Monitoring Report 2020

West Quesnel Land Stability Program
Quesnel, BC
Project # KX0439755

Prepared for:

City of Quesnel
410 Kinchant Street Quesnel, BC V2J 7J5

06/10/2021

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1.0 Introduction

Wood Environment & Infrastructure Solutions (Wood), a Division of Wood Canada Limited (formerly Amec Foster Wheeler) has carried out instrumentation monitoring in West Quesnel as part of the ongoing West Quesnel Land Stability Program. The purpose of the instrumentation monitoring is to track landslide related ground movement, groundwater conditions and precipitation. The monitoring is also used to assess the effectiveness of dewatering programs that have been implemented by the City of Quesnel in 2012 (Phase I) and 2016 (Phase II).

Several sets of Global Positioning System (GPS) ground surface movement hubs have been established in the field and surveyed between 1998 and 2020. Between 2000 and 2007, Amec Foster Wheeler installed geotechnical instrumentation including slope inclinometers and piezometers. Additional instrumentation, including slope inclinometers, piezometers, flow meters and precipitation measurement equipment was installed in 2012 and 2016 in conjunction with the construction of the various phases of pumping wells, horizontal drains and storm drainage.

For detailed background information including geology and project history, the reader is referred to previous Amec Foster Wheeler reports, including our previous annual monitoring reports, the "2012 Subsurface Dewatering System" report dated 21 November 2014, the "Trial Dewatering” report dated May 2008, and the "West Quesnel Land Stability Study" report dated May 2007.

During 2016 a program involving storm drainage, horizontal drain and pumping well construction along with reconfiguration and addition to some of the geotechnical instrumentation was carried out in the West Quesnel area. Some of those works involved temporary disruption or changes to pre-existing instrumentation, and in some cases may have influenced data collection as the new Phase II drainage measures (and related instrumentation) were only gradually brought into service during the latter half of 2016 and early 2017.

During 2018, several of the instrumentation data collection stations experienced communications issues which resulted in data gaps that occurred generally between late spring and mid summer of 2018. In 2018, a program of decommissioning previously sheared slope inclinometer casing and an abandoned pumping well PW10 was completed. Pumping well PW25 was also cleaned.

In 2019, slope inclinometer SI17 was decommissioned and replaced by SI17a. Pumping wells PW5 and PW24 were also cleaned, however not reactivated.

In 2020, pumping wells PW5 and PW24 were reactivated and instrument data logging Station 3 was moved and updated due to school parking lot construction activities. Slope inclinometer installation SI16 failed and several deep VWP sensors failed.

This report summarizes monitoring data collected during 2020 and provides an update on observed trends or interpretations that have developed or changed since our 2018 and 2019 Monitoring Report, dated 21 July 2020.

2.0 GPS Movement Hubs

Beginning in September 1998, FortisBC (formerly Terasen Gas and BC Gas) installed and monitored a series of GPS surface movement hubs. Subsequently, in 2001, 2006 and 2008, the GPS hub network was expanded and modified such that a current total of up to 47 hubs have been monitored. The monitoring consisted of comparing changes in the specific positions of the defined survey reference points over time as measured periodically by survey contractors (most recently McElhanney Consultants Limited), retained by both FortisBC and Wood on behalf of the City of Quesnel. Surveys are typically conducted on a quarterly basis with the results forwarded to us for inclusion in the monitoring program. In 2011 Fortis arranged for installation of some additional closely spaced GPS hubs in a small part of West Quesnel that are monitored annually in conjunction with UBC for a research project. These hubs are not generally monitored as part of the West Quesnel Land Stability Program and are not reported on herein.

During 2020, semi-annual GPS monitoring was carried out in June and December for the GPS hubs established in 1998, 2001, 2006, and 2008 and for one replacement location (GPS Hub 13-02) established in 2013.

A summary table and detailed individual plots of movements for all GPS hubs are provided in Appendix A. Please note that while both horizontal and vertical movement data is recorded, typically vertical GPS survey data has at least one order of magnitude lower accuracy than the horizontal data. Accordingly, while there are some general trends that can be observed regarding vertical and/or the resultant of both horizontal and vertical movement, the following discussion refers primarily to horizontal movement information.

The locations of the various GPS hubs monitored for the West Quesnel Land Stability Program are depicted on Figure 1. Figure 1 also provides a simplified vector movement plot for GPS hubs monitored in the West Quesnel area. The GPS vector plots in Figure 1 show relative magnitude and azimuth of the latest total horizontal movement vectors. Intermediate movements are approximated. Details for individual GPS movement hubs and intermediate movement vectors are provided in Appendix A.

The GPS movement hubs can be separated into four general categories based upon their location and displacement. The first category represents benchmark hubs, which are used to provide reference control for the survey. These benchmarks are theoretically located outside the landslide area on stable ground and have recorded little, if any, movement since installation. The exceptions to this are survey tolerance variations that may suggest no or minor movement (typically less than 15 mm of total horizontal movement over the length of time the surveying has been conducted with no discernible consistent directional trend). While there have been as many as eight benchmark hubs installed, typically only three (Water Tank, GPS 01-38, and GPS 98-23) have been utilized to gauge the accuracy of the obtained survey data. Note that due to construction and replacement of the water tank a control point (Water Tank 3) was added in 2017.

The second category consists of twelve hubs that are at or near the eastern extremity of the study area and are used to define the approximate toe area or likely eastern boundary of active landslide movement. Generally, cumulative total horizontal displacement less than 20 to 25 mm is interpreted to mean that the location is beyond the active movement toe area. This is especially true if there is no long term consistent directional trend observed in successive measurements. Higher values suggest that the hub is on or very near the toe of the slide, more so if there is a consistently observed easterly trend in successive measurements.

The third category consists of two hubs that are located at or near the upper west portion of the study area, which were placed to assist in defining the western extent or crest of landslide. Similar to the toe area, where total horizontal displacement less than 20-25 mm and a lack of consistent directional movement of the hubs has occurred, they have been considered as being outside the area of active landslide movement.

The fourth category comprises 30 GPS hubs that are interpreted to be within the main body of the landslide. These hubs have shown continuing cumulative displacement and consistent directionality of movement (easterly or north-easterly) over the course of the 21 years that the 15 oldest hubs have been monitored. The total horizontal movement measured between September 1998 and December 2019 for the 15 oldest hubs, ranged from 296 to 721 mm, depending on location.

