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ORIGINAL PAPER

Developing an early warning system for a very slow landslide based on displacement monitoring

Renato Macciotta[1] · Michael Hendry[2] · C. Derek Martin[3]

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Abstract The Ripley Landslide is a soil slide moving on a fully developed, sub-horizontal, shear surface. The landslide represents a hazard for two important railway lines across its toe. The landslide is being monitored by an array of displacement measurement systems including GPS units, a ShapeAccelArray (SAA), satellite InSAR, and crack extension metres, as well as an array of piezometers targeting pore water pressures in the vicinity of the shear surface. The displacement monitoring system shows an annual cycle of slope deformations most active between September and May. Annual horizontal displacements range between 60 and 100 mm. Vertical displacements range between 20 and 80 mm of settlement. The average horizontal velocities during the active displacement period are between 0.2 and 0.35 mm/day, with maximum velocities of up to 0.6 mm/day. This paper describes the development of an early warning system based on landslide displacement measurements. The system is based on GPS and SAA measurements, which provide near real-time displacement data. The early warning system focuses on detecting changes in landslide annual displacement cycles and potential accelerations, as well as the effects of slope deformation on the railway alignment. As such, the system monitors both the integrity and performance of the slope.

✉ Renato Macciotta
macciott@ualberta.ca

Michael Hendry
hendry@ualberta.ca

C. Derek Martin
derek.martin@ualberta.ca

[1] Department of Civil and Environmental Engineering, University of Alberta, 6-332 Donadeo Innovation Centre for Engineering, Edmonton, AB T6G 1H7, Canada

[2] Department of Civil and Environmental Engineering, University of Alberta, 6-263 Donadeo Innovation Centre for Engineering, Edmonton, AB T6G 1H7, Canada

[3] Department of Civil and Environmental Engineering, University of Alberta, 6-224 Donadeo Innovation Centre for Engineering, Edmonton, AB T6G 1H7, Canada

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1 Introduction

The Ripley Landslide is a soil slide located in the Thompson River Valley in the Province of British Columbia (Fig. 1) near Ashcroft. This valley hosts an important railway corridor that connects the Port of Vancouver and the rest of the populated parts of North America to the east. Both Canadian Pacific Railway (CP) and Canadian National Railway (CN) use this corridor, and as such, it is vital for the economic health of Canada.

The Thompson River Valley south of Ashcroft has experienced several landslides that have been the subject of study (Stanton 1898; Clague and Evans 2003; Eshraghian et al. 2007, 2008; Bishop et al. 2008). While some of these soil slides have involved volumes of up to 15,000,000 m^3, the Ripley Landslide's estimated volume of 750,000 m^3 is comparatively small. However, because it is moving the fastest and CN and CP's tracks both traverse this landslide, it warrants a proactive hazard management approach.

The Ripley Landslide is estimated to move at a rate between 25 and 180 mm/year (Bunce and Chadwick 2012; Hendry et al. 2015). The landslide velocity classification proposed by Cruden and Varnes (1996) considers very slow and extremely slow landslides (velocities below 1.6 and 15 mm/year, respectively) to have very low destructive significance. The Ripley Landslide velocity is classified as very slow. Examples of structures impacted by very slow and extremely slow landslides that successfully function with regular maintenance are plentiful, e.g. Picarelli (2007), Alonso et al. (2010), Oyagi et al. (1996), Sarkar et al. (2013), Froese (2007), and Brooker and Peck (1993). Mansour et al. (2011) present an analysis of slow-moving landslides within Canada and elsewhere,

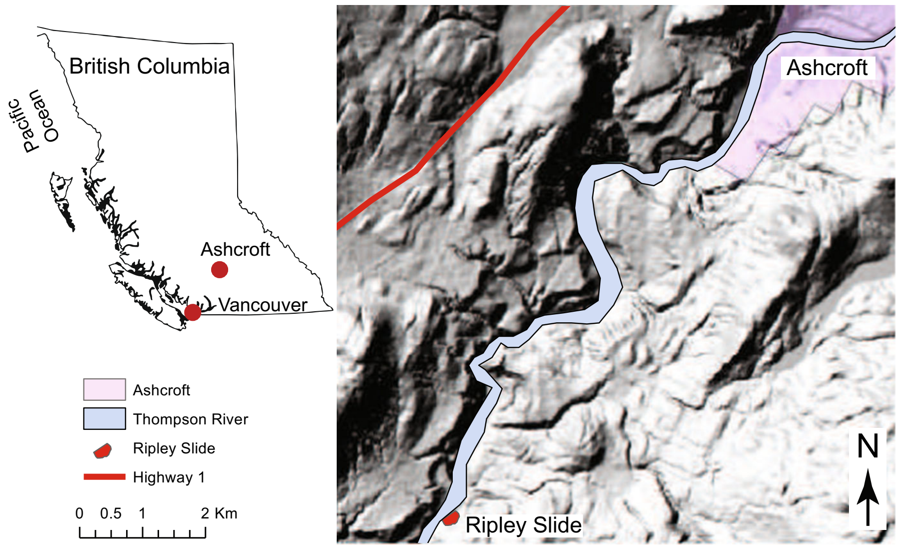

Fig. 1 Location of the Ripley Landslide

detailing the level of damage caused by each landslide and the monitoring approaches adopted.

Even when slow landslides are associated with low destructive significance, monitoring and early warning are essential for hazard management. Recent studies document the development of early warning systems for natural and engineered slopes (Atzeni et al. 2015; Thiebes et al. 2014; Intrieri et al. 2012; Vaziri et al. 2010), and an international workshop held in Italy in 2013 focused on discussing the challenges, problems, and available tools to determine warning criteria (Cloutier et al. 2014). In addition, a volume of the proceedings of the Second World Landslide Forum, dedicated to early warning, instrumentation, and monitoring, has been recently published (Margottini et al. 2013). These recent efforts highlight the need for robust and reliable monitoring and early warning systems as a key part of cost-effective hazard management.

