Case Study of the 1982 Rapid Reactivation of the Goddard Landslide along the Canadian Pacific Railway near Ashcroft, British Columbia

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ABSTRACT
Both Canadian National (CN) and Canadian Pacific (CP) operate main railway lines which traverse the lower portions of several active landslides along the Thompson River south of the village of Ashcroft. Interruption of this national transportation corridor can result in economic losses that grow exponentially with the duration of the outage, as demonstrated by the six-day closure of the CP line for emergency remedial construction following the rapid reactivation of the Goddard landslide in 1982. This paper presents a case study of the Goddard landslide, revisiting previously unpublished field observations and slope displacement measurements from the days preceding the landslide of estimated 2 Mm^3 volume. Natural and anthropogenic factors which may have contributed to the rapid reactivation of the Goddard landslide are discussed. An inverse-velocity method is employed to retrospectively estimate the time of the slope failure to within twelve hours of the actual landslide. Risk management observations arise for coping with natural hazards affecting linear infrastructure.

RÉSUMÉ
Le Canadien National (CN) et le Canadien Pacifique (CP) exploitent les principales lignes de chemin de fer qui traversent les parties inférieures de plusieurs glissements de terrain actifs le long de la rivière Thompson au sud du village d'Ashcroft. L'interruption de ce corridor de transport national peut entraîner des pertes économiques croissantes exponentiellement avec la durée de la panne, comme en témoigne la fermeture de six jours de la ligne CP pour la construction d'un remblai d'urgence suite à la réactivation rapide du glissement de Goddard en 1982. Présente une étude de cas du glissement de terrain de Goddard, en revisitant des observations de terrain inédites et des mesures de déplacement de pente des jours précédant le glissement de terrain estimé à 2 Mm^3. Les facteurs naturels et anthropiques qui peuvent avoir contribué à la réactivation rapide du glissement de terrain de Goddard sont discutés. Une méthode de vitesse inverse est utilisée pour estimer rétrospectivement le moment de la rupture de pente à moins de douze heures du glissement de terrain réel. Des observations sur la gestion des risques surviennent pour faire face aux risques naturels qui affectent les infrastructures linéaires.

1 INTRODUCTION

The Thompson River Valley, in southern British Columbia, Canada, forms an important transportation corridor which contains main lines of both the Canadian Pacific (CP) and the Canadian National (CN) railways, connecting directly to Canada's west coast shipping industry via the port of Metro Vancouver. There are twelve large landslides located along the 10-kilometer reach of the Thompson River Valley south of the village of Ashcroft, collectively referred to herein as the Ashcroft Thompson River landslides. Both the CN and CP railway lines traverse the lower portions of several of these landslides on the east and west banks of the Thompson River, as shown on Figure 1. While the Ashcroft Thompson River landslides are typically inactive or very slow moving, several rapid slope failures have occurred in the past 150 years, some of sufficient volume to temporarily dam the Thompson River (Tappenden 2017).

1.1 Setting

The village of Ashcroft is situated in the low-lying, semi-arid Thompson River Valley, located within the southern Interior Plateau of British Columbia. The Coast Mountains serve as an effective barrier to the moist westerly air flow, creating a much drier and more continental climate on the Interior Plateau in comparison to the wet coastal conditions (Chilton 1981). As the largest tributary of the Fraser River, the Thompson River is an important Pacific salmon spawning waterway, comprising a resource with an annual commercial value in excess of $100 million (Clague and Evans 2003). The varied landscape of the Thompson-Nicola region contains large tracts of arid ranchland, with extensive irrigation required for the cultivation of crops (Province of British Columbia 2016).

1.2 Geology

The Ashcroft Thompson River landslides are situated on the steep walls of an inner valley that was incised in the broader Thompson River Valley during Holocene time (Clague and Evans 2003, Eshraghian et al. 2007). The Quaternary sediment fill in the Thompson River Valley near Ashcroft consists of deposits from three glaciations, separated by unconformities produced by erosion and mass wasting during interglacial periods (Clague and Evans 2003).

