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EFFECTS OF THE 03 NOVEMBER 2002 M7.9 ALASKA EARTHQUAKE MEASURED AT DAMS IN BRITISH COLUMBIA, CANADA

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SUMMARY

Effects of the M_W 7.9 Denali, Alaska earthquake of 03 November 2002 were recorded at hydroelectric projects in British Columbia at epicentral distances of about 1500 km to 2400 km. Low amplitude seiches were recorded at 14 reservoirs and changes in piezometric pressures were recorded in the bedrock foundations of several concrete gravity and earthfill dams. None of the seiches or piezometric effects were of sufficient magnitude to be of concern to the stability or safety of the dams; it is possible that greater effects could occur closer to the epicentre. This case history highlights the potential for large magnitude earthquakes to cause significant piezometric effects in dam foundations that can be difficult to predict or detect without suitable instrumentation.

INTRODUCTION

The M_W 7.9 Denali, Alaska earthquake of 03 November 2002 was the world's largest magnitude earthquake of 2002 and one of the largest earthquakes in North America in the last 100 years. The earthquake occurred at 22:12:41 hrs UTC (14:12:41 hrs Pacific Standard Time), which was mid afternoon in western North America.

One of the prominent features of the 2002 Alaska earthquake was the large number and variety of effects at long distances from the source. Beyond distances of about 750 km, the only "felt" reports were from occupants of high rise buildings in a few locations, but there were many other indicators of seismic effects. Local seismicity was triggered at geothermally active sites from Alaska to California at distances of up to more than 3600 km. In Western Canada effects were reported at distances of up to 3500 km, including disturbances of water wells, seiches in lakes and inlets and swinging of suspended objects. These long distance effects are attributed to the large amplitude, long period waves generated by the earthquake, sometimes in combination with local amplification effects [1, 2].

In British Columbia, BC Hydro owns and operates an extensive network of hydroelectric facilities that includes 61 dams on 42 reservoirs. Many of the dams are instrumented for dam safety monitoring

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purposes and some of the instruments in the large dams are monitored with automatic data acquisition systems (ADAS) or dataloggers that collect frequent readings. Strong motion accelerographs are installed at the large dams and other important electric system facilities. In addition, the levels of most of the reservoirs are monitored in real time or at frequent intervals for operational purposes.

There were no “felt” reports or visual observations of earthquake effects at any of BC Hydro’s facilities. The strong motion accelerographs are set to trigger levels ranging from 0.004g to 0.01g; none of those instruments were triggered. Shortly after the earthquake, however, several piezometers in the foundation of one dam indicated pressures that were outside of their usual trends. The timing of the piezometric pressure changes was found to closely correspond to the time of the earthquake. A comprehensive review of instrumentation data from other dam sites subsequently indicated that numerous instruments had recorded effects of the earthquake, which are described in this paper.

SEICHES

Reservoir Level Monitoring

BC Hydro reservoirs range from small headponds several tens of metres in length to major storage reservoirs several hundred kilometres long. The sensors that monitor the reservoir levels are typically accurate to the nearest 1 cm. At some reservoirs, water levels are sampled at regular intervals, typically either six times per hour or once per hour. For such sites, all sampled levels are archived, but the readings are generally too infrequent to record the effects of short duration water level changes.

At many of the larger reservoirs, automated sensors sample the water level up to 15 times per minute, but to minimize the volume of data, not all sampled levels are archived. The data are filtered such that individual levels are archived only when they fall outside of a predefined set of trend line parameters. Once a specific reservoir level has been archived, no additional values will be archived if the reservoir level remains constant or is changing at a constant rate. If a seiche occurs, the oscillating reservoir levels will likely be recorded, although there is some loss of resolution due to the sampling rate and filtering.

Recorded Effects

Low amplitude seiches caused by the 2002 Alaska earthquake were recorded at 14 reservoirs, with maximum peak to peak amplitudes ranging from 3 to 18 cm. At another 10 reservoirs the data were of sufficient resolution to show that no measurable seiche occurred. The other 18 reservoirs had insufficient data to determine whether a seiche occurred. Details are summarized in Table 1.

The frequency and duration of the seiches were quite variable. Four examples are plotted to the same time and vertical scales on Figure 1. In some cases it is difficult to clearly identify the end of the seiche because the declining amplitude of the waves eventually matches the sensor resolution.

The first seiche started at 14:19:23 hrs at Falls River Dam (Site 3 in Table 1) and the last seiche started at 14:24:00 hrs at Seven Mile Dam (Site 10). A simplified estimate was made of seismic wave velocities, based on epicentral distances and neglecting any delay between the time when the seismic wave reached a site and the time when the seiche was first detected. On that basis, the average velocity of the seismic waves that initiated the seiches was 3490 m/s from the epicentre to Falls River Dam and 3440 m/s from Falls River Dam to Seven Mile Dam, with an average of 3470 m/s from the epicentre to Seven Mile Dam.