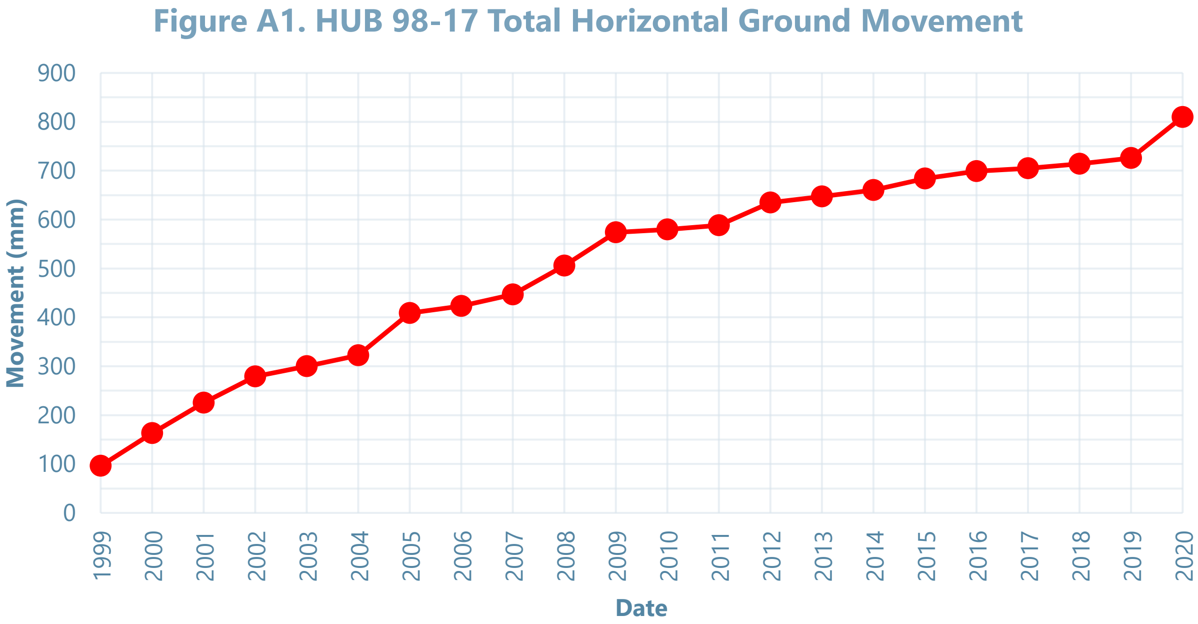
Table 1 below, presents cumulative, annual, and peak rate horizontal movement data for GPS Hub 98-17 since 1998. GPS Hub 98-17 is considered as being a representative but essentially 'worst-case' monitoring location near the middle of the study area. Figure A1 (duplicated from Appendix A) graphically shows the pattern of cumulative annual horizontal movement data presented in Table 1. Prior to 2013, the long-term average horizontal movement detected was in the order of 44 mm per year. Movements in excess of average were detected in eight of the 14 years of monitoring prior to 2013, while there were six years of significantly less than average movements (e.g. less than 25 mm/year). The lower movement years have generally been attributed to three periods of unusually low precipitation extending over successive years, while the higher movement years have been generally correlated with periods of above average precipitation. Between 2013 to the end of 2019, average yearly horizontal displacements were around 13 mm per year, with the lowest displacement of 6 mm measured in 2017 and with the highest displacement of 24 mm measured in 2015. However, in 2020 83 mm of horizontal displacement was measured at Hub 98-17. To date that is the second highest yearly displacement that has been measured since the inception of the GPS hub monitoring.

Table 1. Typical Horizontal Movement (from GPS Hub 98-17) from 1998 to 2020

Year	Cumulative Movement (mm)	Annual Movement Rate (mm/yr)	Peak Movement Rate (mm/yr)[1]
1998	16[2]	n/a[2]	66
1999	96	80	115
2000	163	67	110
2001	225	62	75
2002	279	54	83
2003	300	21	23
2004	322	22	22
2005	409	87	75
2006	423	14	75
2007	447	24	43
2008	506	59	160
2009	574	68	216
2010	580	6	56
2011	588	8	107
2012	635	47	93
2013	647	12	38
2014	660	13	39
2015	684	24	53
2016	699	14	92
2017	705	6	20
2018	714	9	N/A
2019	726	12	N/A
2020	810	84	N/A

Note(s)

1. Peak movement rate typically observed during the spring, as the frequency of GPS hub monitoring changed in 2018 it is not representative to report the short term peak movement rate
2. GPS Hub initialized in September 1998



Figures 2 through 34 show contour plots of total and annual GPS hub movement data selected over different time periods (which also means that only hubs active during the entire time period are included in the contour plotting) and for different components (i.e. horizontal movement, vertical movement and resultant total three-dimensional (3D) movement). Historical ground movement contours (Figures 7 through 20) were drawn using triangulation in AutoCAD Civil 3D (2013); while the relative 2014 through 2020 ground movement contours (Figures 2 through 6, and 21 to 34) were triangulated in ArcGIS (version 10.3 for Desktop). Please note that these are simplified contour plots, and that not all the cumulative movements are necessarily in the same vector direction.

Figure 2 shows total horizontal movement between September 1998 and December 2020, for the GPS hubs installed in September 1998. Significant movement has been observed at the GPS hubs within the slide mass since 1998. A total horizontal movement of 810 mm has been detected at GPS Hub 98-17 (corner of Bettcher St. and Lark Ave.) since the inception of GPS monitoring.

Figure 3 shows total horizontal movement between December 2001 and December 2020, for the GPS hubs installed in September 1998 and December 2001.

Figure 4 shows total horizontal movement between November 2006 and December 2020, for the GPS hubs installed in September 1998, December 2001 and November 2006. Figures 2, 3, and 4 show that the greatest horizontal movement observed since 1998 has generally occurred in the middle and near the northern boundary of the slide area.

Figure 5 shows total vertical movement between November 2006 and December 2020. This contour plot shows generally downwards movement along the upper, north and west edges of the slide (typically near the scarp area, although it should be noted that there are very few hubs in this area to properly define the scarp area separately from the main body of the slide). There were also some observed upwards movement trends (thrusting/bulging) near the toe of the slide. A significant bulge related to toe thrust movements of the slide has been detected on Lewis Drive, just east of Healy Street.

Figure 6 shows total 3D movement between November 2006 and December 2020. As in Figure 4, the largest movements have generally been observed in the middle and near the northern boundary of the slide area.

Figures 7 through 34 show annual horizontal movement and annual 3D movement respectively for the years 2007 through 2020 (two figures per year). In 2020, significant movement was observed throughout the landslide area. Ignoring the GPS Hubs located outside the active landslide area, an average horizontal movement of 54 mm and 3D movement of 57 mm was observed, with the highest horizontal and 3D movements of 101 mm and 108 mm respectively observed at GPS98-06.

The differences in annual movements between the relatively low activity years of 2007, 2010, and 2011 as compared to higher movement years of 2008, 2009, 2012 and 2020 are judged to be mainly attributable to differences in annual precipitation that influenced the groundwater pressures within the landslide area. There also appears to be a cumulative precipitation effect that further contributes to annual movements.

Beginning in the second half of 2012 the effects of the subsurface dewatering have been a significant contributing factor to the reduced movements relative to precipitation observed for 2013 through 2019 (see Section 7.0 for more details on precipitation data and Section 8.0 for a discussion on the relationships between precipitation, groundwater pressures and ground movement).

3.0 Slope Inclinometers

A total of 15 slope inclinometer (SI) casings were installed by Wood in West Quesnel, between November 2000 and August 2006, to monitor depths and rates of subsurface lateral ground movements. Installation details and the results of previous SI monitoring on the original fifteen SI's are described in previous Amec Foster Wheeler reports. In mid-2009, it was noted that all of these slope inclinometers except SI8 and SI11 had been sheared off as a result of the continued ground movement.