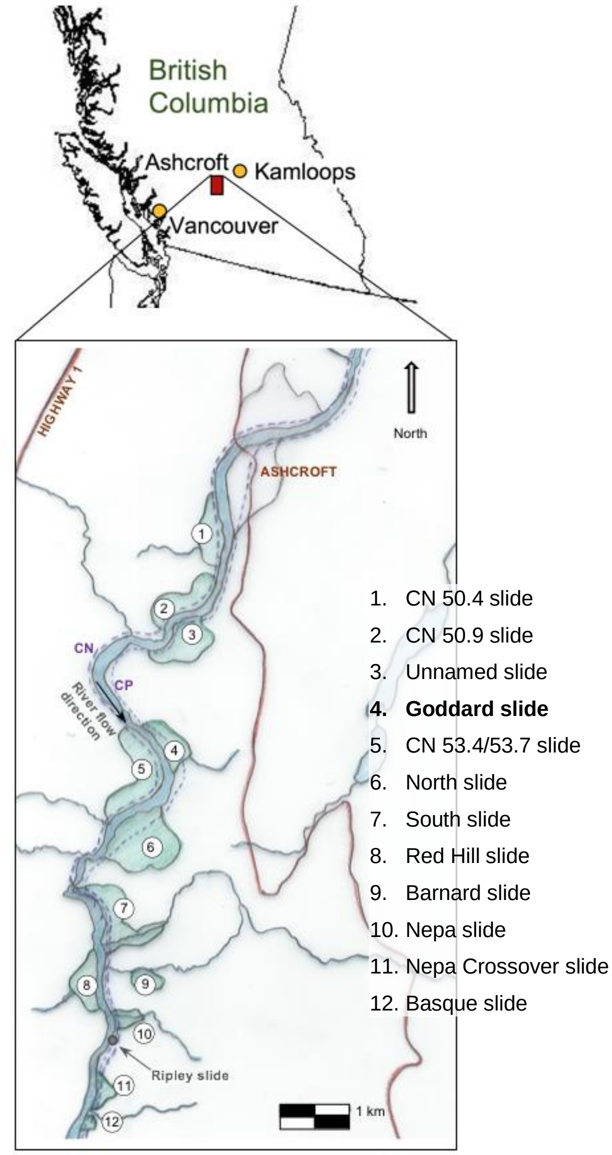

Figure 1. Map of the study area showing large landslides along the Thompson River Valley within approximately 10 km south of the village of Ashcroft.

The valley fill sequence consists predominantly of permeable glacial sediments, with the exception of the rhythmically bedded glaciolacustrine silt and clay (unit 2) near the base of the Pleistocene sequence (Ryder 1976, Clague and Evans 2003), as shown in Figure 2. Large landslides have occurred in areas where this Pre-Fraser glaciolacustrine layer is exposed, corresponding to a 15-km stretch of the Thompson River Valley from approximately 3 km north of Ashcroft to approximately 12 km south of Ashcroft (Figure 1) (Clague and Evans 2003). Pre-sheared discontinuities in these unit 2 sediments may be the result of disturbance by overriding ice of the subsequent glaciations, post-glacial valley rebound (as described by Johnsen and Brennand (2004)) and/or early slope movements. The clay beds of unit 2 are highly plastic, with residual friction angles of 10 to 15 degrees measured in laboratory ring shear tests (Bishop 2008).

Below unit 2, the bedrock is comprised of andesite, rhyolite and pyroclastic beds that are fractured and well-drained (Huntley et al. 2017); the bedrock is overlain in places by gravel (unit 1 in Figure 2) representing ancient, possibly tertiary-age, alluvial deposits (BGC Engineering Inc. 2012, Tribe 2002). Field investigations at several of the large landslides in the Thompson River Valley have confirmed the presence of artesian groundwater pressures contained within the fractured bedrock and buried gravels (unit 1), confined by the overlying clay and silt (unit 2) which contains the rupture surface(s) for the landslides (Porter et al. 2002, BGC Engineering Inc. 2005).

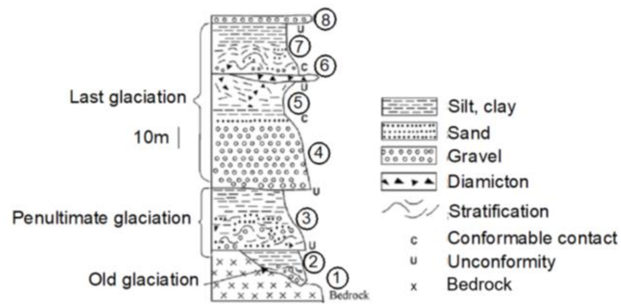

Figure 2: Generalized stratigraphy of Quaternary sediment fill in the Thompson River Valley at Ashcroft (modified from Clague and Evans 2003).

2 HISTORY OF LANDSLIDE ACTIVITY

There is a long history of slope movements in the Thompson River Valley south of Ashcroft that have been sporadically documented over time, as described in Tappenden (2017). In 1877, H.J. Cambie carried out a location survey along the Fraser and Thompson Rivers for the proposed Canadian Pacific Railway route (VanDine 1983). A letter written by Cambie (1895), accompanied by a map, depicted seven landslides along the Thompson River south of Ashcroft. Construction of the CP railway line at Ashcroft was completed in 1885, followed by the Canadian Northern (now Canadian National) railway line in 1915. In 1897, engineering geologist Robert Stanton was commissioned by CP to conduct an assessment of the landslides in the corridor which had proven problematic to the operation of the railway since its inception (Stanton 1898).

The majority of the reported landslide movements which occurred in the study area date from the late-1800's, soon after the introduction of primitive ditch-and-furrow irrigation methods in the mid-1860's (Clague and Evans 2003). The earliest reported landslide, the South slide (No.7), occurred sometime between 1865 and 1877 (Cambie 1895); this was followed by at least six (probably rapid) landslides in the corridor between 1865 and 1898. While ongoing minor movements continued, the only rapid slope movements recorded in the 20th century were the

Red Hill Landslide (No.8) of 1921, and the Goddard Landslide (No.4) of 1982 (Tappenden 2016). Figure 3 displays the earliest aerial photo of the Goddard landslide, dating from 1928, with irrigation ditches and furrows still clearly visible above the slide.