Assuming that these seismic waves propagated outwards from the epicentre uniformly in all directions, concentric contours of theoretical seiche start times are shown on Figure 2. Of the 14 sites that recorded seiches, seven sites (Sites 3, 6, 7, 10, 12, 13 and 14) match the theoretical time contours within 15 seconds, five (Sites 1, 4, 5, 8 and 11) match within 15 to 60 seconds and two (Sites 2 and 9) differ by

Table 1 – Seiche effects at BC Hydro Dam Sites

EFFECT	SITE	DAM	LAT. (N)	LONG. (W)	EPICENTRAL DISTANCE (km)	START TIME (PST)	MAX. PEAK TO PEAK (cm)	APPROX. DURATION (min)
Seiche recorded	1	Buntzen	49.37	122.86	2163	14:23:30	7	12
	2	Cheakamus	49.98	123.14	2096	14:24:02	4	20
	3	Falls River	53.98	129.73	1471	14:19:23	12	4
	4	John Hart	50.04	125.34	2002	14:22:22	10	5
	5	Ladore	50.01	125.39	2003	14:22:58	10	44
	6	Mica	52.08	118.56	2112	14:22:42	4	28
	7	Peace Canyon	55.98	121.99	1647	14:20:20	6	90
	8	Ruskin	49.20	122.41	2197	14:22:54	5	14
	9	Seton	50.67	121.98	2082	14:25:14	18	300
	10	Seven Mile	49.03	117.50	2427	14:24:00	3	14
	11	Stave Falls	49.23	122.36	2197	14:23:10	7	7
	12	Strathcona	50.00	125.58	1997	14:21:58	5	19
	13	W.A.C. Bennett	56.02	122.20	1634	14:20:14	6	29
	14	Whatshan	49.92	118.12	2316	14:23:42	5	0.2
No seiche	15	Clowhom	49.71	123.54	2105			
	16	Comox	49.64	125.10	2049			
	17	Jordan	48.50	123.99	2200			
	18	Kootenay Canal	49.47	117.47	2385			
	19	La Joie	50.84	122.86	2030			
	20	Puntledge Diversion	49.66	125.09	2048			
	21	Revelstoke	51.05	118.19	2216			
	22	Terzaghi	50.79	122.22	2062			
	23	Wahleach	49.25	121.60	2226			
	24	Wilsey	50.30	118.81	2253			
Insufficient data	25	Aberfeldie	49.50	115.35	2477			
	26	Alouette	49.29	122.49	2186			
	27	Bear Creek	48.50	123.92	2202			
	28	Clayton Falls	52.37	126.81	1731			
	29	Coquitlam	49.35	122.77	2169			
	30	Coursier	50.71	118.10	2249			
	31	Duncan	50.25	116.94	2341			
	32	Elko	49.29	115.10	2507			
	33	Elliott	48.48	124.00	2201			
	34	Elsie	49.46	125.11	2066			
	35	Heber Diversion	49.85	125.95	1996			
	36	Hugh Keenleyside	49.34	117.77	2383			
	37	Quinsam Diversion	49.93	125.52	2006			
	38	Quinsam Storage	49.92	125.55	2005			
	39	Salmon River Diversion	50.10	125.67	1984			
	40	Spillimacheen	50.90	116.43	2308			
	41	Sugar Lake	50.35	118.54	2260			
	42	Walter Hardman Diversion	50.81	118.07	2242			