This paper presents the development of an early warning system based on displacement monitoring for the Ripley Landslide. Adequate understanding of landslide deformation mechanisms is essential to develop a reliable early warning system. The deformation mechanisms of the Ripley Landslide are summarized and provide a basis on which to assess the likely slope behaviour preceding a sudden movement leading to collapse of the slope. Displacement monitoring can indicate when cumulative deformations of the slope could lead to excessive damage of existing structures or a transition towards imminent slope collapse (uncontrolled slope acceleration). The system is based on data acquired with a global positioning system (GPS) and a ShapeAccelArray (SAA), which provide near real-time displacement data. The system focuses on warning of potential track deflections, which require lower train speeds be imposed if they occur, as well as uncontrolled acceleration of the slope. The purpose of the system is to provide timely notice for landslide experts to evaluate the hazard level associated with the Ripley Landslide. Analyses of the landslide displacement patterns and near real-time monitoring data are combined with previous studies of landslide-induced railway track deflections and track quality standards to develop early warning displacement thresholds and associated hazard management protocols.

2 The Ripley Landslide

The Ripley Landslide is approximately 200 m long and 40 m high from the highest detected open crack to its projected toe, with a width of approximately 300 m. Figure 2a is a picture of the landslide, highlighting the main scarp and the location of both railway lines. Figure 2b shows a typical cross section of the landslide, which is comprised of overconsolidated glacial deposits (diamicton, glaciolacustrine, and glaciofluvial). The location of the main scarp and inclinometer data has been used to interpret the geometry of the landslide sliding planes in Fig. 2. The sub-horizontal sliding plane at the base of the landslide has been interpreted as a shear surface originated by stress relaxation following glacial melting and river down-cutting. This shear surface could have the potential to extend behind the main scarp, although no signs of present instability have been detected upslope.

The landslide was first identified in 1951 by Charles Ripley (Leonoff and Klohn Leonoff Ltd. 1994). Since then, it has either been inactive or moving so slowly that regular maintenance of the track has kept up to the displacements (Bunce and Chadwick 2012). CN and CP have both recognized the need to increase our understanding of the

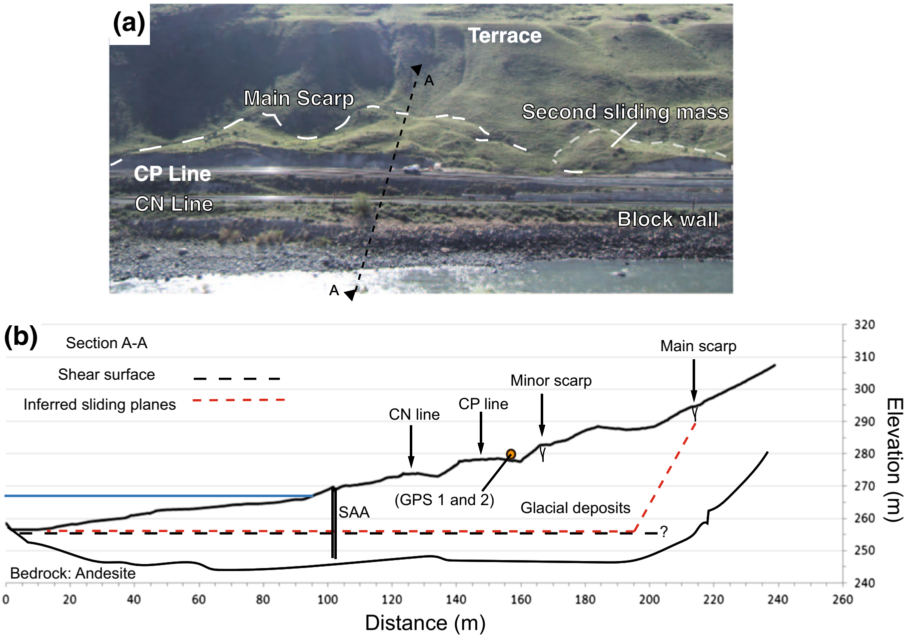

Fig. 2 Frontal view (**a**) and typical cross section (**b**) of the Ripley Landslide. Depths to bedrock are inferred from previous field work and are approximate

mechanisms of and triggers for movement of the slope, as well as to implement a monitoring and early warning system for hazard control.

2.1 Previous studies and slope behaviour

In 2005, CP constructed a new rail siding that required slope cuts and the construction of a lock-block retaining wall. As part of the geotechnical investigation and monitoring for its construction, four boreholes were cored and two inclinometer casings and five vibrating wire piezometers were installed. Shortly after, deformations were noticed at the newly constructed lock-block wall, and the inclinometer casings sheared within 17 months (Bunce and Chadwick 2012; Macciotta et al. 2014).

In 2007, survey pins were installed on the slope to monitor the landslide surface displacement. In 2008, GPS was installed to provide continuous measurements of the landslide displacement and to develop an early warning system (Bunce and Chadwick 2012). Displacement monitoring data and piezometric elevations within the slope have been analysed by several authors (Macciotta et al. 2014; Bobrowsky et al. 2014; Huntley et al. 2014; Hendry et al. 2015), leading to the following conclusions:

(a) The Ripley Landslide is sliding along a weak, shear surface within a high plastic clay layer (Fig. 2b). The materials within the moving soil mass are developing secondary steep shear surfaces.
(b) The elevation of the horizontal sliding surface is coincident with the bottom of the riverbed or slightly below. Thus, the continued down-cutting of the river may result in further instability.

(c) The piezometers indicate that there is an upward hydraulic gradient at the base of the sediment layer containing the slide base.

(d) The pore pressures within the landslide are defined by both the regional hydrogeological regime and the elevation of the Thompson River (Bishop et al. 2008). When the river is at its highest level, the slope velocity is at its lowest. This most likely corresponds to increased stability of the landslide due to a combination of a buttressing effect of the river and the increase in mobilized shear strength with increasing effective stress along the sliding surface (evaluated numerically by Hendry et al. 2015).