Historical accounts by both Cambie (1895) and Stanton (1898) contended that the landslides of the late-1800's were directly caused by irrigation. However, Morgenstern (1986) cautioned that "large landslides seldom have a single and unambiguous cause", suggesting that these slope failures of the late-1800's were likely reactivations of prehistoric landslides, the forms of which may not have been recognizable without the assistance of aerial photography. Water-efficient sprinkler techniques eventually replaced ditch-and-furrow irrigation by the mid 1960's (Clague and Evans 2003).

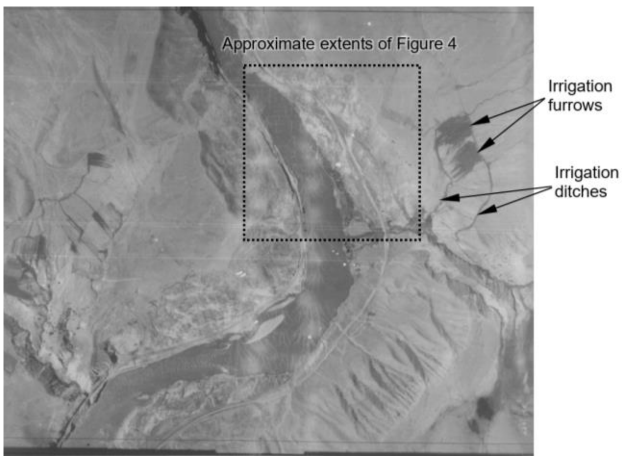

Figure 3: 1928 aerial photo showing the Goddard landslide and upslope ditch-and-furrow irrigation; National Research Council, roll A291 #55.

3 GODDARD LANDSLIDE OF 1982

3.1 General

The Goddard landslide of September 24, 1982 represents an important event from a railway risk management perspective, as it is the only rapid slope movement in the study area which has impacted the railways during the 20th century, and the only reported rapid slope failure since the introduction of sprinkler irrigation techniques.

The volume of the 1982 Goddard landslide was approximately 2 Mm^3 (Eshraghian et al. 2007). Figure 4 displays a 2015 aerial photograph of the Goddard landslide. The area that failed in 1982 is located within a larger, possibly ancient, landslide feature, as delineated by the dashed line (Brawner 1982, Wood 1982, Thurber Consultants Ltd. 1984). The landslide of 1982 occurred at the same location as a similar landslide in 1886, three years after the original construction of the CP track near the toe of the slope (Cambie 1895, Stanton 1898, Thurber Consultants Ltd. 1984).

Figure 4: 2015 aerial photo of the Goddard landslide on the east bank of the Thompson River (courtesy of CN rail); shaded area corresponds to the limits of the 1982 reactivation (as per Eshraghian et al. (2007)), dashed line delineates broader extents of an older, possibly ancient landslide feature.

3.2 Field Observations

Engineering geologist David Wood was on site during the 1982 Goddard landslide, and in the days leading up to the major movement. This section presents his first-hand observations of the landslide characteristics and measurements of accelerating surface displacements as recorded in an unpublished memorandum (Wood 1982).

Following a train derailment at the location of the Goddard landslide on September 23, 1982, Wood arrived on-site and began recording surface offset measurements from monitoring point MP-1, located near the railway tracks at the north flank of the landslide (as depicted in Figure 5) (D. Wood, personal communication, 2016).

Surface displacement measurements recorded by Wood (1982) beginning on September 23, 1982, indicated movement rates at the north flank of the slide (MP-1) were 24 to 40 mm/hour (0.44 to 0.95 m/day), as plotted on Figure 6. These accelerated to a maximum rate of movement in the early morning of September 25, 1982 of approximately 1.2 m/hour (29 m/day), based on vertical offset measurements made at MP-1. The offset measurements show a classic exponential form associated with the transition from decelerating to accelerating stages of deformation.

Cruden (1974) suggested that when brittle materials reach a critical crack density, such that the cracks begin to intersect, the intersections grow at an accelerating rate and lead to failure (Cruden 1974). The Goddard landslide of 1982 was preceded by very/extremely slow slope movements in 1974 (Morgenstern 1986) and October 1976 (Golder Associates 1977, Morgenstern 1986, Porter et al. 2002), which produced surface cracking in the vicinity of the culvert shown in Figure 5 (Golder Associates 1977).

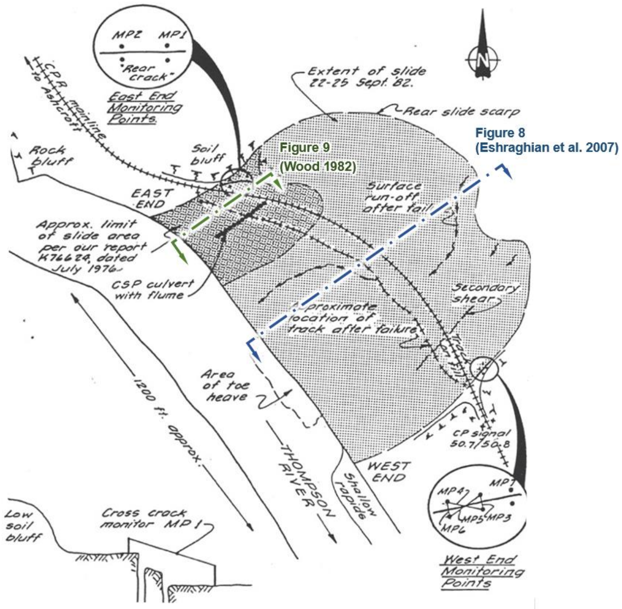

Figure 5: Sketch plan view of the 1982 Goddard landslide; note location of monitoring point MP-1 on the north flank of the landslide (modified from Wood (1982)).