In November 2018, to accommodate the revised BC Groundwater Protection Regulation 152/2016 a decommissioning program was completed by Westech Drilling Corp., monitored by a Wood representative. All previously sheared SI installations installed between November 2000 and August 2006 were decommissioned. Please refer to the 2018 and 2019 Monitoring Report, dated 21 July 2020 for additional decommissioning details.

In 2012, as part of the monitoring package for the Phase I dewatering program, two real time in-place slope inclinometer (IPI) strings were installed across the approximate depths of previously detected sub-surface landslide failure surfaces. These in-place inclinometers allow determination of subsurface lateral displacement in real time. The real time data allows for the most accurate correlation between movement, water infiltration and the dewatering activities. Real time data collection for these instruments, SI16 and SI17, commenced 20 September 2012 and 16 October 2012 respectively. Prior to installing the IPI's, manual baseline SI survey measurements were also performed. In mid-2016 a third real time IPI (SI18) was installed as part of Phase II of the West Quesnel dewatering works. Real time data collection of SI18 commenced in mid-2017. The locations of the installed IPI's and their associated displacement magnitude and direction are shown on Figure 1.

In early fall 2018, it was noted that SI17 was displaying very irregular readings across most of the sensors, and in late 2019 it was decommissioned, using the same decommissioning procedure described above. SI17 was replaced by SI17a in an immediately adjacent location.

In late 2019, it was noted that SI16 was starting to have irregular readings indicating that the sensors were approaching end of life. These readings continued to be irregular through out 2020, however some of the sensors did seem to provide representative data. On 8 November 2020, the entire SI16 sensor array failed. The highest displacement, SI16D sensor, of 84.8 mm was observed on 14 July 2020.

In late spring 2020 at SI18, a significant movement direction change was noted. Prior to late spring 2020, the movement direction was generally trending east to northeast, similar to the GPS Hubs in the area. However post spring of 2020, the movement direction was observed to be trending towards south to southwest. This change in movement direction is peculiar and is possibly a result of an instrumentation orientation/wiring issue. The instrument is scheduled to be checked in the upcoming year.

The collected IPI sensor displacement data is presented in Appendix B. The data associated with the plots depicting the IPI displacement presented in Appendix B has been automatically collected utilizing Wood's web-based data management system, custom developed for the West Quesnel Land Stability Program. Although the IPI's provide continuous real time movement detection, only the average daily horizontal ground displacement at specific depths along each IPI sensor string is presented on the Appendix B plots.

Between the 2012 installation and the beginning of 2014, the SI16 and SI17 IPI sensors detected similar small movement events, with SI16 showing an additional event prior to SI17 being initialized (20 - 22 September 2012). The four events occurred on 17-18 October 2012, 3-7 January 2013, 29 April – 7 May 2013, and 19-22 December 2013. SI16 moved a total of 12 mm over this time frame with individual event movements of approximately 1.5 mm, 1.5 mm, 3 mm, 5 mm, and 1 mm respectively. SI17 moved a total of 15 mm with individual event movements of approximately 2 mm, 4 mm, 6 mm and 3 mm respectively. Typically, the movements were observed to be relatively short events; however, creep like movements were also observed at SI17 between the two major movement events (7 January through 29 April 2013).

In 2014, a total of 7 mm and 8 mm of movement was observed for SI16 and SI17, respectively. The movement occurred in two distinct movement events: 20-25 April, and 26 May – 11 June. The April event had an approximate relative movement of 3 mm for both SI16 and SI17, while the May-June event had an approximate relative movement of 4 mm and 5 mm for SI16 and SI17, respectively.

The total 2015 movement for SI16 was on the order of 25 mm. SI17 recorded a total movement of approximately 14 mm before its failure in April. A larger than average movement event was noted at SI16 between 10 March and 15 May, with a total of 18 mm of movement. The beginning of this movement event was also noted at SI17 before the instrument began to malfunction. Additional smaller movements of 2 mm and 1 mm were noted on 7-23 February and 31 July – 22 August respectively, at SI16. In addition, 4 mm of creep movement occurred between approximately 14 September and the end of 2015 at SI16.

During 2016, total movements on the order of 8 mm and 10 mm were observed at SI16 and SI17, respectively. The movements occurred in five distinct movement events at SI16: 7-10 March, 22-27 April, 22-28 July, 27-30 November, and 13-20 December. Individual event movements in SI16 were small (from 0.5 to 1.5 mm each) however there was also about 2 mm of creep movement throughout the year not associated with any specific event. The SI17 sensor string had not been reinstalled until after the first 2016 movement event was detected in SI16, but it did record the three distinct movement events on 22-27 April, 22-28 July, and 27-30 November of 2016. Movements recorded for each event were slightly greater at SI17, being approximately 4 mm, 3 mm and 2 mm respectively.

In 2017, only three small movements in the order of approximately 1 mm each were detected between late March and mid-May at SI16 and SI17. SI17 and SI18 indicated a movement event on the order of 1 mm in October 2017, and a 0.5 mm movement event at SI18 in late December.

In 2018, SI16 showed a net 5 mm inverse movement or relaxation over the course of the year, however two positive slide type movement events were noted. A 0.5 mm movement was observed between 25 and 31 May, and a 1.4 mm creep movement was observed between 7 and 31 December. Total movements on the order of approximately 8 mm were observed at SI17 (prior to failure on August 31) and at SI18. Three distinct movement events were observed at SI17 consisting of: a 2 mm movement event between 16 and 18 March, a 0.5 mm movement event between 23 and 31 May, and an approximately 1.5 mm event that started on 28 August. In addition to the distinct movement events, a 4 mm creep movement was observed, between 1 July and 28 August. Three distinct movement events were also observed at SI18 consisting of: 1.5 mm between 16 and 20 March, 2 mm between 3 and 13 April, and 2.5 mm between 14 and 25 November. Between April 25 and October 29th there was a communication error with the data logger for this station that resulted in data loss. Based on SI16 and SI17 movement events, it is likely that another 2 mm of movement occurred at SI18 in early to mid-May.

In 2019, total movements on the order of 8.5 mm and 4.5 mm were observed at SI16 and SI18, respectively. SI17 failed in 2018 and was not replaced by SI17a until late 2019. SI17a did not detect any movement in 2019. The majority of the movement observed at SI16 occurred between March 17 and May 8. During this period four distinct movement events and four creep movements were observed totalling 8 mm of movement. A distinct movement event of 0.5 mm was also observed between 19 and 23 November. In addition to the distinct and major movement events creep like movement (positive and inverse) were also observed throughout the year with no overall change. On 25 November, the SI16A and SI16B sensors recorded a significant inverse movement. This movement is not consistent with other sensors and is an indication that this sensor may no longer be reliable. At SI18, movement events observed in 2019 consisted of two distinct and two creep like movement events. A 0.5 mm movement was observed between 7 and 10 January, and a 2 mm movement event was observed between 30 March and

6 April. Creep like movement (positive and inverse) with no net change was observed between 2 February and 30 March, and a 2 mm creep like movement was observed between 6 April and 31 December.