CP completed a risk assessment of the Ripley Landslide, comparing the risk to life and the environment with the cost of stabilizing the slope. The risk to life and the environment was concluded to be extremely low, but that stabilizing the slope would be costly, may not be effective, and could have a substantial negative impact on the Thompson River (Bunce and Chadwick 2012). Therefore, a monitoring and early warning system based on GPS was adopted to manage the risks associated with the operations and to increase understanding of the displacement mechanisms and potential triggers for sudden movement.

The monitoring instrumentation at the Ripley Landslide was enhanced in May 2013 (Macciotta et al. 2014), as illustrated in Fig. 3. A Measurand Inc. ShapeAccelArray (SAA in figure inset) was installed within a borehole cored in the vicinity of a previous inclinometer. Nine steel corner reflectors (GSC in figure inset) were installed and their

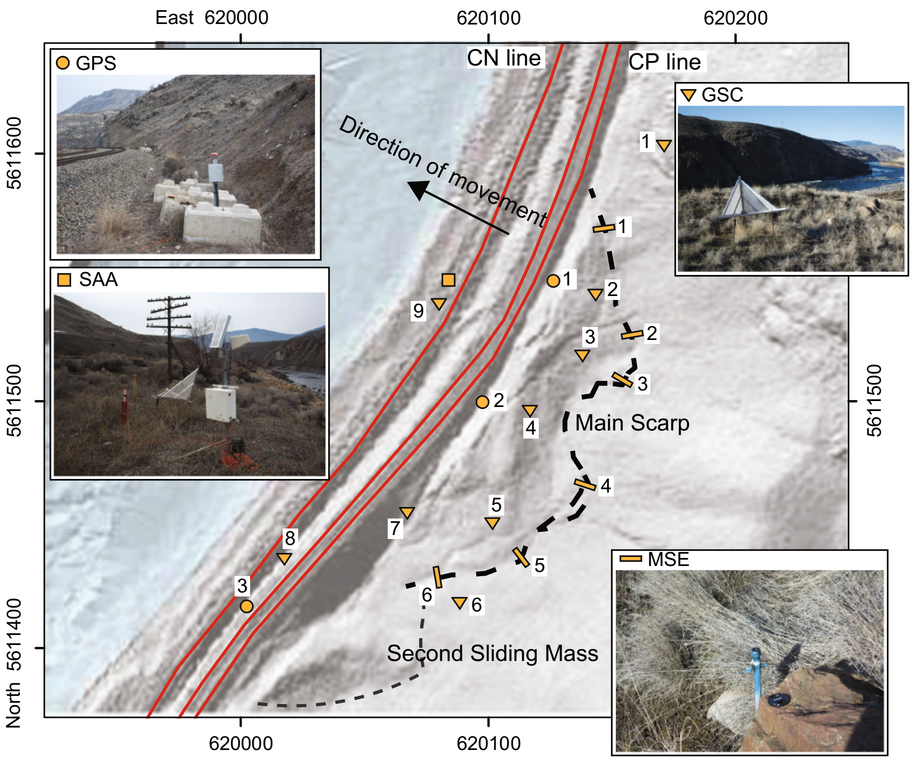

Fig. 3 Location of instruments measuring the landslide displacement

displacement tracked via satellite interferometric synthetic aperture radar (InSAR). Manual measurements of the extension of the main scarp were initiated (MSE in figure inset), and laser scans of the slope were also taken from a ridge across the Thompson River from the landslide. The scans had an average 10 cm resolution and were combined with the existing bathymetry of the Thompson River bed and used to generate a digital elevation model with values every 0.2 m. The extensive array of displacement monitoring tools is being used to gain increased knowledge about the details of deformation patterns of the slope.

3 GPS and SAA displacement monitoring of the Ripley Landslide

3.1 GPS monitoring system

The existing system consists of three GPS monitoring stations (Fig. 3) and one reference station located on stable bedrock outside the landslide area. The Leica GPS stations consist of single-phase receivers in a differential GPS mode. It has been demonstrated that the system is capable of detecting 12.5 mm of cumulative ground movement with a variability of ±1 mm. Leica GeoMOS software is used to retrieve GPS data, which basically consist of latitude, longitude, and vertical positioning coordinates (daily average of hourly recorded GPS position) that are processed to calculate lateral and vertical displacements (Bunce and Chadwick 2012).

Figure 4 shows the cumulative displacement measured by the three GPS stations between February 2008 (at installation) and September 2014. Horizontal displacement in the direction of slope movement increases towards the positive values, and negative changes in elevation correspond to downward displacement. Data gaps in Fig. 4 correspond to periods of time when the system did not record positioning due to system malfunction, upgrades being installed or required maintenance. These measurements suggest that the landslide is moving towards the Thompson River at an average velocity over the monitoring period of 60–100 mm/year. The displacement is less at the north end of the landslide (between 60 and 70 mm/year based on GPS 1 and GPS 2) than at the south end (100 mm/year based on GPS 3). The rate of vertical settlement also increases towards the south portion of the landslide; GPS 1 and 2 show about 20 mm/year of vertical

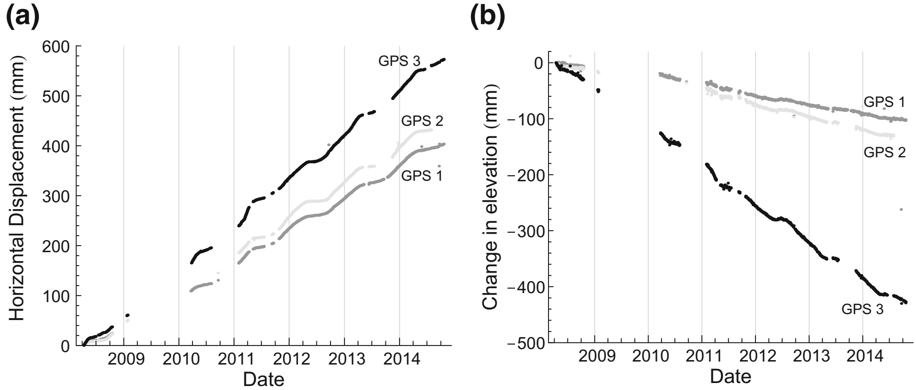

Fig. 4 GPS cumulative horizontal (**a**) and vertical (**b**) displacements

settlement, whereas GPS 3 shows closer to 80 mm/year. However, GPS 3 is located on a retaining wall which may be exaggerating the vertical movement of this location. Both the horizontal displacements and vertical settlements show a seasonal deformation trend that accelerates in the cold months and is near zero in the warm months. During the active period of the landslide (September through May), the average horizontal velocity is between 0.2 and 0.35 mm/day.