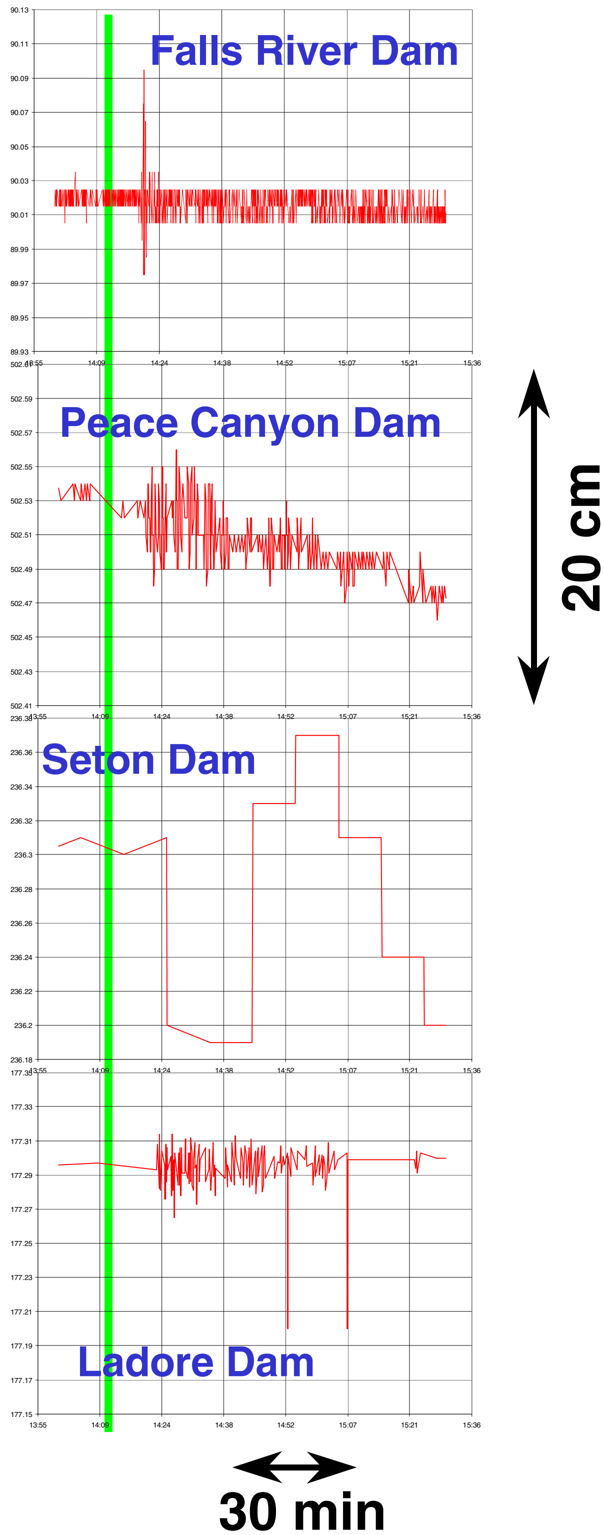

Figure 1 – Seiche time histories recorded at four dam sites. Records are plotted to the same horizontal and vertical scales. The green line indicates the time of the 03 November 2002 Alaska earthquake (14:12:21 PST).

more than 60 seconds. In all cases where is a difference, the actual start time is delayed in comparison with the theoretical time.

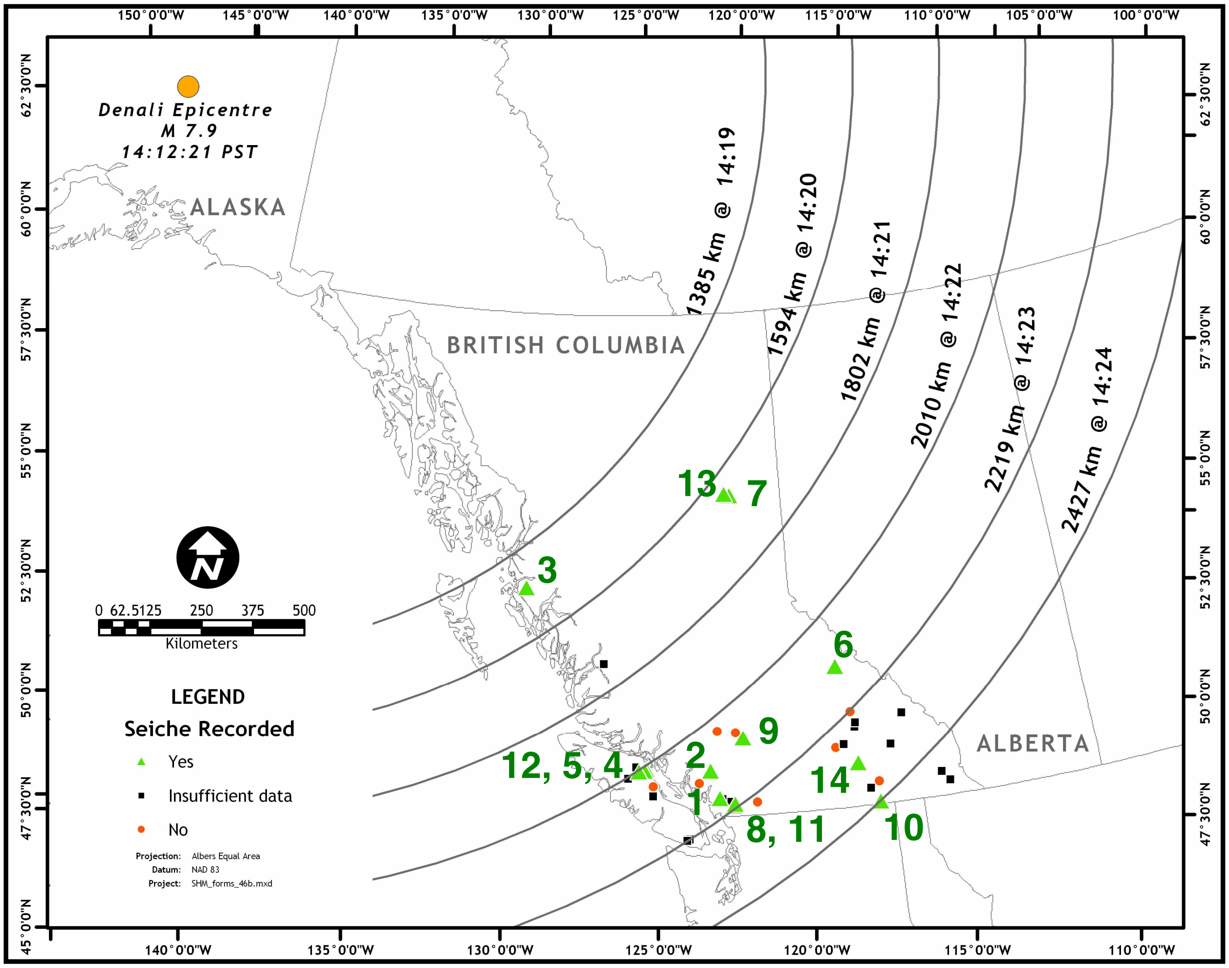

Figure 2 – Locations of dam sites where seiches were recorded. Numbers indicate dam sites listed in Table 1. Contours show theoretical seiche start times based on estimated average seismic wave velocity of 3470 m/s (see text).