In 2020, total movements on the order of approximately 25 mm, 53.5 mm and 60 mm were observed at SI16 (highest, prior to failure), SI17a and SI18, respectively. All the movement at SI16 was observed between 13 April and 20 May (13.5 mm) and between 10 June and 14 July (11.5 mm). The majority of the movement (37 mm) observed at SI17a occurred between 9 April and 9 June with a relatively consistent movement rate of 0.6 mm/day, and between 6 May and 29 July (37 mm) at SI18 with a relatively consistent movement rate of 0.44 mm/day. In addition to the large movement events noted above at SI17a and SI18, there were several distinct and creep like movement events observed. At SI17a, four distinct movement events were observed: in early January (1.5 mm), in early August (3 mm), mid October (4.5 mm) and late October (2 mm); with three creep like events that occurred between mid January to late March (4 mm), between mid June to late July (3.5 mm) and between early November to the end of 2020 (inverse 2 mm). At SI18 (under review), there were four distinct movement events observed: in early August (3 mm), mid August (2 mm), in mid September (2 mm) and in mid October (3 mm); a creep like movement was observed between late October to the end of 2020 (13 mm).

In general, there is a strong correlation between the ground movement data collected through surface GPS hub monitoring and the subsurface IPI sensors (with the possible exception of SI18 currently under review), however like GPS hub movements, subsurface IPI movements vary between locations. Figure 1 depicts ground movement observations from the IPI sensor measurements.

4.0 Piezometers

Two general types of piezometers (with three different installation configurations) have been utilized in West Quesnel to monitor groundwater pressures in the vicinity of the landslide area. The predominant type of piezometer used in West Quesnel is a vibrating wire piezometer (VWP), which is an electronic water pressure sensing device that is installed directly in the ground via grouting in a borehole, to continually and remotely detect and obtain a record of groundwater pressure over time. VWPs measure water pressure acting at the specific depth of its tip and can provide a rapid response to a change in ambient pressure. A number of retrofit installations have also been created where vibrating wire piezometer sensors were suspended inside open pipes (standpipes or well casings) for automated electronic detection of water pressures. Figure 35 depicts the locations for the various groundwater instruments and their related data logger stations.

The second type of installed piezometer at the site is a standpipe, which generally consists of a vertical pipe (plastic or steel) with openings (slots or screens) at depth that admit groundwater from the surrounding horizon where the screen is placed. The slotted screen sections of the standpipe piezometers are typically surrounded by a sand pack and have a bentonite seal both below and above the sand pack. Water pressures were historically measured manually using a water level dip tape, but these readings were discontinued at the end of 2012 as this information was more readily available with the addition of the automated VWPs installed during the 2012 full scale subsurface dewatering program.

Four standpipes have since been retrofitted with vibrating wire piezometer transducers installed inside the standpipes (VWP 3A/B and VWP 4A/B). A total of 48 vibrating wire piezometers were grouted directly in the ground to various depths at 21 different locations during the trial dewatering program prior to 2008. An additional 32 vibrating wire piezometers were grouted in at 14 new locations during the 2012 Phase I dewatering program. An additional nine vibrating wire piezometers were installed at six new locations during the Phase II dewatering program in 2016, bringing the installed total to 93 vibrating wire piezometer instruments. However, some of these instruments have been damaged or become dysfunctional (or dry) over time. In 2020, four previously active instruments, VWP17B, VWP28B, VWP29B and VWP34C failed in mid to late spring. As of the end of 2020, there were 81 active, 5 failed and 6 dry vibrating wire piezometers. The locations of the boreholes in which the various piezometers are installed is shown on Figure 35.

All of the vibrating wire piezometer sensors are connected to Campbell Scientific data loggers (stations). These data loggers are used to automatically record sensor water pressures at set intervals and can store large quantities of data. Studies have shown that barometric pressure changes impact VWP readings[1]. Thus, all collected VWP readings have been corrected using readings from a barometer installed in data logger Station 2. The Campbell Scientific data loggers are connected to cellular modems, such that near real time data can be collected and accessed remotely by Wood staff.

A summary table listing the various piezometers, along with their groundwater pressures (phreatic surface elevation plots) can be found in Appendix C. Depending on the location of the piezometers, they depict various short and long-term groundwater pressure conditions within the West Quesnel area. Some near surface installations are more sensitive to seasonal precipitation trends, short-term weather events and potential water service line breaks, particularly if they are installed in shallow sands or gravels. Deeper installations tend to show longer term background trends with subdued seasonal response indicative of larger scale, more regional groundwater conditions. Some of the piezometers show the effects of nearby dewatering installations (pumping wells and horizontal drains).

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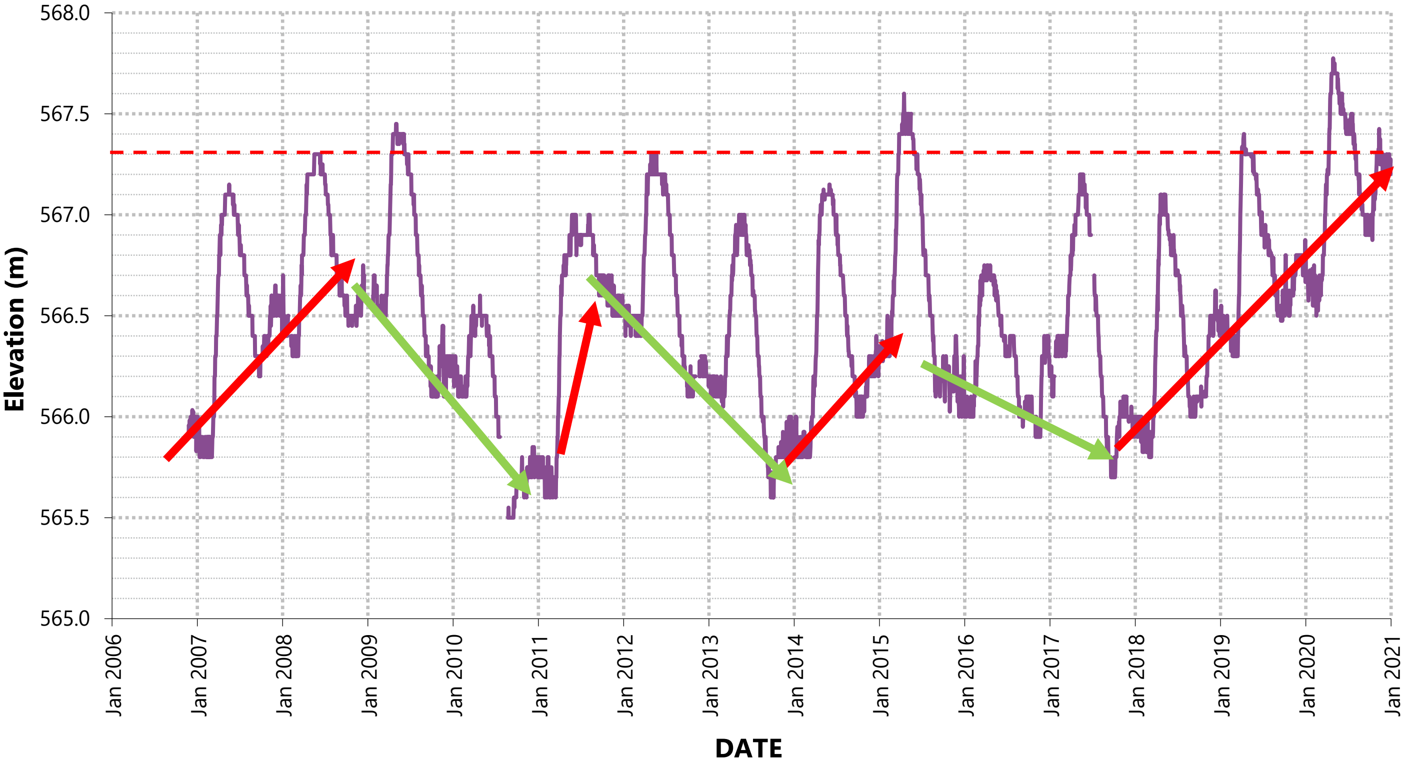
[1] Contreras, I.A., Grosser, A.T., Ver-Strate, R.H; 2012,"Update of the Fully-grouted Method for Piezometer Installations". Geotechnical News, Volume 30, No. 2., June 2012, www.geotechnicalnews.com/instrumentation_news.php