According to the court testimony of Krahn (1984), the maximum rate of movement, attained on September 24, 1982, was 6 m/hour, or rapid failure in the terminology of Cruden and Varnes (1996). Notwithstanding the discrepancy between the maximum movement rates reported by Wood (1982) and Krahn (1984) for the Goddard landslide, both rates are three to four orders of magnitude larger than the maximum rate of the precursory movements reported in 1976 (approximately 10 mm/day in the direction of movement), and two orders of magnitude larger than those measured up to about 7 hours prior to the onset of rapid failure in 1982 (Wood 1982).

In the hours following the 1982 Goddard landslide, Wood (1982) observed that *"The complete soil mass was sheared and broken with ground water running from the face and collecting into small streams. Clay zones of soil were saturated"* (p. 8). Wood (1982) also observed "silt boils" in the Thompson River during and following the slope failure. His observations suggest that groundwater seepage may have played a significant role in the 1982 reactivation. Wood (1982) also noted that he was told by CPR crews two days before the slide that there had been an *"unusual amount of water introduced to the slope above the track"* (p. 2) that year by the irrigation of the upslope terrace. However, in the ensuing litigation, *"the plaintiff [Canadian Pacific] …failed to prove the irrigation practices of Highland caused or contributed to the [Goddard] landslide [of September 1982]"* (p. 26) (BC Court of Appeal 1990). Brawner (1982) observed that the central portion of the 1982 slide area, in particular, was persistently wet, as evidenced by the presence of willows. The presence of a culvert in the vicinity where the initial cracks were observed, both in 1976 and 1982 (Wood 1982), suggests that groundwater seepage, regardless of its source, was concentrated in the area that failed.

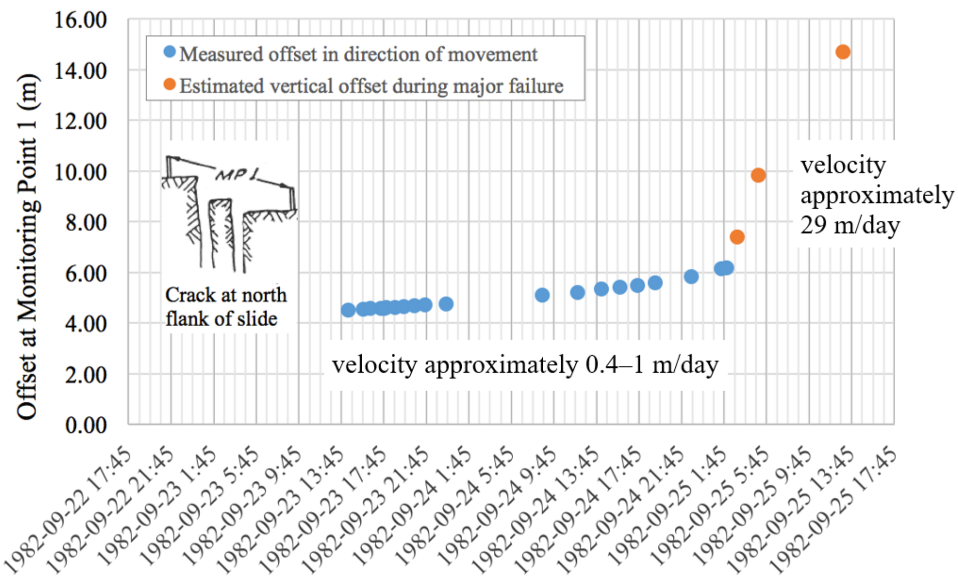

Figure 6: Cumulative surface displacement at north flank of 1982 Goddard slide, as determined from surface offset displacements recorded by Wood (1982).

4 DISCUSSION

Hungr et al. (2005) observed that while certain types of landslides tend to behave in a ductile manner, and others are typified by brittle failure, there is unfortunately a large "transitional" group that may exhibit either behavior, or both in sequence. The periodic rapid reactivations of the Goddard landslide in 1886 and 1982 suggest that a rapid, brittle failure may occur despite the previously disturbed condition of the slope, which would generally be associated with slow and relatively limited displacements (Skempton and Hutchinson 1969). Risk management strategies for other large, slow moving landslides along the railway lines in the Thompson River Valley should therefore consider the potential for a rapid reactivation of the historical landslide deposits.

Several mechanisms which may lead to rapid failure along pre-existing rupture surfaces are discussed by Hutchinson (1987). Of these, the three factors which appear most relevant to the Goddard slide are: 1) unloading of the toe due to river erosion, 2) brittleness within the slide mass (as compared to the bounding slip surface), and 3) hydraulic thrust generated by the entry of surface water into open cracks. To these, I would add 4) groundwater seepage pressures due to a confined aquifer near the toe of the slope. These causal factors are discussed in the following subsections as they relate to the 1982 Goddard landslide.

