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Dear Mr. Slocomb,

INDUCED SEISMICITY: EFFECT OF INDUCED SEISMIC EVENTS ON THE PEACE CANYON DAM, HUDSON'S HOPE, BC

1 Introduction

Advisian was retained by the BC Oil and Gas Commission (OGC) to evaluate the potential of induced seismic events to negatively impact the Peace Canyon Dam (PCD), located near Hudson's Hope, BC.

This letter report summarizes our review of existing knowledge on mechanisms associated with induced seismicity, examines the assumptions made in the analysis of seismic stability of the PCD structure and provides our preliminary recommendations and precautionary measures for the consideration of the OGC.

In addition to reviewing background information provided by OGC, a general literature review was conducted of induced seismicity potential and effects. Literature included in the review is listed in Section 9.

The primary objective of the review work was to inform comment on the nature of damage to PCD, if any, which could potentially occur as a result of an induced seismic event, considering that the seismic withstand has been determined by BC Hydro to be in a threshold range of PGA of 7% to 17% of gravity.

The review included the following aspects:

1. Review of background information provided by OGC and BC Hydro, with a focus on the "Technical Review – Canada Energy Partners (CEP) Portage Suspension Order" – dated April 10, 2017.

2. A general literature review of induced seismicity events affecting key infrastructure.

3. Preliminary comments on potential effects of induced seismicity on the PCD stability.

OGC supplied documents and technical papers, as well as other literature, reviewed for the scope are listed in the reference section (Section 9).

2 Induced Seismicity

National Research Council of the National Academies (2012) indicates that induced seismicity is caused by pore pressure change or the alteration in stress state that can adversely affect nearby faults or the existing critical state of stress of rock. This change in stress can result in fault movement and lead to a seismic event. Seismicity can be induced by a range of activities, including but not limited to mining, reservoir filling, hydraulic fracturing (fracking) and injection wells.

Holland (2014) attributes the cause of induced seismicity from fracking and injection wells to both an increase in shear stress and/or pore pressure due to fluid injection. Roeloffs (2013) suggested the following criteria to qualify if a seismic event is an induced one:

- If the event is the first known one in the region,
- Good spatial and time correlations between injection and seismic event,
- If there is known geologic structure that may direct the fluid flow to the seismic event site, and
- If fluid pressure within the injection zone is adequate to cause fault movement.

Another important factor that can be evidence of induced seismicity is the increase in frequency of seismic events after commencing injection activities.

The increased pore pressure from fluid injection reduces the friction and the strength of faults. Since most of the Earth's upper crust is near failure, even a minor decrease in effective stress may trigger an earthquake seismic event (Holland 2014).

3 Historical Operation of Well CE Portage A-20-D/094-A-07

Well A-20-D/094-A-07 is located 3.25 km from the PCD and was drilled to a depth of 1610 m. The well was in operation from 2008 to 2010, with a cumulative injection of 99,150 m^3 of fluid at a depth of 1514 m. It recommenced operations in January 2017 and disposed an additional 15,768 m^3 of fluid injected between January 10, 2017 and March 16, 2017 (approximately 275 m^3 per 24 hours day of actual operation). It was suspended due to BC Hydro providing information to OGC regarding the seismic withstand of PCD.

4 Buffer Zone Around critical structures and the Damage Threshold

Atkinson (2017) provides a discussion on buffer zones associated with oil and gas activities around critical infrastructures such as high-consequence dams. She emphasizes the fact that this buffer zone might be determined on a case-by-case basis. The type of activity, likelihood of the event, structure vulnerability and the failure consequences are the factors that must be taken into account. Bourne et al. (2015) found that the dominant contributions to induced-seismicity hazard are generally within a very short hypocentral distance of approximately 3 km from magnitude 4 to 5 seismic events.