Table C1 (Background Piezometers), in Appendix C, presents the individual trends and observations from 2020 for piezometer locations that were judged to be unlikely to have been affected by the dewatering efforts, and are more reflective of general background subsurface groundwater patterns in the West Quesnel study area. At some of the near surface piezometers, temporary increases in response to seasonal precipitation and freshet have been observed. In addition to the seasonal temporary increases there appears to be some secondary fluctuations, typically observed over the fall-winter months. The seasonal increases are predominantly dependent on relatively short-term weather influences while the general trends are more dependent on long-term weather patterns and also the ability and capacity of the area to drain and/or retain groundwater. Although similar pore pressure observations can be made for most of the near surface piezometers, VWP14A is considered typical of background conditions and is plotted in Figure 4.1. While the influence of typical annual freshets is clearly indicated, the plot also indicates gradual trends in base and peak conditions over the years. Most notable is a recent sustained rise in both base and peak groundwater elevations since 2018, suggesting a longer-term climate influence creating higher natural groundwater conditions over that time.

Figure 4.1: VWP 14A



At VWP39, atypical pore pressures have also been observed since 2018. Pore pressure spikes of approximately 4 m, 3.5 m and 1.5 m have been observed in 2018, 2019 and 2020 respectively without any significant post freshet dissipation. The general overall increasing trend is similar to that observed at VWP14A, however relatively recent clearing and regrading of a nearby upslope property may be contributing to some of the observed pattern through a potential change in groundwater infiltration.

Table C2 (Piezometers Near Pumping Wells), in Appendix C, presents overall trends and observations for piezometers that are situated near the pumping wells and may have been influenced by them. The piezometers nearest the pumping wells and closer to surface have experienced the greatest influence (decrease in groundwater pressure) since pumping started and many have reached a new steady-state pressure, depending on how productive and what the radius of influence of the well has been. Piezometers that have groundwater pressures remaining at steady state (with or without seasonal influences) are likely out of the radius of influence of the well or are too deep to be influenced. Some of the piezometers influenced by the pumping wells are also still reactive to seasonal precipitation. Generally, for this set of piezometers, in 2020 there was an increase noted relative to 2019 and previous years. In late 2019, there was a temporary localized groundwater pressure increase noted in VWP9B and VWP9C that corresponded with the drill installation for SI17a. In 2020, pore pressure dissipation resumed, however the pore pressures have not returned to pre-installation levels. Some instrument locations still indicated slight influences from seasonal or storm events.

Table C3 (Piezometers Near Horizontal Drains), in Appendix C, presents the overall trends and observations from 2020 for piezometers situated above or near the horizontal drain (HD) installations. These piezometers have generally been at a steady state since initial drawdowns in 2012 when the majority of the horizontal drains were installed. Several of the instruments also exhibit regular variation patterns in reaction to seasonal weather and precipitation conditions.

The plots depicting the groundwater elevations found in Appendix C have been generated, utilizing Woods's data management system, custom developed for the West Quesnel Land Stability Program. The average daily groundwater elevation (phreatic surface) is presented in the plots. However, in order to allow practical plotting of the instrument data, digital filters were utilized to remove some erroneous data points, and to smooth or bridge data gaps.

In general, historic groundwater pressures within the West Quesnel area have been generally quite high relative to the ground surface, and thus detrimental to slope stability. In 2020, there was a general increase in pore pressures observed in the vicinity of the horizontal drains, with some short-term more significant seasonal groundwater increases. While the groundwater levels are still generally below the pre-HD Drain installation elevations there is a gradual rising trend, indicating that although the dewatering system is working, the effectiveness of the dewatering system is reduced during high precipitation (wet) years. Figure 36 is a simplified graphic showing the estimated groundwater drawdown at the end of 2020 relative to what was inferred to be natural background elevations just prior to the implementation of the subsurface dewatering system.

5.0 Pumping Wells

Prior to 2012, there were four pumping wells (PW) installed in West Quesnel. PW1 and PW2 were installed in 2003 and PW4 and PW5 were installed in 2007 as part of previous trial groundwater dewatering assessment studies. As part of the 2012 Phase I subsurface dewatering program, 14 new potential pumping well locations (PW6 through PW19) were drilled and pumps were installed at 13 of the locations (potential well PW10 was dry upon completion so no pump was installed). Though the pumps were installed and tested during the latter part of 2012, they were not fully activated until April 2013. As part of the Phase II dewatering works, six new wells (PW20 through PW25) were drilled and pumps installed during 2016, bringing the total number of installed and instrumented pumping well sites in West Quesnel to 23. Figure 35 shows the locations of the pumping wells.

A summary table of the well installation details, along with charts of well water elevations and production rates since installation are presented in Appendix D. The plots depicting the pumping well levels and production rates have been generated, utilizing Wood's data management system, custom developed for the West Quesnel Land Stability Program. The pumping well flow measurements were collected on an hourly basis and summed to establish a daily flow rate. Water well elevations presented are average daily values with digital filtering to remove erroneous readings.

In 2020, an estimated 123 million liters was removed by the pumping wells. This represents the highest annual well production, and almost 30% of overall pumping well production since inception of the dewatering program. Close to 100 million liters were removed by PW24 and PW25. Increased production relative to 2019 was observed in most of the wells. Of note, a significant production increase was observed at PW9 and it was the third highest producer in 2020, removing over 7 million liters, compared to just over 4 million in 2019, and only 0.6 million liters in the 2013.