4.1 Toe Erosion by the River

Hutchinson (1987) cited toe erosion as perhaps the most common trigger of landslides on pre-existing shears, noting that *"… the removal of a given weight of material from the toe of a slide will cause a considerably larger reduction in factor of safety than the addition of the same weight at its head. This follows from the tendency of the stress systems at the toe and head of a slide to approximate to the passive and active modes, respectively"* (p. 182). During an inspection of the Goddard landslide on September 26, 1982, Brawner (1982) noted the role that river erosion may have played in triggering the slide two days prior:

"The C.N. Rail has had slide instability on the opposite side of the river [CN 53.4/53.7 slide] *and have placed rip rap directly across from the* [Goddard] *slide. In addition, rip rap has been placed about 1500 feet upstream. This has pushed the river harder against the C.P. bank and increased scour"* (p. 2).

Based on an extensive geophysical investigation at the smaller Ripley landslide, Huntley et al. (2017) suggested that the landslide toe extends under the Thompson River, where greater than 20 m of clay-rich colluvial, glaciolacustrine and till deposits are confined to a bedrock basin, with the largest slope movement rates measured adjacent to areas of active toe erosion.

4.2 Brittleness Within the Slide Mass

Hutchinson (1988) described compound slides as being of such geometry that failure is only made kinematically admissible by the development of internal displacements and shears, with the velocity of the slide reflecting the brittleness of these internal failures. Their geometry is otherwise locked in-place and generally reflects the presence of a heterogeneity, typically a weak layer (Hutchinson 1988)—in this case, the pre-Fraser glaciolacustrine sediments of unit 2 (Figure 2).

Substantial movement in a compound slide is not possible without internal shearing of the slide mass, allowing the rear part of the slide to subside to form a graben, and the main slide body to move forward. It follows from energy considerations that the resistance on such internal shears can contribute significantly to the overall stability of the slide, and this contribution will be higher in more strongly non-circular slides with larger ratios of strength and brittleness on internal shears to those on the bounding slip surface (Hutchinson 1987).

As depicted on a cross-section of the 1982 Goddard landslide prepared by Eshraghian et al. (2007) (Figure 8), the slope moved on two rupture surfaces as a multiple compound translational earth slide; the deeper rupture surface was located in the pre-sheared glaciolacustrine unit 2 deposits. The overlying unit 3, however, of which the main body of the slide was comprised, was described in borehole loggings as hard to very hard silt of low plasticity, with partings of fine sand and clay, having a high strength exhibited by Standard Penetration Test blow counts in the range of 42 to greater than 100 (refusal) (Klohn Leonoff Consulting Engineers 1986). There is a marked contrast between the hard, surficial silts of unit 3 comprising the slide mass, compared to the ductile, pre-sheared clay partings of unit 2 which form the bounding slip surface.

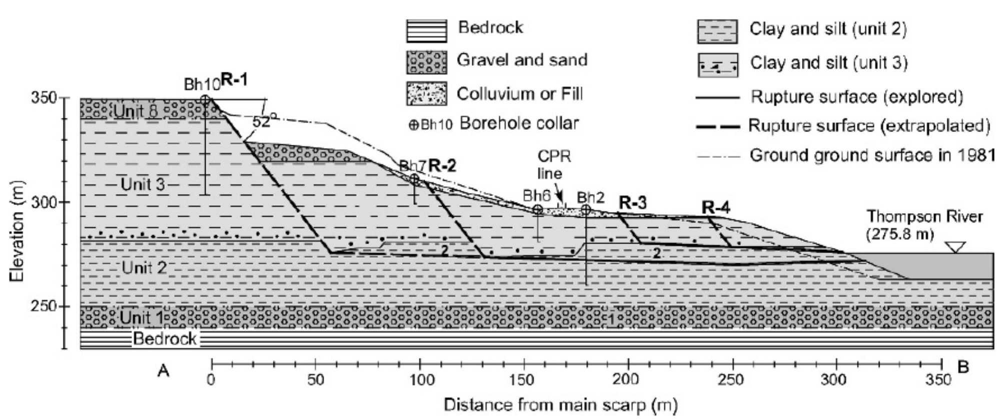

Figure 8: Simplified stratigraphic cross-section of the 1982 Goddard landslide, with pre-slide surface profile indicated by the dashed line (Eshraghian et al. 2007); location shown on Figure 5.

A sketch of the Goddard landslide immediately prior to, and during, the 1982 reactivation was prepared by Wood (1982) based on his firsthand observations, and is presented in Figure 9. The slide has the characteristic features of a compound failure, with internal shearing of the slide mass evidenced by the numerous cracks forming scarps and grabens. David Wood (personal communication, 2016) recalled substantial internal deformation and “chaotic” behavior of the moving mass during the 1982 Goddard landslide. The rapid velocity of the 1982 Goddard landslide may have resulted from the brittleness of these internal failures.