The start time of the Seton Lake seiche was almost 3 minutes later than the theoretical start time. The oscillations at Seton Lake were of significantly longer period than those at most other sites and it is possible that the initial oscillation began at a slow rate that did not immediately trigger more frequent archiving of the water level data. Seton Lake also experienced the largest peak-to-peak wave amplitude (18 cm). It is of interest to note that a seiche was also recorded at Seton Lake due to the 1964 M_W 9.2 Alaska earthquake. In the original daily Seton Lake water level records for 1964, there is a note that reads *"As a result of the Alaska earthquake a surge of 0.54 feet (16.5 cm) was recorded in the stilling well at approximately 7:00 pm on 27 March. Observer noted a 3 foot (90 cm) surge on the lake."* The magnitude of the surge measured in 1964 compares closely with the seiche recorded in 2002.

LOCAL EFFECTS AT DAM SITES

Dam Safety Instrumentation

Much of British Columbia experiences significant seasonal climatic cycles, with cold winters and warm summers. Many of the large storage reservoirs are also operated with significant seasonal variations in level that are related to the annual cycles of snowmelt and precipitation.

Dam safety instrumentation installed in many of BC Hydro's dams monitors seepage flows, piezometric conditions and displacements. Instruments are installed both in the dams and their foundations. Individual instruments often respond to seasonal changes in reservoir level, temperature or precipitation, and may also indicate long term trends.

The frequency of readings for an instrument depends on the purpose and the expected behaviour of the feature or parameter being monitored. Many instruments are read manually, with monthly readings being a typical frequency. Displacement and settlement surveys are generally performed annually. Most of the instruments monitored with ADAS or dataloggers are read at scheduled frequencies ranging from several times per hour to daily. For key ADAS instruments, customized software is used to automatically identify readings that fall outside of expected bounds. In some, but not all cases, there is an automated increase in reading frequency for instruments with out-of-bounds readings. All instrument readings, whether manual or ADAS, are archived.

Effects of the 2002 Alaska earthquake were detected at several BC Hydro dam sites as described below. With instrument readings mostly being taken at regularly scheduled times, it was not possible to precisely determine whether there was any delay between the arrival time of the seismic waves and the start times of site-specific effects. However, both short term and long term effects can be clearly identified.

Piezometric Effects

More than 100 changes in piezometric pressures were recorded in the bedrock foundations of several concrete gravity and earthfill dams. Most of the effects were recorded at Peace Canyon, Seven Mile, W.A.C. Bennett and Revelstoke Dams, BC Hydro's four most heavily instrumented dams (Sites 7, 10, 13 and 21 in Table 1). Similar changes or possible changes were noted on a few piezometers in several other dam foundations.

A variety of effects occurred, including both temporary and long term increases and some decreases in piezometric pressures. Some effects occurred rapidly and others developed over time. Several examples are provided below.

W.A.C. Bennett Dam

W.A.C. Bennett Dam is a 183 m high embankment dam founded on a gently dipping sequence of sandstones and shales. Figure 3 shows a cross section of the dam with 13 foundation piezometers that are read four times per day by ADAS. Following the 2002 Alaska earthquake, five of the piezometers recorded increased pressure, and eight recorded no change. One foundation piezometer, FP43, is highlighted and its behaviour over 2002-03 is shown on Figure 4.

FP43 displays an annual variation of about 10 m in piezometric level, which follows the seasonal reservoir cycle. There was an unexplained drop of about 1.5 m in March 2002, followed by a partial recovery. Similar local small changes in piezometric pressures are periodically observed in the foundations of various dams and are thought to be due to local adjustments in stress and piezometric pressures that result from the seasonal changes in reservoir levels. Note that an instrument calibration in August 2003 resulted in a 2.3 m upward adjustment of the pressure.