3.2 ShapeAccelArray (SAA)

An SAA was installed in May 2013 within a borehole located in the toe of the slope. Its location is shown in the cross section in Fig. 2b and the plan view in Fig. 3. The SAA consists of 33 segments and an overall length of 10 m, between elevation 250.5 and 260.5 m above sea level (masl). SAA data consist of relative displacements measured every hour.

Figure 5a shows the cumulative horizontal displacement with depth measured by the SAA. The shear surface identified by the SAA is at an elevation between 256 and 257 masl. Both the magnitude of the displacements and the elevation of the shear plane in Fig. 5a are consistent with the GPS measured displacements and inclinometers. The vertical displacement profiles are sequenced in 6-month intervals (Fig. 5a). The slope displacement measured by the SAA is concentrated along its shear surface, with no significant measured displacement above or below.

Figure 5b shows the total horizontal displacements measured by the SAA across the shear surface. The onset and halt of displacements are consistent with the GPS measurements and indicate the landslide accelerates in September and decelerates in May of each year. The amount of displacement measured by the SAA during the active period was just over 80 mm, which is consistent with GPS measurements.

4 Early warning system based on displacement monitoring

As noted above, the cyclic slope displacement and velocities of the Ripley Landslide have been associated with low risk to life and the environment (Bunce and Chadwick 2012), and the impact of slope deformation on railway operations is successfully managed with

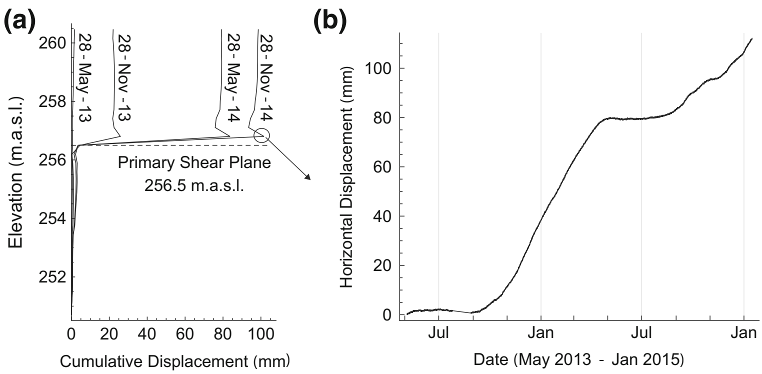

Fig. 5 SAA displacements with depth (**a**) and total displacement across the shear surface (**b**)

regular maintenance of the railway alignment. Therefore, the level of stability of the Ripley Landslide can be considered adequate, provided the cyclic deformation pattern remains unchanged. Two types of unfavourable changes in the slope deformation can be foreseen. One is a significant increase in the measured displacement (or velocity), such that railway operations cannot continue in a safe manner because of deviations in the railway alignment. The other is a sudden motion of the landslide leading to a collapse of the slope. Monitoring and early warning aims to inform landslide experts of excessive deformations and any potential for a sudden collapse of the slope into the Thompson River. This requires understanding the annual displacement trends, periods of active deformation, average velocities, and maximum velocities in the short term.

4.1 Expected landslide behaviour

A thorough understanding of the landslide deformation mechanism is required to develop a reliable early warning system based on displacement monitoring. The deformation mechanisms of the Ripley Landslide discussed in Macciotta et al. (2014) and Hendry et al. (2015) and summarized above provide a basis on which to assess the likely slope behaviour preceding a sudden movement leading to collapse of the slope. The annual displacement trends and velocities provide a baseline measure of the slope behaviour.

The cyclic balance between driving forces and resisting forces governs the movement of slow landslides sliding over fully formed shear zones (Picarelli 2007). As further sliding occurs after initial formation of the shear zone, the frictional resistance along the sliding surface (or surfaces) reaches a residual state. Subsequent sliding occurs every time the residual strength is mobilized. This implies that the main contributors to velocity changes in the short-term are the boundary conditions of the landslide (i.e. imposed surcharge loads, pore pressure fluctuations).

If the boundary conditions change gradually, the response of the landslide should be a similar gradual change in velocity. However, the potential for a sudden collapse of the slope with little warning exists if gradual changes in boundary conditions (and further sliding) lead to one of three conditions:

1. A sudden change in the relationship between driving and resisting forces after a critical geometric configuration is reached, such as loss of the landslide toe due to river erosion, or steeper downslope topography. The Ripley Landslide has a confined geometry (Hendry et al. 2015), where the rate of river erosion at its toe seems to be gradual and balanced with the slope's gradual change in geometry as it deforms. Sudden erosion at the toe can only be foreseen for extreme flood events of the Thompson River. Other scenarios would require an abrupt morphological change, which is considered unlikely.
2. The landslide is composed of metastable materials that are prone to a collapse of their internal structure with further straining of the landslide. The Ripley Landslide is not composed of metastable materials, but over consolidated glacial deposits (Huntley and Bobrowsky 2014), therefore this condition is not applicable; and
3. A change in landslide deformation mechanisms such as full development of internal shearing required for the kinematical feasibility of the slide or the progressive failure of brittle materials. The internal shearing required for the kinematical feasibility of the Ripley Landslide (formation of internal wedges) is likely fully developed, as suggested by active tension cracks in the body of the landslide (Huntley and Bobrowsky 2014; Macciotta et al. 2014).