Atkinson also showed the damage threshold, taking into account the correlation between the Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and the Modified Mercalli Intensity. PGV is a suitable indicator of damage potential with a value toward the upper end of this range (9-10 cm/s) suggested as appropriate for vulnerable engineered structures. Interestingly, a PGV of 9 cm/s is correlated by Atkinson to a PGA of 18 % of gravity for M4 to 5 events at <10 km. This limit is close to the 17 % of gravity limit suggested by BC Hydro for PCD. A PGV range of 5 to 10 cm/s (equivalent to a PGA of 10 to 20 % of gravity) was provided. These PGA/PGV values correspond to a buffer zone of 5 km. Mahani (2016d) presented the results of a research in Northeast British Columbia on synthetic values of PGV based on the event magnitude and distance. These results reveal that, for a magnitude 4 event and a distance of 1 to 3 km from the source, a PGV of 5cm/sec to 1 cm /sec is expected, respectively.

5 Seismic Activity in the Northern Montney Play and Horn River Basin

The largest Canadian seismic event to date that has occurred in the vicinity of oil and gas operations (including the wastewater disposal and hydraulic fracturing) is the August 2015 earthquake with a moment magnitude of 4.6 in the Northern Montney Play of British Columbia.

Wastewater disposal wells have been active at nine locations in the area. The relationship between the long-term, low volume (maximum monthly volume of 2200 m^3) wastewater disposal and seismicity in the area was investigated by Mahani et al. (2017b). They concluded that the magnitude 4.6 event is more strongly correlated with hydraulic fracturing than with other types of injections.

Mahani (2016d) presented the results of other research in the Horn River Basin in north-east British Columbia on an injection well and concluded that a larger seismic moment release (exceeding M=3.5) occurred when the monthly injected volume exceeded 150,000 m^3 (5000 m^3 per day). A review of the time histories from the induced seismic events recorded in the Northern Montney Play indicate that the total duration of ground motion is less than two seconds and the total duration of strong ground motion is less than one second based on information provided in e mail correspondence (Slocomb et al. 2017). This duration is different from the traditional suite of time histories used to model expected earthquakes in BC, which were used to develop the withstand capacity of PCD based on the PSHA for PCD provided by BC Hydro

(2012). A short duration event is unlikely to increase pore water pressures sufficiently to liquefy soils, generate localized slides into the reservoir, cause amplified rocking for structures with similar natural periods of motion to that of the seismic event, open up fractures in the dam foundation to transmit excess pore pressures, or potentially overcome initial friction resistance to cause a prolonged sliding failure.

6 Seismic Stability Analysis

The seismic stability of the Peace Canyon Dam and Spillway Structures was assessed in a dam safety review (Charlwood & Assocs. 2009) and a Spillway Performance Report by BC Hydro (2015).

BC Hydro (2017) also provided a synopsis of the seismic stability, which included a plot of the relationships among the critical acceleration ratio, drainage efficiency during an earthquake, friction angle along bedding planes in the foundation, correlating with a Factor of Safety (FoS) of 1.0 for a peak acceleration value of 17% of gravity, decreasing to 7% of gravity if the dam foundation's drainage system is damaged. In the BCH stability analysis, the peak ground acceleration is converted into a pseudo-static inertial force which is a horizontal incremental gravity load.

A review of the above reports reveals the following factors contributing to the resistance of the structure in withstanding a low to moderate seismic event associated with deep well injection:

a) The critical failure surface is anticipated to be along a bedding plane in the sedimentary rock foundation; most likely along bedding planes 3 or 4, where the frictional resistance is assumed to be at least 36 degrees. Zero cohesion was assumed on the basis that the cohesive bond would be broken during a large seismic event with a sufficiently long wave duration and number of cycles to rupture the bond. In the case of a low to moderate event associated with operating an injection well, it is unlikely that the cohesive bond would be ruptured. For the purpose of this report, a low magnitude event is considered to be 3 or less and a moderate level event is in the range of 4-5.