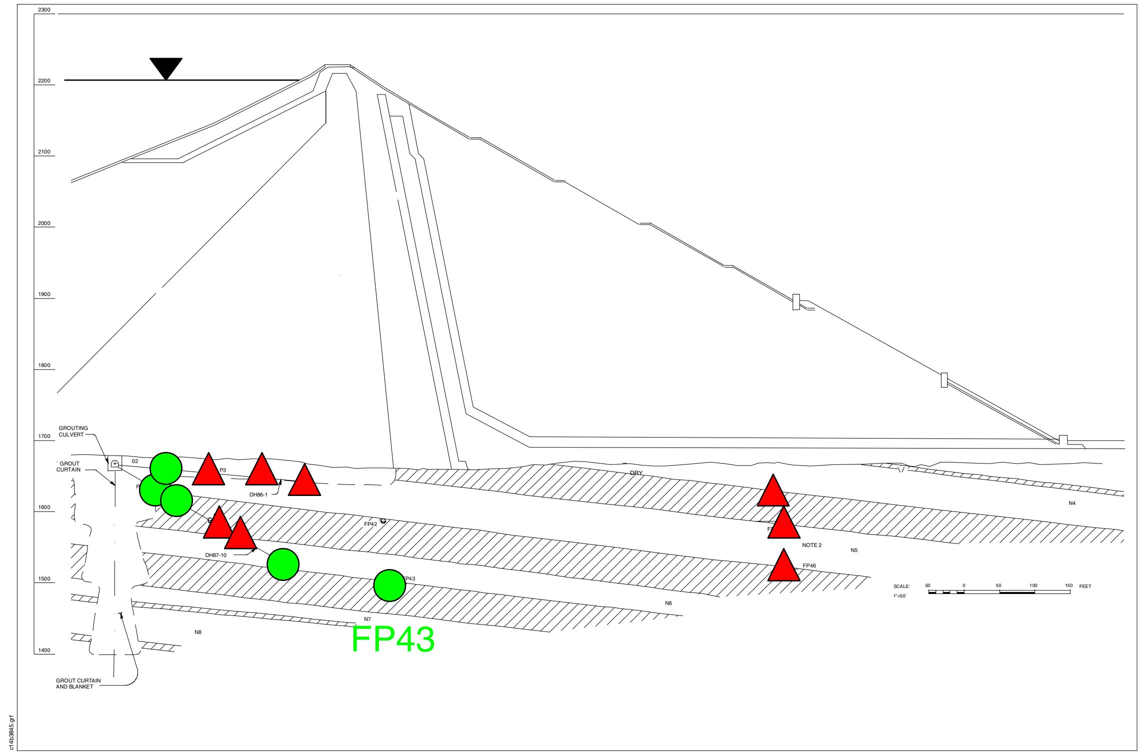

Figure 3 - Cross section of W.A.C. Bennett Dam and its foundation of interbedded sandstones and shales. Green circles indicate foundation piezometers that recorded increased pressure; red triangles indicate piezometers that showed no change in pressure. Data for FP43 are plotted on Figure 4.

Following the 03 November 2002 earthquake, the piezometric pressure at FP43 increased by 1.8 m over a 14-day period. Based on the shape of the piezometric level vs. reservoir level plot (Figure 4), it is estimated that it then took until early to mid-February 2003 for the piezometric pressure to return to its original trend.

Peace Canyon Dam

Peace Canyon Dam is a 61 m high concrete gravity dam founded on a flat-lying sequence of sandstones, siltstones and shales. The dam is operated as a run-of-river project with a relatively constant reservoir level.

Figure 5 shows time history plots since 1996 for two foundation piezometers located in the foundation of one dam block. P12-1 is located about 5 m vertically above P12-2. The piezometers are read manually about six times per year and have historically shown annual cyclic pressure changes in the range of about 0.3 m to 0.6 m. These cycles correspond to seasonal temperature cycles, which cause shrinkage and expansion of the concrete dam, which in turn result in changes in foundation stress conditions.

The readings closest to the time of the earthquake were taken about six weeks prior to and one day after. The earthquake apparently caused rapid increases in pressure of about 1.4 m in P12-1 and 1.0 m in P12-2. The increase in P12-2 pressure appears to be permanent, and that piezometer is again cycling seasonally with a pattern similar to that prior to the earthquake. In contrast, P12-1 pressure has continued to rise steadily and had increased an additional 3.3 m by late 2003.