In 2020, the operation of the wells was generally good, however there were some notable issues observed that impacted dewatering efforts. PW1 operation was interrupted in late 2019 and was not restarted until end of January 2020. PW5 was replaced and restarted in early May 2020. PW6, PW7 and PW8 controlled by Station 4, experienced programming issues and pumping well operations were impacted between mid March through early May 2020. In addition, PW6 had further control issues between mid October through late November, and the issue has still not been resolved. From early October to year end, operation of PW20 was noted to have been impacted and the pumping rates have been reduced. The cause of this impact is currently unknown but is likely associated with subsurface movements. Operation of PW21 in 2020 was not consistent and is currently being optimized. PW21 was noted to be off line during January 2020 and for most of the period between late April and mid July. Operation of PW23 was optimized in mid February. Operation of PW24 and PW25 continue to present a challenge. PW24 was operational approximately 70% of the time, and additional optimization is required. Although PW25 was primarily in operation throughout the entire year, there was a significant interference being observed by the controlling VWP level, and additional optimization is required.

Overall, more than 415 million litres of water has been removed by all wells since installation. This estimate is based mostly on automatic flow metering data, but interpolations were required for data gaps due to instrument communication outages. Figure 37 depicts a simplified diagrammatic comparison of average daily pumping well production rates at various well locations for 2020. Further details of annual production totals per well installation are presented in Appendix D, Figure D1.

6.0 Horizontal Drains

During the fall of 2007, four trial horizontal (gravity) drains (HD) were installed at two different locations (HD1, HD4) into the slope underlying the West Quesnel study area. In mid-2012, as part of the Phase I subsurface dewatering program, 64 additional horizontal drains were installed at ten other sites (HD5 through HD14, see Figure 35). A total of 21 of the drains were observed to be dry (at the discharge end) shortly after installation. This included all the drains at sites HD1, HD5, HD6, HD7 and HD14 as well as three drains at HD9 and one drain at HD11. Although there was no initial water flowing from any of the drains at HD14, one drain did begin to produce water during the 2013 spring melt, and the flow rate was manually measured periodically until it stopped flowing in mid-2013. In mid-2016, 14 new horizontal drains were installed at three different sites (HD15, HD16, and HD18) as part of the Phase II dewatering program. Six of these drains were noted to be dry (at the discharge end) shortly after installation (five at HD16 and one at HD18). The installation and activation of PW25 also appears to have resulted in curtailment of production from HD10, as PW25 has effectively drained HD10’s recharge source. A summary table of the drain installations can be found in Appendix E.

Appendix E also contains individual production charts for each of the horizontal drain installations. The plots presented in Appendix E depicting the flow rate measurements for the horizontal drain sites have been generated, utilizing Wood’s data management system, custom developed for the West Quesnel Land Stability Program. The flow measurements were collected on an hourly basis and summed to establish daily flow rates. Where flow data gaps exist, or an incomplete daily data set was collected, false drops in flow rates were recorded. These are temporary data aberrations and can generally be disregarded, as the horizontal drains flow regardless of the flow meters being functional or not.

To date almost 788 million liters of water has been removed through the horizontal drains, with 76% (over 598 million liters) removed by HD8. An overall production summary is presented in Appendix E, on Figure E1. In 2020, almost 74 million liters of water was removed, with more than 62% (46 million liters) removed by HD8. HD8 continues to be a significant producer however the production has been gradually decreasing, and the steady state flow rate is approaching detection limit for the installed model of flow meter. In 2020 there were two notable peaks observed in flow from HD8, one associated with the spring freshet from mid April though mid September, and another between late October and the end of 2020. Two seasonal peaks, for relatively the same time frames were observed at HD9, HD11, HD12 and HD13. At HD4 the flow rate year after year is consistently around 1,565 liters per day and is most likely limited by the flow meter. At HD10, limited flow periods were observed in 2020, in May through July and in late November, these limited flow periods correlate with significant well production periods observed in PW25. HD15 was not monitored in 2020. Flow rates at HD16, were still significant, but somewhat lower for 2020 as compared to 2019.

7.0 Precipitation Data

Precipitation has a significant influence on groundwater patterns and hence ground stability in West Quesnel. The primary source of precipitation information has been data from Environment Canada[2] for the Quesnel Airport weather station variously known as Quesnel AWOS (prior to June 2010), Quesnel (from June 2010 to the end of 2012) and Quesnel Airport Auto (from 2013 to present), located approximately 6 km northeast of West Quesnel. Where missing or incomplete daily data is reported at Quesnel Airport Auto weather station, where possible, the data from the Quesnel weather station was used to infill the missing data. Monthly and daily precipitation records, including current and previous historic 30-year climate normals, were obtained from the Environment Canada stations. Table 2, below, presents a comparison between published climate normals[3] data and computed 30-year average with associated observed trends, and 2020 data.

Table 2. Monthly Precipitation Historical Data Trends and 2020 Data (mm)

	Quesnel Climate Normals[3]			30 yr Average[2]	Quesnel Airport	WS1
	1961-1990	1971-2000	1981-2010	1991-2020	Auto 2020	2020
Jan	50.5	48.5	47.8	43.0	38.2	49.2
Feb	28.7	24.4	22.7	22.5	31.4	48.5
Mar	28.2	28.9	24.9	24.9	71.1	48.3
Apr	22.6	21.9	24.5	27.8	15.4	15.3
May	42.5	40.7	42.6	40.1	40.5	57.0
Jun	56.7	68.6	66.4	59.1	78.0	97.9
Jul	59.0	61.6	65.6	61.4	85.8	108.9
Aug	56.3	50.0	46.2	39.9	36.6	44.8
Sep	49.3	44.8	50.2	44.7	39.1	38.6
Oct	49.6	51.4	52.6	52.0	114.5	105.1
Nov	46.0	49.8	51.3	46.0	60.7	84.3
Dec	49.3	49.7	41.6	38.3	24.6	22.6
Year	**538.7**	**540.3**	**536.4**	**499.7**	**635.9**	**720.6**

The annual total precipitation recorded by Environment Canada at the Quesnel Airport for 2020 was 635.9 mm which is significantly higher than the climate normal and the 30-year average. Over the last 30 years, an annual precipitation over 600 mm has only been observed three other times; in 1996 (656.5 mm), in 1999 (628.1 mm), and in 2004 (692.1 mm).

In general, higher than average precipitation was observed throughout 2020, however significant increases were observed in March and October. In March, 71.1 mm of precipitation was recorded which is almost triple the 30-year March average of 24.9 mm and in October, 114.5 mm of precipitation was recorded which is more than double the 30-year October average of 52.0 mm.

In August 2015, an optical precipitation sensor (Optical Scientific Inc. ORS-815-DS) was installed within West Quesnel (Station 31) on Dixon Street north of Lewis Drive. This sensor (WS1) allows near real-time measurement of local precipitation (rain and snow events) intensity and duration within the West Quesnel Land Stability Program area. The optical sensor collects data by measuring the amount of obstructions, typically rain and snow, but unfortunately it also appears to measure suspended particulates, such as dust and ash from wildfires. Thus, this instrument can be expected to record precipitation generally higher than actual precipitation depending on air quality at the time. In 2020, it was also noted that the optical sensor

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[2] Environment Canada, 2020. Historical Data https://climate.weather.gc.ca/historical_data/search_historic_data_e.html Last visited July 13, 2020.