4.3 Surface Water Ingress and Artesian Groundwater

The potential role of surface water ingress in facilitating the Goddard landslide (by irrigation and antecedent precipitation), was alluded to in Section 3.2. In spite of the prevailing dry and semi-arid conditions associated with British Columbia’s Southern Interior, early summer is often relatively wet (Moore et al. 2010), with localized precipitation events that could fill surface cracks with water and exert the hydraulic thrust to trigger a landslide on a marginally-stable slope. In the case of the 1982 Goddard landslide, the winter preceding the failure had an unusually high snowpack, with localized late persistence of snow on the ground (Tappenden 2017). 1982 also experienced the highest summer precipitation recorded at Ashcroft over the 10 years of record between 1973–1983 (Thurber Consultants Ltd. 1984).

The travel angle of the Goddard landslide, based on the cross-section prepared by Eshraghian et al. (2007), was approximately 14 degrees (inverse tangent of scarp height to toe of the slide). This is within the range of residual friction angles of 10 to 15 degrees measured in ring shear laboratory tests on the unit 2 glaciolacustrine clays comprising the rupture surface (Bishop 2008). For a wedge of frictional soil sliding on a horizontal rupture surface with a water-filled tension crack at the rear, the stable slope angle is approximately equal to the internal friction angle of the soil; however, movement requires that the rear crack be filled with water such that cleft water pressures are exerted (Cruden 2003). Morgenstern (1986) was of the opinion that antecedent precipitation contributed very significantly to the magnitude of the 1982 slide, noting that substantial rain fell while the Goddard slide was in progress, and that the pressure of water-filled cracks likely contributed to the movements.

In addition to surface water infiltration, groundwater seepage pressures due to the confined bedrock aquifer also likely played a role in the Goddard landslide. Field investigations at several of the large landslides in the Thompson River Valley have confirmed the presence of artesian groundwater pressures contained within the fractured bedrock and buried gravels (unit 1), which are confined by the overlying glaciolacustrine clay and silt (unit 2) containing the rupture surface(s) for the landslides (Porter et al. 2002, BGC Engineering Inc. 2005). Numerous studies (Freeze and Witherspoon 1967, Záruba and Mencl 1976, Hodge and Freeze 1977, Lafleur and Lefebvre 1980, Tutkaluk et al. 1998, Clague and Evans 2003, Bishop 2008) have demonstrated the profound destabilizing effect that a low-permeability unit at depth may have on natural slopes, especially where it confines an underlying aquifer which acts to transmit regional groundwater to the discharge area, producing substantial uplift seepage pressures.

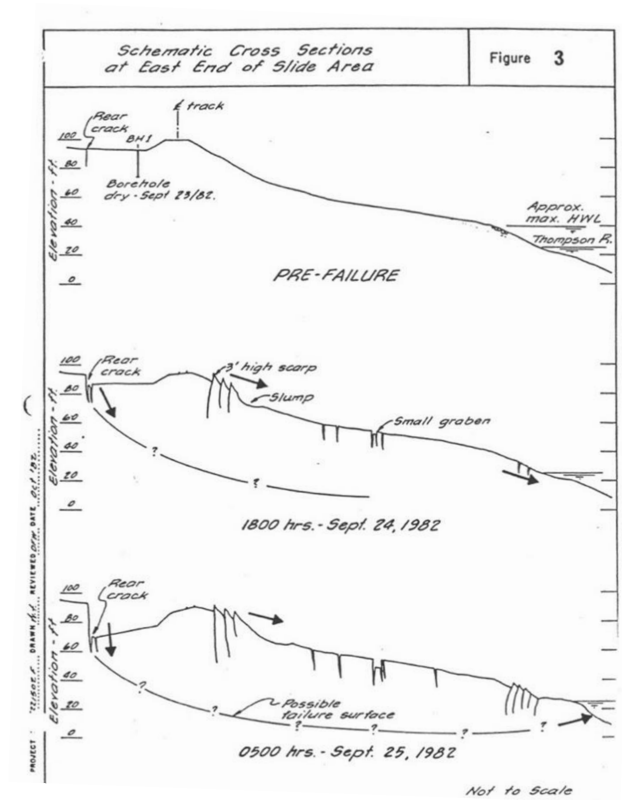

Figure 9: Schematic cross sections of the 1982 Goddard landslide before, during and after failure (Wood 1982); location shown on Figure 5.

The Ashcroft Thompson River landslides have historically been most active in the autumn months, when the river level drops and a positive gradient is established from the bedrock aquifer towards the river. During a period of increased monitoring at the CN 50.9 landslide, upstream of Goddard (Figure 1), frequent groundwater level and slope inclinometer readings were collected from 2001 to 2004. Figure 10 demonstrates the relationship between the displacement rate measured on the unit 2 rupture surface at the CN 50.9 slide, and the direction of groundwater flow produced by the interplay of the Thompson River stage and the artesian porewater pressures near the base of unit 2.