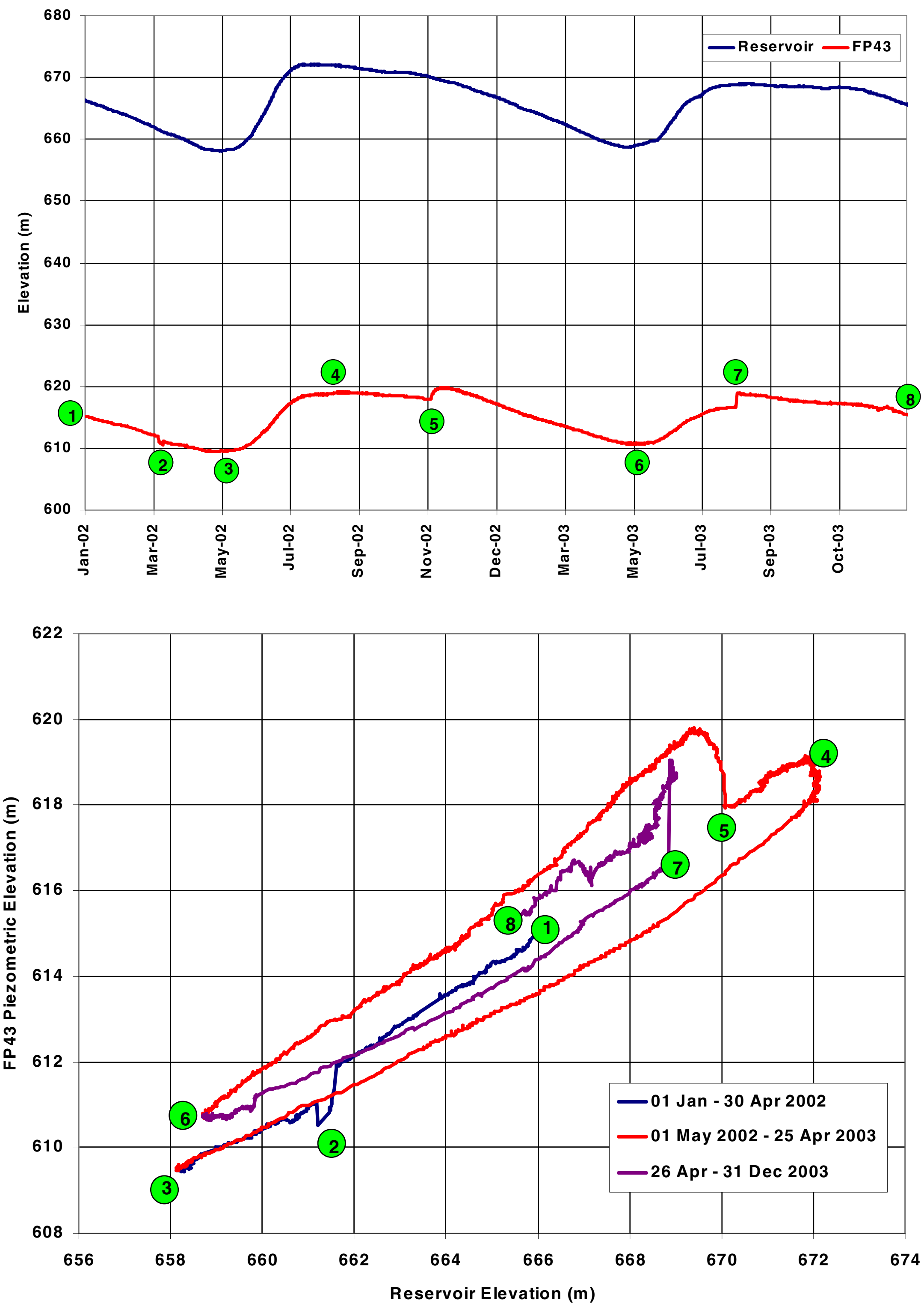

Figure 4 - W.A.C. Bennett Dam foundation piezometer FP43 time history (upper) and piezometric level vs. reservoir level (lower). Numbers are: 1 = 01 Jan 2002; 2 = unexplained (non-earthquake) drop; 3 = 2002 seasonal low; 4 = 2002 seasonal high; 5 = 03 Nov 2002 Alaska earthquake; 6 = 2003 seasonal low; 7 = calibration adjustment; 8 = 31 Dec 2003.

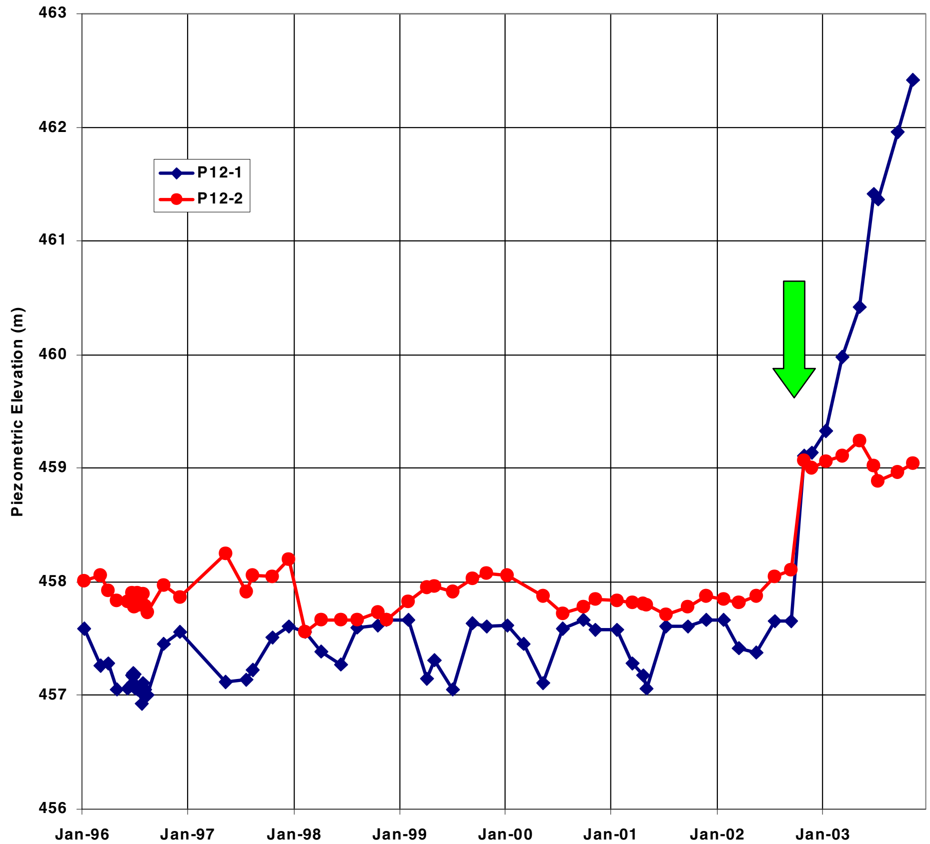

Figure 5 - Peace Canyon Dam foundation piezometers P12-1 and 2. These piezometers are read manually; the symbols indicate individual readings. The green arrow indicates the time of the 03 November 2002 Alaska earthquake.

Revelstoke Dam

The Revelstoke hydroelectric project includes a 175 m high concrete gravity dam and a 125 m high earthfill dam founded on metamorphic rocks, mostly gneiss and quartizite. This facility is another run-of-river project with a relatively constant reservoir level.

Some piezometers in the foundations of both dams reacted to the Alaska earthquake. Figure 6 shows the locations of six piezometers in the foundation of Block R2 of the concrete dam that reacted to the earthquake as shown on Figure 7.