b) A large seismic event would result in a safety factor below 1.0 in the pseudo static analysis, resulting in a displacement, but not outright failure of the structure in the range of 3 cm as determined in the Newmark (1965) method of displacement analysis. The worst case scenario is that the effectiveness of the foundation drainage holes would be reduced by 50% due to the partial severing of the NX holes which are 7.5 cm in diameter. Any displacement associated with an injection well seismic event is anticipated to be minimal to nil, so that the performance of the drainage system is likely to remain fully intact. Hence, the seismic withstand would remain at 17% of gravity, rather than decreasing to 7% as illustrated in the BC Hydro synopsis plot (2017).

c) In the BC Hydro spillway performance report (2015), it is suggested that a major shake could open cracks (joints) and expose the critical bedding planes to full reservoir hydrostatic pressure, which could extend beneath the structure towards the toe of the spillway and challenge the effectiveness of the drainage system, which may already be compromised by a translation of the structure as described in item b). This eventuality is most unlikely in the case of a low to moderate magnitude event associated with deep well injection.

d) A crack which forms as described in item c) would be subject to opening and closing cycles during a natural earthquake event, causing exposure to significant uplift pore pressures and a reduced sliding resistance. This effect is not anticipated for a low to moderate induced event due to the differences in the respective response spectra. This phenomenon is further described in section 7.

7 Seismic Response

A review of the time histories from the induced seismic events recorded in the Northern Montney Play indicate that the total duration of ground motion is less than two seconds and the total duration of strong ground motion is less than one second, or essentially a "pulse", rather than a "wave", based on information provided in a recent unpublished paper (Mahani 2017c). This duration is different from the traditional suite of time histories used to model expected earthquakes in BC, which were used to develop the withstand capacity of PCD based on the PSHA for PCD provided by BC Hydro (2012). A short duration event is unlikely to increase pore water pressures sufficiently to liquefy soils and generate localized slides into the reservoir, cause amplified rocking for structures with similar natural periods of motion to that of the seismic event, or overcome initial friction resistance to cause a prolonged sliding failure.

The PCD has a set of natural frequencies based on modes of movement. For an earthquake event lasting several seconds, the ground will oscillate back and forth through several cycles of motion and if the frequency of the ground motion aligns closely with the natural frequency of one or more of the modes of motion, that motion will be amplified and potentially result in damage to the structure. As the induced seismic events in this region have all been recorded as a pulse of motion and not a motion that cycles back and forth several times, the potential for damage is reduced, as there is minimal potential for amplification from the alignment of frequencies.

The Spillway Performance Investigation Report by BC Hydro (2015) makes the following statements and conclusions with respect to the seismic response of the PCD:

- The report states that there are assumptions used in the analysis that are conservative and also that it is not appropriate to take the largest pulses from seismic time histories to determine the seismic demand forces:
  - Section 7.1: "Conventional rigid body analyses were carried out for [representative sections of the dam]. Rigid body analysis of concrete gravity dams relies on broad assumptions with significant implications. In particular, the rigid body assumption results in a linear variation of normal stress at the base of the dam. "The effects of elasticity in the foundation and the dam result in actual normal stress profiles that are highly non-linear. The prediction of tensile cracking at the base of the dam based on a rigid-body analysis is therefore a poor representation of the actual behaviour."
  - Section 7.3.3: "The earthquake load case was considered with both full (100%) and reduced (67%) earthquake demands. Mid-level response spectrum demands were adopted as the reference level for these cases. Full earthquake demands were used to determine the extent of cracking at the assumed sliding surface, with uplift pressure assumed to remain unchanged during the earthquake. "These peak demands would only occur over very short time intervals, and evaluation of stability criteria at these levels would be conservative. As a better representation of sustained

shaking, the reduced demands were used as a basis for evaluating the location of the [resultant force for overturning and its position from the base of the dam]."