Therefore, a sudden collapse of the Ripley Landslide without measurable changes in displacement trends or increased accelerations is considered unlikely.

The current displacement trends of the slope were considered tolerable and are the baseline to assess the potential sudden collapse of the slope. Based on the preceding discussion, it is expected that a sustained acceleration of the slope movement will occur prior to collapse, in excess of that observed during typical annual cycles. This requires that the time between the onset of the sustained slope acceleration and collapse is large enough to allow for proper warning and risk mitigation actions to be in place. The connection of the GPS monitoring system to the wayside train control provides the timely response needed, provided the warning thresholds are appropriately set (See Bunce and Chadwick 2012).

4.2 Annual displacement trends

Compared with the annual horizontal displacement measured by the SAA (Fig. 5), the GPS is able to provide a longer period of measurements on which to assess the timing and magnitude of the slope deformation cycle. Annual horizontal and vertical displacements measured by the GPS for the active periods of 2011–2012, 2012–2013, and 2013–2014 are depicted in Fig. 6 and summarized in Table 1.

Figure 6 shows a consistent annual displacement cycle with an active period between September and May, as discussed in Sect. 3.1. Annual variations are less than 5 mm for GPS 1 and GPS 2; however, GPS 3 shows larger variations in cumulative displacement. These variations have not shown a clear increasing or decreasing trend. Based on GPS displacement data, horizontal displacements of about 70 mm in GPS 1 and 2, and up to about 100 mm in GPS 3, are considered representative of the annual displacement cycle. Changes in elevation about −20 mm/year for GPS 1 and 2 and up to −80 mm/year for GPS 3 are considered representative.

Horizontal velocities and elevation change velocities were calculated using

$$R_i = \frac{D_i - D_{i-1}}{\Delta t}, \tag{1}$$

where R_i is the velocity at time i, D_i is the cumulative displacement at time i, and Δt is the time period between measurements. GPS displacements are based on the daily average of hourly position records. Therefore, Δt corresponds to 1 day and i is the date of the measurement. The velocity is expressed in units of mm per day. As an example, Figs. 7 and 8 show the horizontal velocity and elevation change velocity for GPS 3, respectively.

Figures 7 and 8 show the daily-average value, the 7-day running average, and the 35-day running average for GPS 3 for the 2-year period between October 2012 and October 2014. The running average for any given window size was calculated using

$$\bar{R}_{iw} = \frac{\sum_{i-\frac{(w-1)}{2}}^{i+\frac{(w-1)}{2}} R_i}{w}, \tag{2}$$

where $\bar{R}_{iw}$ is the running average of the velocity with a window size w at time i. For the GPS measurements, w is in day units.

Figure 7 shows that the 35-day running average of the daily-average position of GPS 3 provides a close representation of the seasonal trend of horizontal velocities. The 7-day running average shows some variability with respect to the seasonal trend, likely a combination of real velocity fluctuation in the short term and scatter of the measurements. The