All six piezometers normally show stable levels that vary within a range of about 0.2 m to 0.5 m per year. Following the earthquake, five of the six piezometers recorded drops in pressure ranging from 0.7 m to 2.3 m over a five-day period. Subsequently, one piezometer (ER2432) returned to its original level within about 2 months, and one piezometer (ER2423) recovered only a small amount, then remained steady at a lower level. The other three (ER234R, ER2421 and ER2422) slowly rose in pressure for at least one year and appear to have stabilized at levels that are slightly lower than their pre-earthquake levels.

One piezometer (ER2431) recorded an increase of 0.3 m within one day after the earthquake. Since then, it has been within its typical pre-earthquake operating range.

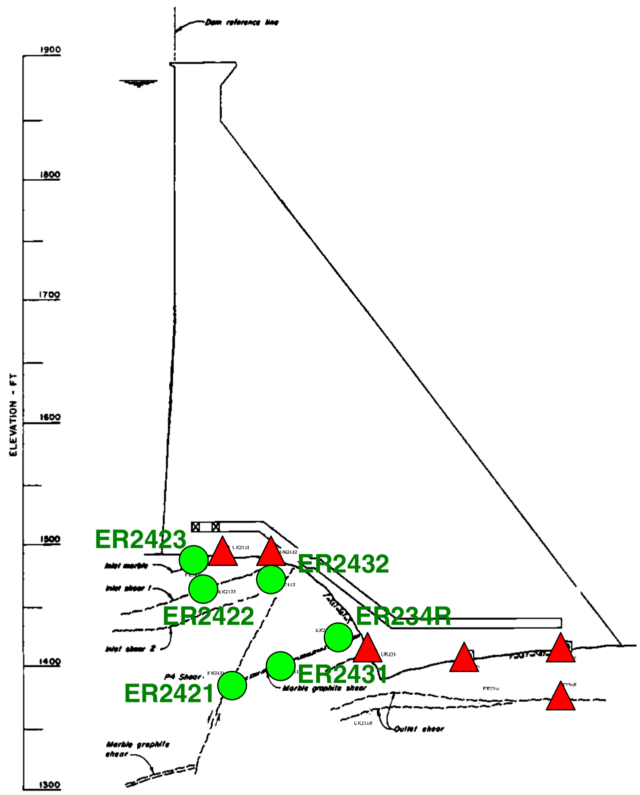

Figure 6 - Cross section of Revelstoke Concrete Dam Block R2. Several shear zones in the metamorphic rock foundation are shown. Green circles indicate foundation piezometers monitored by daily ADAS readings that recorded pressure changes. Red triangles indicate manually-read piezometers for which there are insufficient data to determine whether there was a change in pressure. Data for piezometers indicated by green circles are plotted on Figure 7.

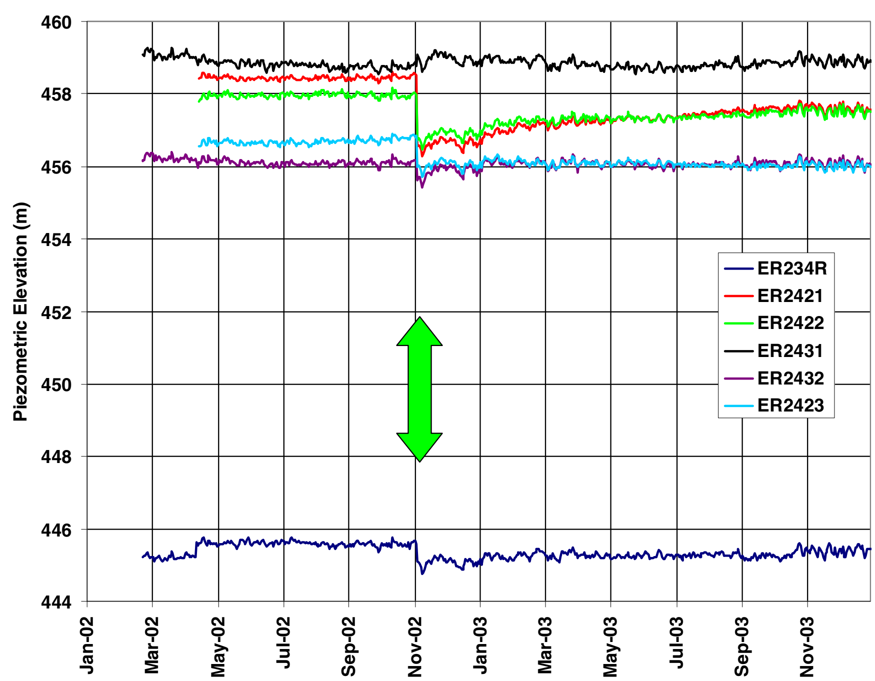

Figure 7 - Revelstoke Concrete Dam Block R2 foundation piezometers, which are read daily by ADAS. The green arrow indicates the time of the 03 November 2002 Alaska earthquake.

Effects on Seepage Flows

Temporary increases in volume of seepage flow were recorded in foundation drainage tunnels at two dams. Similar increases were also recorded in seepage flow from the drainage adits installed in two reservoir shoreline slopes - Downie Slide and Dutchman's Ridge, located upstream of Revelstoke and Mica Dams, respectively. These two sites are located more than 2100 km from the epicentre of the earthquake.