- The probability of the primary mode of failure, which is sliding, is highest in years that have large run-offs that cause increased river levels and thus prolonged need to use the PCD spillway. Avoiding usage of the disposal well when it is known that there will be high river levels will significantly reduce the likelihood that an induced seismic event will negatively impact the ability of the dam to efficiently drain during river elevations that will result in spillway usage, thus increasing the probability of a sliding failure. Scouring of the riverbed materials immediately downstream of the dam, which have been scoured out during the repeated large flood events with significant flows over the spillway. The location of the scouring takes place in what is called the plunge pocket. The report makes a recommendation that BC Hydro spend approximately $3.5M to install tremie concrete on the riverbed to fill the area of scoured material and prevent future scouring. The ability of the dam to withstand a sliding failure will be increased if the reinforcing plan proposed in the Spillway Performance Investigation is implemented for the area of the riverbed just downstream of the dam known as the plunge pocket.
- Construction of the Site C dam will not negatively affect the seismic response of the PCD. In fact, after construction of the Site C dam, the increased elevation of the tail waters downstream of the PCD will slightly increase the PCD's resistance to a sliding failure.
- The bucket structures at the base of the spillway have been analysed in the past to determine their susceptibility for failure. The factor of safety against a sliding failure of the buckets alone is several times higher than for the remaining earth and concrete structures. However, the buckets are vulnerable to failure if the scour issues discussed above are not addressed, so that scour continues to propagate back towards the dam and undermines the buckets

8 Conclusions

The following factors will be crucial for the evaluation of wastewater disposal on the potential for induced seismicity:

1. PGV monitoring is recommended within 5 km of the dam site, with an alert level triggered if the measured particle velocities exceed a range of 5 to 10 cm/s.
2. A pulse type motion, as is expected from a low to moderate induced seismic event, is considered to have a reduced probability of causing failure or damage to the PCD for the following reasons that were presented in the BC Hydro Spillway Performance Investigation report:
    a. There is insufficient duration to cause a significant increase in pore water pressures in the bedrock foundation that could lead to a sliding failure of the dam.
    b. There is insufficient duration to cause repeated rocking of the dam that could lead to a small crack at the toe of the dam increasing in length and depth to cause overturning of the dam.
    c. The withstand strength of the upper bucket structures is much higher than the rest of the dam to sliding failure, including to pulse type seismic events.

d. Because it is unlikely that a sliding failure of the dam will occur during a pulse type seismic event, the assumption in the spillway report that drains in the dam will have reduced efficiency because they are partially blocked from the sliding is not considered to be applicable to pulse type seismic events.

e. We have not identified any compelling reason for induced seismicity to result in significant damage to, or an outright failure, of the PCD. Based on the recorded history of fracking and injection well induced seismic events in north-east BC, and provided that reinjection conditions remain similar to the practice to date, the probability of significant damage or a failure occurring is within expected norms for life safety, based on the British Columbia Building Code and our present understanding of the stability of the PCD structure.

f. It is noted that consideration of any linkage between injection operations and average reservoir pressure to either the likelihood of triggering an event, or to the size of the event was beyond the scope of the present assignment.

9 Recommendation

Monitoring of particle velocities is recommended within 5 km of the PCD. The potential damage threshold is considered to be in the range of 5-10 cm/sec.

10 Closure

We trust that this report satisfies your current requirements and provides suitable documentation for your records. If you have any questions or require further details, please contact the undersigned, or Daniel Leonard, at any time.

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Reviewed By:

for **Daniel Leonard, MSc, P. Eng.**
Principal Consultant

11 Bibliography

Atkinson, G.M., 2016. "Rationale for 5-km buffer zone around critical infrastructure".

Atkinson, G.M., 2017. "Mitigation strategies to prevent damage to critical infrastructure due to induced seismicity".

BC Hydro, 2012. "Dam Safety Probabilistic Seismic Hazard Analysis (PSHA) Model Volume 1- Methodology".

BC Hydro, 2012. "Dam Safety Probabilistic Seismic Hazard Analysis (PSHA) Model Volume 2 – Seismic Source Characteristics Model".

BC Hydro, 2012. "Dam Safety Probabilistic Seismic Hazard Analysis (PSHA) Model Volume 3 – Ground Motion Characterization Model".

BC Hydro, 2012. "Dam Safety Probabilistic Seismic Hazard Analysis (PSHA) Model Volume 4 – Implementation and Results".