[3] Environment Canada, 2020. Canadian Climate Normals https://climate.weather.gc.ca/climate_normals/index_e.html Last visited July 13, 2020.

did not operate in extreme cold temperatures. On 15 January, a daily low of -41.9°C was recorded by the Quesnel Airport Auto weather station, and erroneous precipitation data for that day was recorded by the optical sensor.

Table 3, below, presents the annual total precipitation (rainfall and snow water equivalent) for the respective weather data station sources from 1996 to 2020. It also presents the antecedent total precipitation (i.e. precipitation in the months leading up to spring freshet from the previous November through to April) compared to a 1981-2010 historic normal of 213 mm for those same months.

Table 3: Annual and Antecedent Total Precipitation from 1996 to 2020

		Annual		Antecedent	
Year	**Data Source**	**Total Precipitation (mm)**	**Difference from Historic Normal (1981 to 2010) (mm)**	**Nov-Apr Precipitation (mm)**	**Difference from Historic Normal (1981 to 2010) (mm)**
1996	Quesnel AWOS	657	+121	231	18
1997	Quesnel AWOS	579	+43	287	74
1998	Quesnel AWOS	488	-48	181	-32
1999	Quesnel AWOS	628	+92	275	62
2000	Quesnel AWOS	554	+18	189	-24
2001	Quesnel AWOS	554	+18	172	-41
2002	Quesnel AWOS	471	-65	213	0
2003	Quesnel AWOS	478	-58	140	-73
2004	Quesnel AWOS	692	+156	226	13
2005	Quesnel AWOS	524	-12	249	36
2006	Quesnel AWOS	465	-71	142	-71
2007	Quesnel AWOS	541	+5	273	60
2008	Quesnel AWOS	530	-6	206	-7
2009	Quesnel AWOS	423	-113	238	25
2010	Quesnel AWOS/Quesnel	315	-221	135	-78
2011	Quesnel	450	-86	104	-109
2012	Quesnel	427	-109	163	-50
2013	Quesnel Airport Auto	404	-132	161	-52
2014	Quesnel Airport Auto	416	-120	168	-45
2015	Quesnel Airport Auto	428	-108	233	20
2016	Quesnel Airport Auto	495	-41	169	-44
	West Quesnel WS1	761	N/A	215	N/A
2017	Quesnel Airport Auto	301	-235	128	-85
	West Quesnel WS1	488	N/A	224	N/A
2018	Quesnel Airport Auto	448	-88	177	-36
	West Quesnel WS1	728	N/A	243	N/A
2019	Quesnel Airport Auto	500	-36	237	24
	West Quesnel WS1	638	N/A	264	N/A
2020	Quesnel Airport Auto	636	100	277	64
	West Quesnel WS1	721	N/A	291	N/A

Figure F1, presents the 2020 monthly precipitation collected from Quesnel Airport and WS1 compared to Canadian Climate Normals, 10 year and 30 year moving averages. An overall drying trend between 2010 to approximately mid 2019 is evident in Figure F2, a chart which presents the cumulative difference of total monthly precipitation relative to the 30-year monthly average. Starting in June of 2019 and through to the end of 2020, a significant reversal in trend towards a wetter climate is apparent. Of note the recent wetter trend is similar in scope to such periods observed in 1996, 1999 and 2004.

Figure F3 presents the cumulative daily precipitation for 2020 for both Quesnel Airport and WS1, along with the average temperature recorded for that day at the Quesnel Airport.

Figure F4 presents precipitation storm events that occurred in 2020 that had a rate of at least 0.2 mm/hr with an overall minimum accumulation of 10 mm relative to associated durations.

In 2020, twelve storm events were recorded by WS1 that met the minimum criteria of at least 0.2 mm/hr accumulation with a minimum accumulation of 10 mm. Prior to 14 April, the last day the average daily temperature typically stayed below 0 °C, two storm events on 8 February and 23 March, were recorded and were likely snow events as opposed to rainfall. In late May on the 20th and 23rd, two additional storms were recorded. During the summer months four events were recorded, one on June 6th and three events in early July, on the 2nd, 7th and on the 8th. In the fall, four storm events were recorded, one on 16 October and three in November, on the 13th, 17th, and 27th . Post December 8, the day after which the average daily temperature typically stayed below 0 °C, no events were recorded.

8.0 Trends & Correlations

Selected typical data from different types of instrumentation was plotted to determine if any general trends or correlations were apparent. Although the availability of relatively comprehensive data sets across the study area was only phased in between 2007 and 2012, several trends can be identified, and are discussed below. Charts illustrating the data comparisons are presented in Appendix G.

8.1 Precipitation Effect on Groundwater

Figure G1, depicts total monthly precipitation compared to general groundwater pressures (elevations) at selected VWP sensors. Upon reviewing the collected data it is apparent that a significant natural seasonal rise in groundwater elevations occurs just after the winter season (during the freshet) each year. In some rarer instances, post-freshet secondary rises in groundwater levels can also be seen, generally corresponding with individual storm events or general late fall (pre-freezing) increases in precipitation. These seasonal rise patterns are more obvious on some instruments than others and can be artificially influenced by drainage systems and/or utility leaks. In general, the natural groundwater increases are observed to occur either gradually (e.g. as depicted by VWP 14A) or relatively rapidly (e.g. VWP 15A and VWP 39B). Examples of more subdued seasonal responses (VWP 9A and VWP 10C) and little or no apparent spring freshet response (VWP 4) are also depicted on Figure G1. The freshet response at a particular location is highly dependent on local ground permeability and precipitation accumulated over the preceding winter months. Shortly after the freshet increase, a gradual decrease in groundwater pressures can typically be observed. The rate of decrease is also dependent on ground permeability and dissipation capacity within the overall regional groundwater system but can also be influenced by the connectivity to the natural hydro-geologic environment and/or artificial dewatering systems.

An example of the apparent influence of the 2012 subsurface dewatering system is shown in the data plot for VWP 10C. Prior to activation of PW14, a natural but muted seasonal variation in groundwater pressure at VWP 10C can be seen in the winter of 2011 and 2012. In the spring of 2013, the natural groundwater fluctuation pattern observed for VWP 10C was interrupted by a sharp drop in groundwater pressure followed by a gradual stabilization and resumption of an even more subdued seasonal variation pattern approximately 5 m below the previous elevation. The interruption of the previous natural pattern coincided with the activation of nearby pumping well PW14, and the gradual decrease since then is considered attributable to the ongoing dewatering effects of this well. Similarly, a sharp upward spike in the groundwater pressure at VWP 10C observed in November of 2017 coincided with the same period when the pump in PW14 was off. In 2020, although pump PW14 continued to operate at the same rate with similar and slightly elevated production levels there appears to be a slight pore pressure increase of approximately 0.7 m. This increase shows the limitations and influence of PW14 with respect to ground permeability in this area.