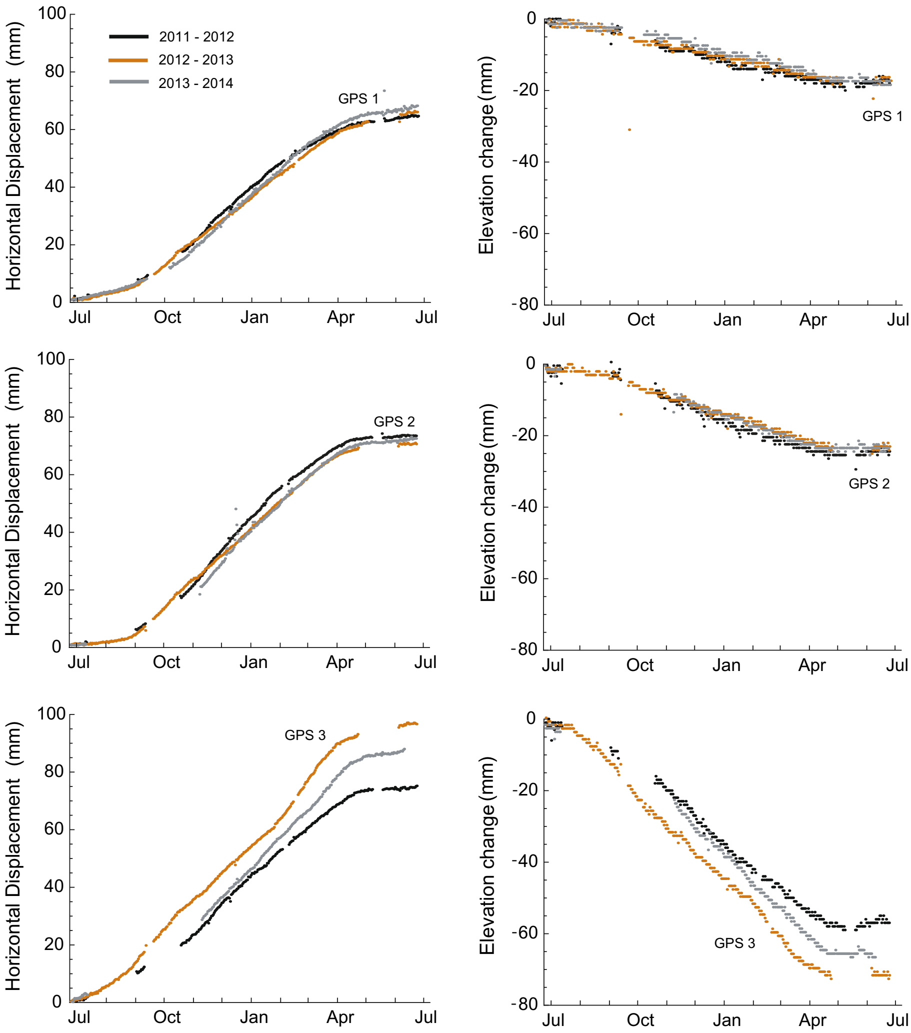

Fig. 6 Annual (July to June) cumulative displacement of GPS stations

trends of elevation change velocity were not clear based on data from GPS 1 and GPS 2; however, GPS 3 (Fig. 8) data show a clear seasonal trend (35-day running average). The scatter of the 7-day running average for the elevation change velocity is too large to observe any short-term fluctuation in velocity. It is worth noting the differences in accuracy between horizontal and vertical measurements. Vertical accuracies for these GPS units are 2–3 times that of the horizontal accuracy (USGS 2014). Analysis of GPS data will mainly focus on the horizontal displacement measures, particularly when displacement rates are being assessed.

Table 2 presents a summary of the maximum velocities measured by the GPS. Running average windows shorter than 7 days were considered to have too much scatter for any trend to be clear. This variability is discussed later in this section.

Table 1 Summary of annual displacements

Year	Cumulative horizontal displacement (mm)				Cumulative elevation change (mm)		
	GPS 1	GPS 2	GPS 3	SAA	GPS 1	GPS 2	GPS 3
2011–2012	64	73	75	–	−17	−24	−56
2012–2013	65	70	96	–	−17	−22	−72
2013–2014	67	72	88	80	−18	−23	−65

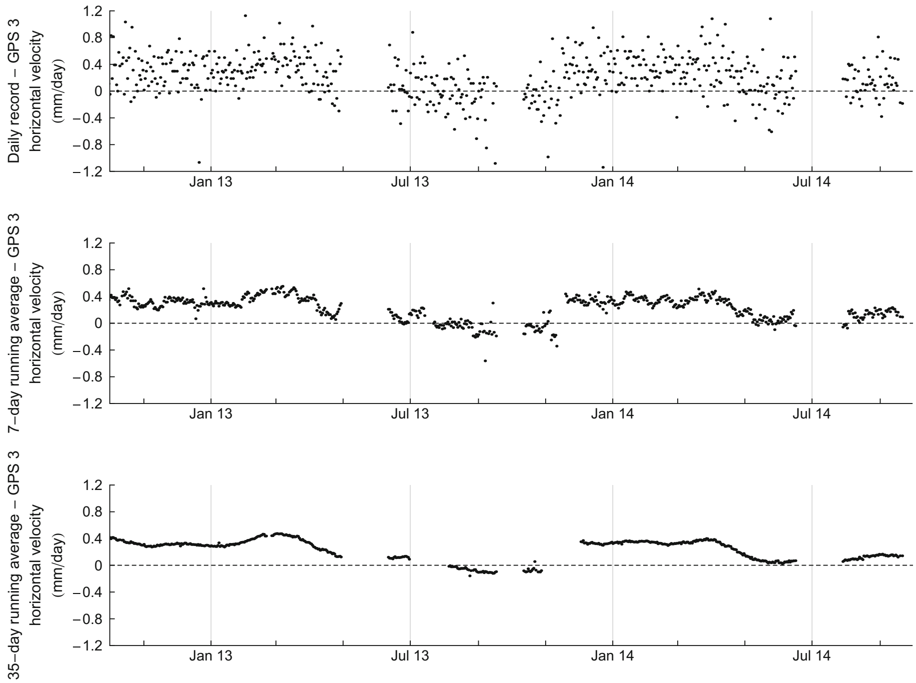

Fig. 7 Horizontal velocities of GPS 3 for the 24-h measurements, and the 7-day and 35-day running averages

Table 2 shows that the seasonal horizontal velocity during the active period of slope motion can reach 0.4 mm/day at GPS 1 and GPS 2 and up to 0.5 mm/day at GPS 3. Short-term accelerations, as estimated from the 7-day running average values, increase this rate to up to 0.6 mm/day. The seasonal elevation change velocity during the active period of slope motion can reach 0.3 mm/day. The 7-day running average of the elevation change velocity also suggests that short-term vertical rates could reach up to 0.6 mm/day; however, as discussed previously these values show more scatter.

Figure 9 shows the total horizontal velocity measured by the SAA. SAA measurements correspond to hourly readings; therefore i, Δt, and w in Eqs. (1) and (2) are in units of hours. However, velocities are presented in mm/day to be consistent. Figure 9 shows the hourly rate and running average windows of 12 h and 3, 7, and 35 days. The SAA seasonal trend in horizontal velocity (represented by the 35-day running average) during the 2013–2014 active period reached a rate of 0.5 mm/day, consistent with the GPS. The short-

