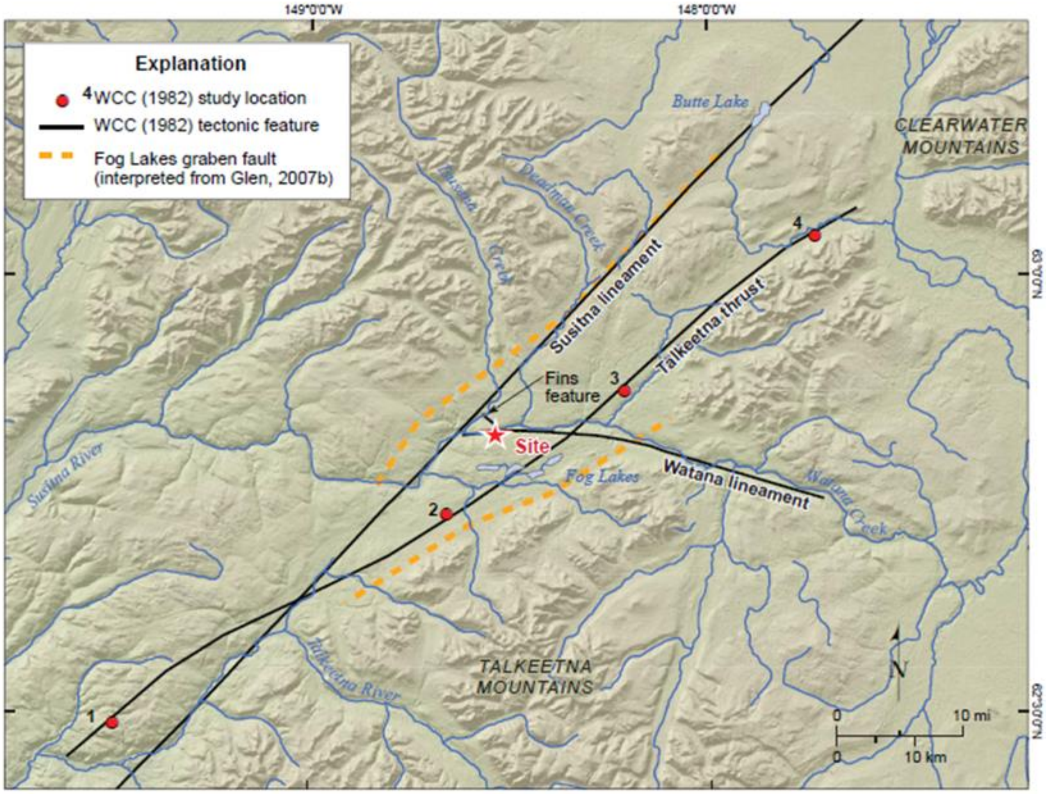

Figure 5.1-1. Dam Site Area Tectonic Features (Fugro 2015a)