Rupture surfaces in the CN 50.9 landslide are located at 275.7 m and 280.9 m (Eshraghian et al. 2007). Incrementally higher rates of movement (3 mm/year) were recorded on the deeper rupture surface when the river was falling, as opposed to when the river was rising (<1 mm/year) (Figure 10). The seasonally high river levels serve to substantially reduce, if not equilibrate, the upward gradient of porewater pressures measured near the toe of the landslide, while upon recession of the river, movements at a rate of 3 mm/year are re-established as soon as the gradient is greater than zero (Figure 10). These data suggest that the movements are not simply due to saturation and erosion at the toe of the landslide, but are related to the direction of the groundwater flow. Wood (1982) observed "silt boils" in the Thompson River during and following the 1982 Goddard failure, which may be interpreted as evidence of upward groundwater seepage emanating from the confined aquifer and being expelled through the submerged toe of the landslide.

Rapid river drawdown may also be suggested as a trigger for renewals of movement at the Ashcroft Thompson River landslides, but this explanation overlooks the importance of groundwater seepage from the confined aquifer that is produced by the interplay of the river level and the artesian porewater pressures illustrated in Figure 10.

Groundwater isotope testing, recently undertaken at the site of the smaller Ripley landslide (Figure 1), indicated that groundwater within the bedrock aquifer derives from a distal source (Tappenden 2017). Artesian porewater pressures in the confined aquifer below the landslides are therefore likely controlled by climate factors on a regional, rather than local, scale. Tappenden (2016) found that the Ashcroft Thompson River landslides have historically been active in years when the Thompson River flow departure from normal exceeded 114 percent of the average annual discharge. These years of higher-than-average river flows were related to increased regional recharge, including above-average snow pack in the Thompson River basin (Tappenden 2017). Tappenden (2016) also correlated years of persistent landslide activity in the Thompson River Valley to negative (wet) phases of the Pacific Decadal Oscillation (PDO) (Tappenden 2016). The PDO is a coupled ocean-atmosphere climate phenomenon centred over the North Pacific Ocean, which is characterized by alternating periods of cool-wet and warm-dry climate regimes lasting approximately 30 years in length, with attendant impacts on the hydrologic regime in the Pacific Northwest (Mantua 2002).

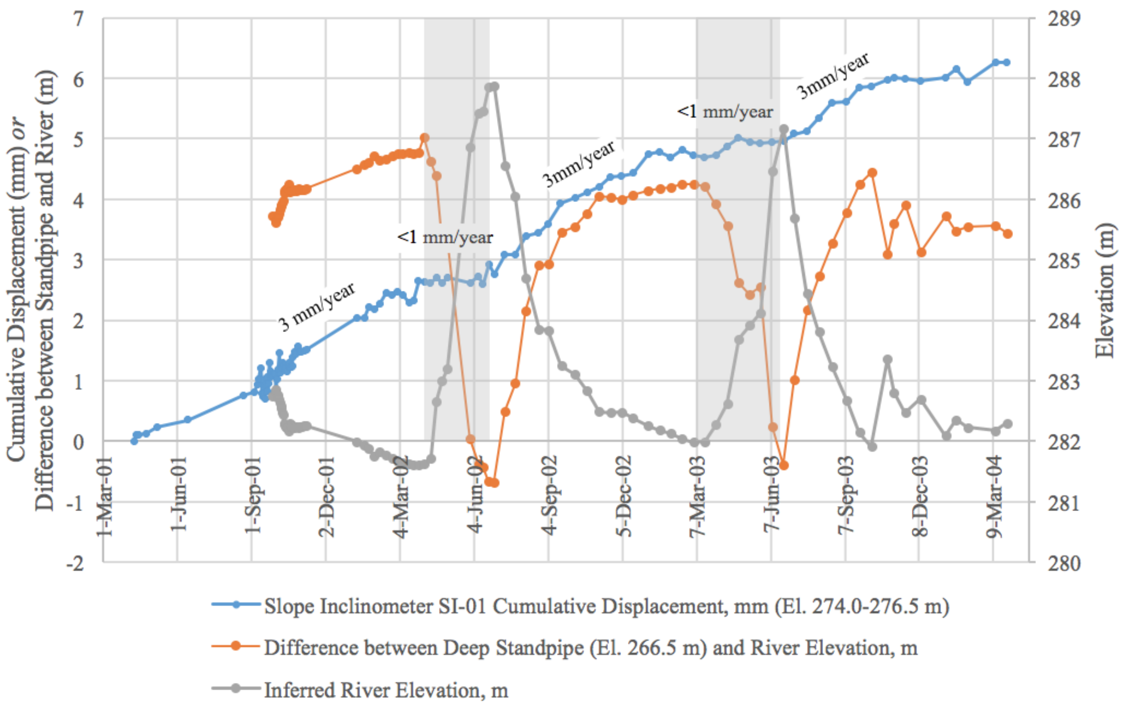

Figure 10: Relationship between CN 50.9 landslide displacement (deep shear zone, el. 266.5 m), Thompson River elevation, and deviation of bedrock pore pressure elevation from river level (Tappenden 2017). Figure prepared based on instrumental data provided by BGC Engineering Inc., with the permission of Canadian National Railway.

4.4 Use of Inverse Velocity Method for Forecasting Onset of Rapid Failure

Given the complex interplay of several causal factors implicated in the Goddard landslide of 1982, it is difficult to develop a predictive model of the slope behaviour. In this case, a risk management strategy that focuses on anticipation and coping, as opposed to risk mitigation and control, may be appropriate. One such means for improved anticipation of rapid slope failures is the inverse velocity method for forecasting the time to failure.