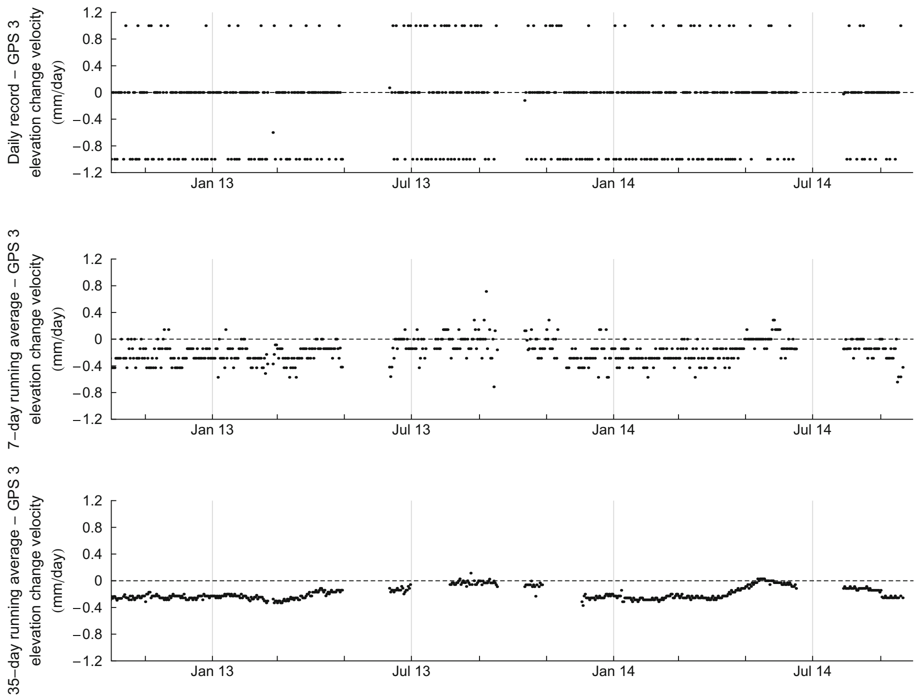

Fig. 8 Elevation change velocities of GPS 3 for the 24-h measurements, and the 7-day and 35-day running averages

Table 2 Summary of maximum GPS velocities measured

GPS station	Measured maximum velocity (mm/day)			
	Horizontal		Vertical	
	35-day trend	7-day running average	35-day trend	7-day running average
GPS 1	0.4	0.55	0.2	0.6
GPS 2	0.4	0.5	0.2	0.6
GPS 3	0.5	0.6	0.3	0.6

term trend (represented by the 7-day running average) reached maximum values of about 0.6 mm/day, also consistent with the GPS.

4.3 Short-term velocities

The 7-day running average of both the GPS (Fig. 7) and the SAA horizontal velocities (Fig. 9) provide a means to evaluate short-term trend variations in displacement. However, for an early warning of a potential sudden collapse of the slope, the 7-day running average window may be ineffective if the instability progresses faster. Thus, the GPS and SAA measurement scatter was further analysed to evaluate a suitable metric for an early warning under such scenario.

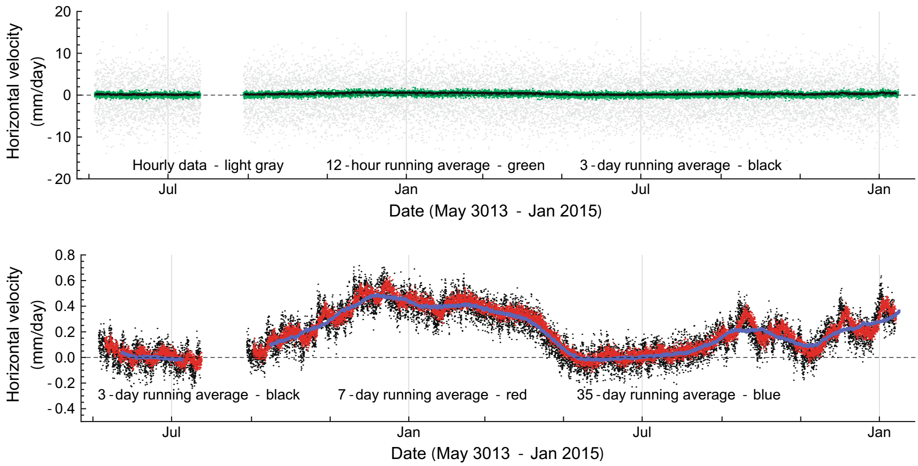

Fig. 9 Horizontal velocities measured by the SAA

Figure 10 shows the horizontal velocities for GPS 1 (daily, 7-day running average, and 35-day running average—top), SAA 24-h and 7-day running averages (centre), and SAA daily average (bottom). This figure focuses on data from January to May of 2014 for illustrative purposes. The SAA daily-average calculations (bottom in Fig. 10) are based on the average velocities of the 24 SAA measurements within a given day. The SAA calculations are compared against a trend (black line in Fig. 10 centre and bottom) calculated as a weighted average. For each daily calculation of this trend, the weight value selected was 7 for the measure on the day being assessed. The weight then decreases by 1 each day forward or backwards. This means that each weighted average considered 13 days of data. This weighted average can be easily calculated by the 7-day running average of the 7-day running average. This double average successfully captured variations in velocity and minimized scatter.

Further analysis assumes that the SAA and GPS trends in velocity can be approximated by the double average and the 35-day running average, respectively. The measurement scatter was then quantified by estimating their dispersion around the trend. The dispersion was calculated as the difference between measurements and the trend according to

$$\Delta R_{iw} = R_{iw} - R_T, \tag{3}$$

where R_{iw} is the rate measurement at date i for a running average with a window size w, R_T is the rate trend for the same date, and ΔR_{iw} is the difference. A value of zero represents no dispersion, and positive and negative values indicate the measurement is larger than or lower than the trend, respectively. Figures 11 and 12 present the frequency distribution of ΔR_{iw} for the GPS and for the SAA, respectively.

These figures show the large dispersion of the GPS daily-average measurements and the SAA hourly measurements, which correspond to the large scatters shown in Fig. 10. There is a dramatic decrease in dispersion for all other average horizontal rate measurements, illustrated by frequency distributions accumulating towards zero. The vertical rate measurements of the GPS appear more dispersed and even shifted towards positive values. Only for a 21-day running average window do the distributions accumulate towards zero.