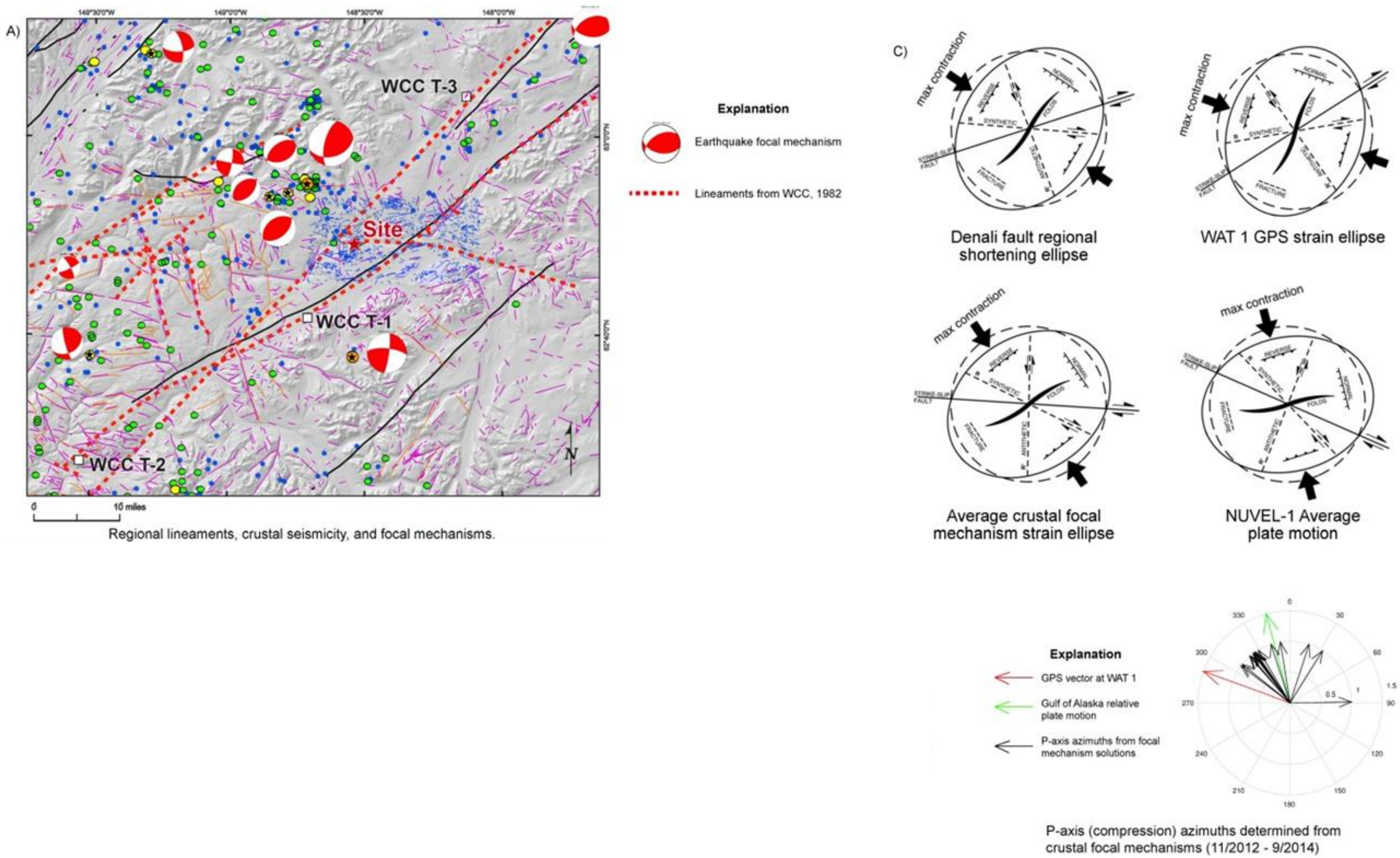

Figure 5.2-1. Crustal Stress Orientations and Strain Ellipses (Fugro 2015a)

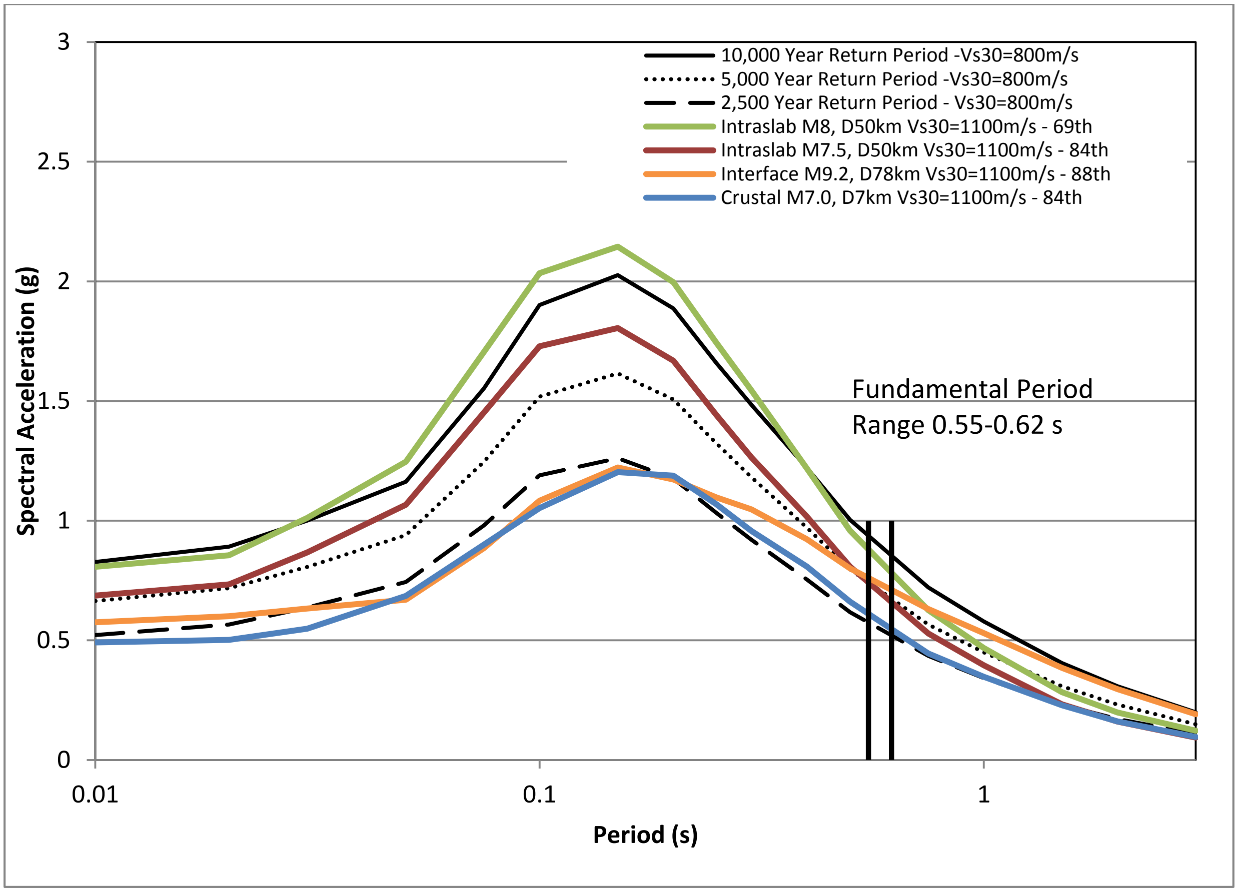

Figure 5.4-1. Design Response Spectra