Dutchman's Ridge is a large potential landslide, consisting of a steep mountain slope underlain by a basal shear zone. Stability of the slope has been improved by construction of a drainage system that comprises an adit and numerous drilled drain holes. Seepage flows from the adit typically vary between about 1000 to 3000 litres/minute on an annual cycle (Figure 8) with peak flows corresponding to spring snow melt and runoff conditions. Seepage flows from the drainage adit are read daily by ADAS.

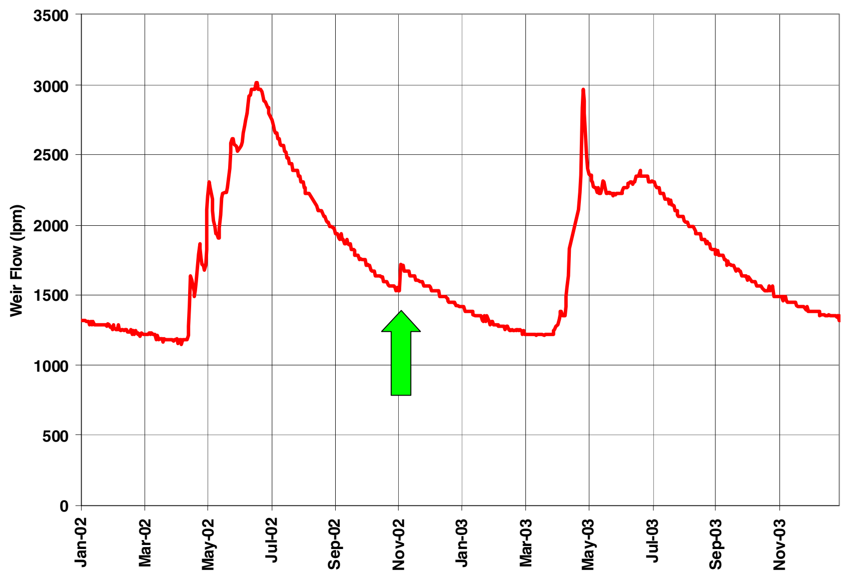

Figure 8 – Seepage flows from the drainage adit at Dutchman's Ridge, a large potential landslide located along the Mica Dam reservoir shoreline. The green arrow indicates the time of the 03 November 2002 Alaska earthquake.

In late 2002, seepage flows were following the seasonal decrease typical for that time of year. The first post-earthquake reading was taken about 10 hours after the earthquake and showed that the seepage flow had increased by 184 litres/minute from the day before (a 12 percent increase). The flow stayed at that elevated level for three days, then began to decrease at approximately the same rate as it had prior to the earthquake. Visual comparison of the seepage trends suggests that the post-earthquake seepage flow remained higher than would be estimated by projecting the pre-earthquake trend, at least until the seasonal low in April 2003.

DISCUSSION

Responses of groundwater and stream flows to distant major earthquakes are well known phenomena. Although not fully understood, the responses are attributed to factors such as deformation of aquifers, dislodging of fracture infillings, fracturing of bedrock and consolidation of soil deposits [3, 4, 5]. Pore pressure responses to earthquakes have even been measured on the deep ocean floor, where they have been attributed to changes in crustal strain [6].

The seiches recorded at 14 BC Hydro dams as a result of the 03 November 2002 Alaska earthquake confirmed that significant coseismic ground displacements occurred across southern British Columbia. Although assessed by a simplified method, the start times of the seiches fit a remarkably consistent pattern that is interpreted to show the propagation rate of long period seismic waves along the length of British Columbia.

It is likely that the characteristics of each seiche were influenced by the orientation and dimensions of the reservoirs, but that aspect was not evaluated in detail. In any case, the seiches were very small in amplitude relative to the sizes of the dams, did not pose a concern to the safety of the dams and are mostly of scientific interest.

The widespread piezometric and seepage effects recorded at several BC Hydro dam sites following the earthquake all occurred in the bedrock foundations of the dams or in bedrock slopes. To date, no effects have been confirmed within the body of any dam.

The variable piezometric responses recorded indicate that a general redistribution of pore water pressures occurred within the near-surface bedrock. There is no reason to believe that the responses recorded in the dam foundations did not occur throughout the entire region. Widespread changes in bedrock fracture apertures induced by coseismic ground displacements and crustal strain changes could account for such effects, although no attempt has yet been made to evaluate this hypothesis.

None of the measured piezometric effects were of sufficient magnitude to be of concern to the stability or safety of the dams. In fact, many of the induced piezometric pressure changes were less than the cyclic ranges of pressures that normally occur each year. However, the continued increase in pressure still being recorded by a few instruments indicates that ongoing monitoring is required. Similar effects likely occurred at other dams with no instruments or with manually-read instrumentation, however, the less frequent readings taken at those sites do not provide sufficient data to confirm such effects.

Seismic design for dams usually focuses on the effects of strong ground motions on dam stability. This case history highlights the potential for large magnitude earthquakes to cause significant piezometric effects in dam foundations that can be difficult to predict or detect without suitable instrumentation. In this example, piezometric effects were recorded in dam foundations at epicentral distances of about 1600 km to 2400 km. It is possible that more significant piezometric effects could be experienced closer to an earthquake.

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