BC Hydro, 2015. "Spillway Performance Investigation". June 2015.

BC Hydro, 2017. "Peace Canyon Stability Synopsis". April 2017.

BCGC - Draft of Meeting Summary, 2017. "Technical Review CEP Portage Suspension Order".

Boore, David M., 2009. "Comparing Stochastic Point-Source and Finite-Source.

Bourne, S.J., Oates, S.J., Bommer, J.J., Dost, B., van Elk, J., Doornhof, D., 2015. A Monte Carlo Method for Probabilistic Hazard Assessment of Induced Seismicity due to Conventional Natural Gas Production, BSSA".

Charlwood & Assocs., 2009. Dam Safety – Peace Canyon Dam. Excerpt from Draft 2008 Dam Safety Review. Report No.: P1038. May 2009.

Ground-Motion Simulations: SMSIM and EXSIM", Bulletin of the Seismological Society of America, Vol. 99, No. 6, pp. 3202–3216.

Groundwater Protection Council, 2013a. "White Paper I Summarizing a special session on induced seismology".

Groundwater Protection Council, 2013b. "White Paper II Summarizing a special session on induced seismology".

Holland A., 2014. "Presentation on induced seismology from fluid injection and draft best practices, Oklahoma geological Survey".

Mahani, A.B., Kao, H., Walker, D., Johnson, J., and Salas, C., 2016a. "Performance Evaluation of the Regional Seismograph Network in Northeast British Columbia, Canada, for Monitoring of Induced Seismicity".

Mahani, A., 2016b. "Update on the Evaluation of Network Performance in NE BC".

Mahani, A., Walker, D., 2016c. "Site C Ground Motion. Personal email communication".

Mahani, A., 2016d. Presentation on Monitoring of Induced Seismicity in Northeast British Columbia.

Mahani, A.B., Kao. H., Johnson, J., and Salas, C.J., 2017a. "Ground Motion from the August 17, 2015, Moment Magnitude 4.6 Earthquake Induced by Hydraulic Fracturing in Northeastern British Columbia".

Mahani, A.B., Schultz, R., Kao, H., Walker, D., Johnson, J., and Salas, C., 2017b. "Fluid Injection and Seismic Activity in the Northern Montney Play, British Columbia, Canada, with Special Reference to the 17 August 2015 Mw 4.6 Induced Earthquake".

Mahani, A.B., 2017c. "Duration of Strong Motion Accelograms in North-Eastern BC". Publication pending.

National Research Council of the National Academies, 2012. "Induced seismicity potential in energy technologies".

Natural Resources Canada, 2017. Earthquakes Canada; Natural Resources http://www.earthquakescanada.nrcan.gc.ca//.

Newmark, N.M., 1965. "Effect of Earthquakes on Dams and Embankments". Geotechnique, pg 139-159.

Robin Charlwood and Associates, 2009. Excerpt from "Dam Safety Report, Peace Canyon Dam". May 2009.

Roeloffs, E., 2013. "Presentation on U.S. Geological Survey earthquake research on injection-induced seismic activity: a progress report, USGS Earthquake Science Center".

Ryan, B., 2017. "CBM Completion and Deep Injection Practices NE BC Possible Impacts of Concern to Local Populations".

Slocomb, R., 2014. "Order 08-08-008 (Amendment #1)".

Slocomb, R., Claridge, F., Gaucher, M., 2017. "Wellhead and Sandface Pressure. Personal email communication".

Van der Elst, N., 2013. "Enhanced remote earthquake triggering at fluid injection sites in the Midwestern U.S., Presented at Groundwater protection Council meeting St. Louis, Missouri.

Worden, C.B., Gerstenberger, M.C., Rhoades, D.A., and Wald, D.J., 2012. "Probabilistic Relationships between Ground-Motion Parameters and Modified Mercalli Intensity in California", Bulletin of the Seismological Society of America, Vol. 102, No. 1, pp. 204–221.

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