Fukuzono (1985) proposed a simple graphical method for predicting the time of failure of an accelerating slope based on the reciprocal of mean velocity, v, which forms a negative linear trend immediately before catastrophic failure; failure time can be estimated as the time when the 1/v trend intersects the horizontal axis, forecasting the time at which 1/v equals zero and the slope acceleration is infinite. This inverse velocity method is predicated on the assumption that the increment of the logarithm of acceleration is proportional to the logarithm of velocity of the surface displacement immediately before catastrophic failure (Saito 1965). The method is empirical, overlooking the kinematics and causes of failure, while relying on the surface manifestation of the instability—measurements of ground displacement (Hungr et al. 2005).

Fukuzono's (1985) inverse velocity method is applied to Wood's (1982) surface offset measurements from the Goddard 1982 slide in Figure 7. As evident in Figure 7, the 1/v data initially do not show a coherent trend; the data then begin to linearize, commencing at approximately 23:40 hours on September 23, 1982, indicating that rapid failure may be imminent. The linear portion of the plot (from 23:40 hours on September 23 to 01:30 hours on September 25) is projected to intersect the horizontal axis at time 13:00 hours on September 25, 1982. The actual onset on rapid failure occurred just ten hours earlier at approximately 3:00 hours on September 25, 1982 (Wood 1982).

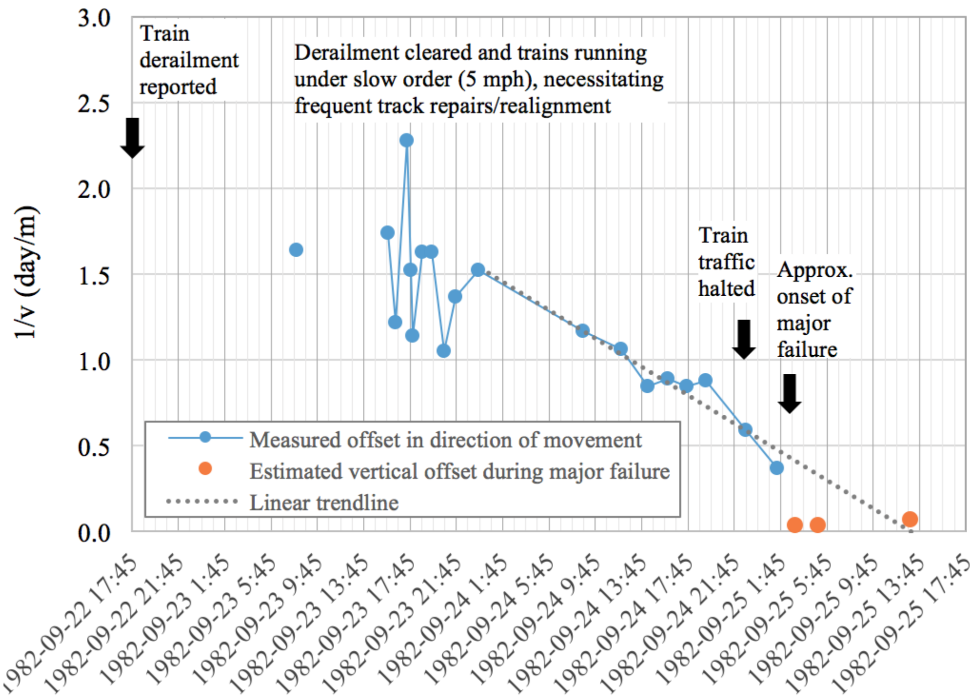

Figure 7: Inverse velocity of surface offset displacements during 1982 Goddard slide, with linear trendline establishedusing surface displacements recorded by Wood (1982) from approximately 27 hours prior to onset of major failure.

5 CONCLUSION

In Canada, ground hazards pose a significant risk to the safety and reliability of railway operations. Between 1922 and 2002, earth landslides were the highest-frequency cause of ground hazard incidents on Canadian National (CN) track (Keegan 2007).

This paper described several factors which may have contributed to the rapid reactivation of the Goddard Landslide in 1982, with implications for the risk management of the numerous other large landslides traversed by the railways along the Thompson River Valley south of Ashcroft. Causal factors, including predisposing geological conditions, surface water ingress, toe erosion, and groundwater seepage pressures from the confined aquifer, likely acted in concert to produce the rapid slope failure.

The 1982 Goddard landslide demonstrates the utility of using the inverse-velocity method for forecasting the approximate time to failure for a reactivated, rapid compound translational landslide in the corridor. Notwithstanding, inverse velocity methods should only be viewed as giving an order of magnitude prediction of the failure time (Crosta and Agliardi 2003). The practical application of an empirical monitoring approach, such as the inverse velocity method, requires that site-specific warning thresholds be set as part of an integrated risk management strategy. Annual displacement and velocity thresholds which may be applicable to the Ashcroft Thompson River landslides have been proposed in Tappenden (2017).

ACKNOWLEDGEMENTS

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