There is also likely an over-riding time-lag effect of infiltration of previous rainfall or snow melt (during frozen/non-frozen and dry/saturated ground conditions) which likely influences groundwater pressures, along with the long-term precipitation trends. There may also be additional factors operating such as infiltration variability depending on surface moisture conditions and near surface groundwater conditions, lawn watering, variable losses from sewers and water systems and other unknown factors. In addition, in some landslide masses, the degree of infiltration has been found to vary with ongoing ground movement over time, as internal flow paths, tension cracks and shear zones change as movement occurs.

Starting in 2018 and continuing through to the end of 2020, a generally increasing pore pressure trend has been observed within most of the near surface VWP sensors. This increasing trend is directly related to increasing precipitation observed in the area over the last few years. In 2020, significantly higher precipitation was observed causing the highest to date pore pressure observations within some instruments during the spring freshet and the highest to date secondary fluctuations that typically are observed during the late fall to early winter months. This pore pressure increase is concerning, and if similar precipitation is observed in 2021, the trend will continue and likely be reflected by higher ground movement rates.

8.2 Precipitation Effect on Ground Movement

Previous Wood reports describe a general and expected correlation between periods of higher precipitation and subsequently increased ground movements as measured by quarterly or annual GPS surveys, with the majority of movement observed within any one year generally correlating with spring freshet. As noted in previous annual reports, there also appears to be a time-lag between increased precipitation and resulting magnitude of annual total ground movement, likely due to the delayed effect on groundwater pressures from the location, timing, type and amount of precipitation as noted above. Figure G2 illustrates this time-lag effect between the magnitude of total movement in any given year and the total amount of antecedent precipitation (i.e. that occurring in the previous November to April) prior to the movement. Although still a fairly general and simplistic correlation made with limited available data, it is clear that up until 2012 there was a relatively good correlation between the antecedent precipitation and the magnitude of movement, i.e. whenever the total antecedent precipitation was higher than about 150 mm for one or two years then the annual ground movement was typically in excess of 50 mm (averaging 54 mm per year). However, from 2013 onwards, whenever the antecedent precipitation has been above 150 mm the observed annual ground movement has been averaging 13 mm per year. This change in the historic correlation pattern is attributed to the early effects of components of the subsurface dewatering system coming online in 2012- 2013 and again in 2016. In 2017 the antecedent precipitation fell to below 150 mm, and at the same time the annual movement was the lowest recorded (6 mm). In 2018 and 2019, the departure from the historically higher movement pattern observed prior to 2013 continued, with movements of only 9 mm and 13 mm per year against antecedent precipitation of 177 mm and 237 m in 2018 and 2019, respectively. In 2020, the antecedent precipitation increased to 277 mm which is the highest recorded level since monitoring started. The corresponding ground movement was also much higher, and similar in magnitude to the ground movements observed in peak precipitation years of 1999 and 2004, prior to installation of the subsurface dewatering system.

Beginning in the fall of 2012, more detailed (daily) ground movement data from the IPI instruments (as opposed to intermittent GPS surveys) became available. Also starting in August 2015, higher detailed local precipitation data became available from WS1, and although the precipitation data recorded via this optical sensor appears to be over-stated due to air quality issues, a preliminary correlation between significant precipitation storm events and ground movement can be seen. Figure G3 depicts detailed plots of cumulative ground movements against daily precipitation and temperature for the last 5 years.

8.3 Groundwater Correlation with Ground Movement

While precipitation patterns can be shown to have a general influence on ground movement, typically it is actually the resulting groundwater pressures that more directly influence landslide movements. Previous Wood reports have described how increased groundwater pressures acting on a landslide failure surface reduce overall stability and potentially cause subsequent increases in ground movement. Figure G3 depicts daily precipitation, ground movement (as determined by horizontal GPS surveys and daily IPI data) and daily groundwater elevation from a typical background groundwater instrument (VWP 14A). A clear correlation exists between the most significant movement events that do occur, and the corresponding spring freshet groundwater pressure rises. Some non-freshet movement events also occurred; however those were noted to correspond with reports of significant water main and sewer utility leaks, and storm events. The detected leak events demonstrate the importance of the City of Quesnel's annual leak detection and repair program.

Figure G4 presents a longer-term plot of horizontal ground movement (GPS 98-17, SI6C, SI17B/SI17aB, and SI18B) versus typical background groundwater pressure (VWP 14A). From 2008 to 2012 a clear pattern of increased ground movement and corresponding annual spring freshet groundwater pressure increases is evident. During 2010 and 2011 there was a very subdued spring groundwater pressure rise (likely due to an extended period of significantly lower than normal antecedent precipitation), which also corresponded with a period of lesser ground movement. However, starting in 2013 there has been appreciably less ground movement despite background seasonal groundwater pressures at or above elevations that would have been expected to trigger greater movements in previous years. This change in the historic pattern is deemed to be due to the incremental effects of the Phase I subsurface dewatering works installed and initiated between mid-2012 and the spring of 2013. The timing of the installation of the dewatering works as well as the output from select horizontal drains are overlain on Figure G4 to illustrate this effect. The even further reduced movement observed in 2017 through 2019 is contrasted against still significantly high natural seasonal groundwater peaks is judged to be further evidence of the cumulative positive stabilizing effect of the storm drainage, additional pumping wells and horizontal drains being brought on line during the last half of 2016.

Figure G5, presents an approximate correlation between ground movements and groundwater levels (pore pressures). To establish the correlation, ground movement at GPS 98-17 was compared to the VWP 14A pore pressures. Specifically, the number of days in a calendar year that the average daily VWP 14A readings were measured to be equal to or greater than an observed pore pressure elevation of 567 m. This correlation contains a number of very simplistic assumptions but does demonstrate a general correlation between higher-than-normal natural groundwater levels (as observed at VWP 14A) and expected ground movement.

Beginning in 2019 and extending through 2020, generally increased groundwater levels over previous steady state and gradually declining elevations were observed throughout the area within the near surface instruments. This was also evidenced by the higher flow rates from the dewatering system. It is considered that the elevated groundwater levels (attributable to the much higher-than-average antecedent precipitation), compounded by the freshet and seasonal peak precipitation resulted in the significant increase in ground movement observed for 2020. This higher movement happened despite the presence of the dewatering measures and indicates that under severe and/or prolonged precipitation patterns the current system capacity to drain groundwater can be exceeded.

9.0 Closure

This report presents the results of the annual monitoring carried out by Wood for the 2020 calendar year. This report has been prepared for the exclusive use of the City of Quesnel and their representatives for specific application to West Quesnel Land Stability Program. Any use which a third party makes of this report, or any reliance on or decisions made based on it, are the responsibility of such third parties. Wood accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report.

This report was prepared in accordance with generally accepted geotechnical engineering principles and practice. No other warranty, express or implied, is made. This report and associated data are subject to the attached limitations (Appendix H).

Please do not hesitate to contact the undersigned at (250) 564-3243 should you have any questions or require further information.

Respectfully submitted,

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