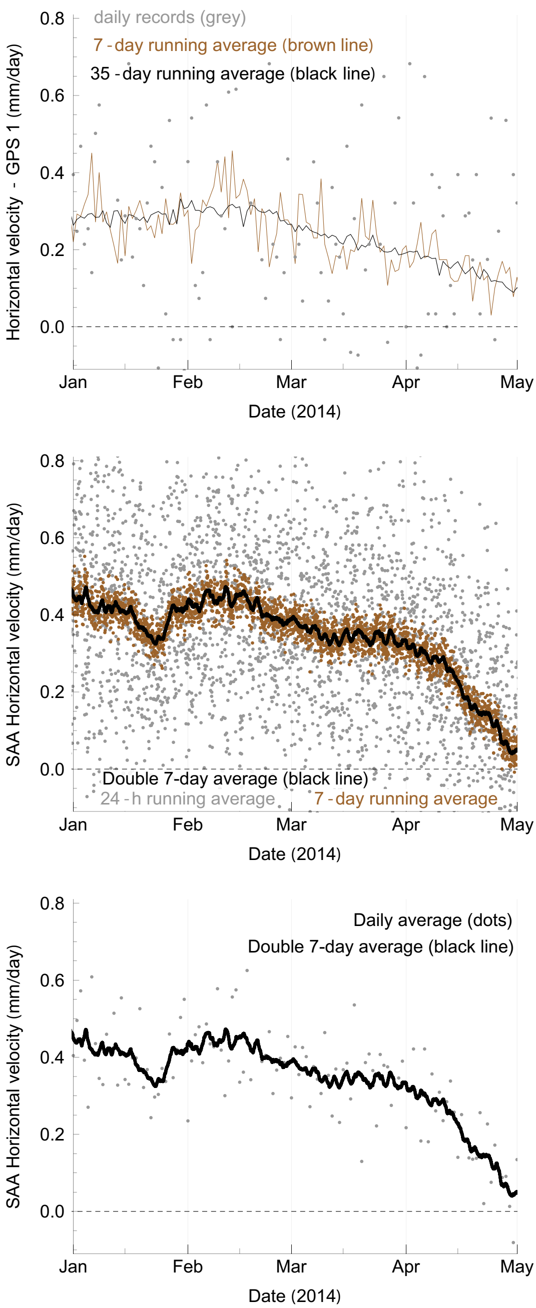

Fig. 10 Horizontal velocities for GPS 1 (*top*), SAA 24-h and 7-day running averages (*centre*), and SAA daily average (*bottom*), compared against trends

The maximum and minimum values of ΔR_{iw} as well as the 0.5 and 99.5 % percentiles of the frequency distributions in Figs. 11 and 12 were used to assess the dispersion of velocity measurements. These values are presented in Table 3.

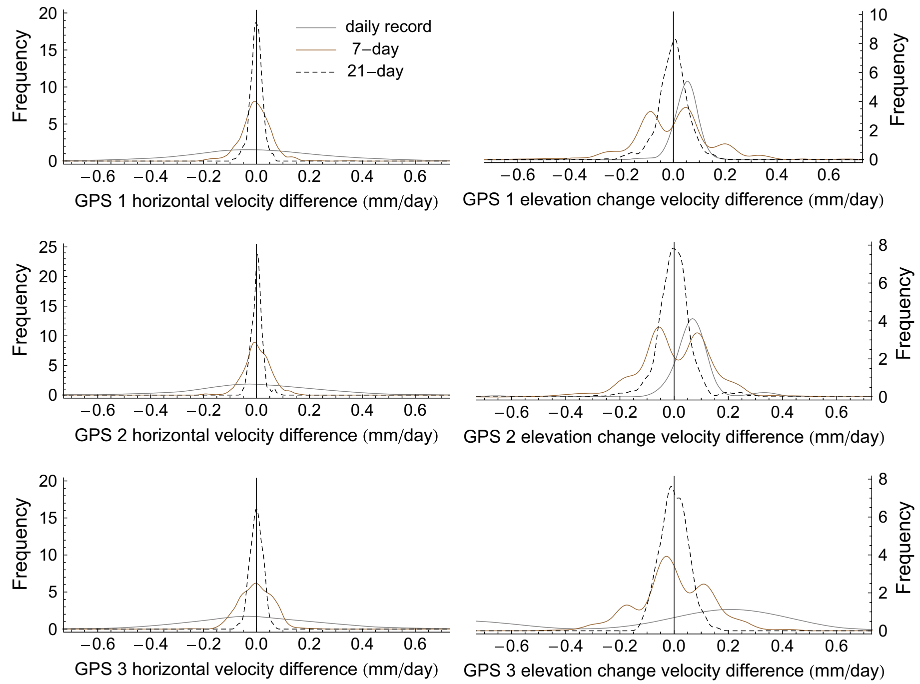

Fig. 11 Dispersion of GPS horizontal velocity and elevation change velocities with respect to the displacement trend (35-day average)

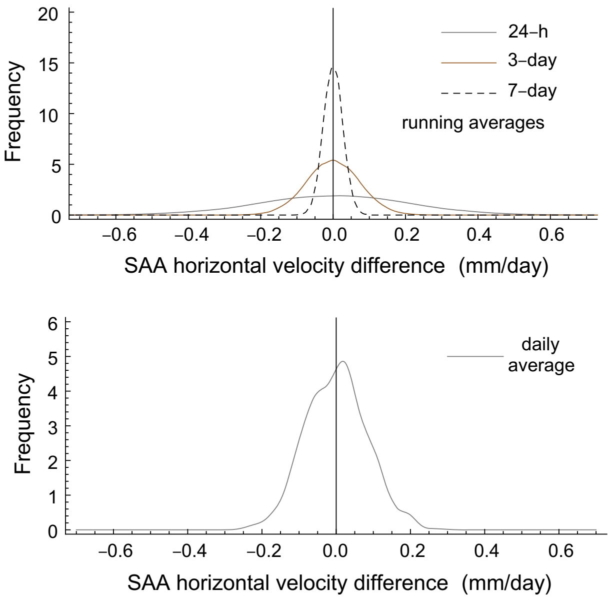

Fig. 12 Dispersion of SAA horizontal velocities with respect to the displacement trend

4.4 Proposed early warning system based on displacement monitoring

An early warning system at the Ripley Landslide based on displacement monitoring should be able to monitor:

1. The annual displacement cycle. Focused on deviations from seasonality (onset and end of active period), total annual displacements and average displacement rates. Variations of these could suggest an evolution of the deformation mechanisms, kinematics, or a transition towards a less stable condition; and
2. Sudden accelerations. These could accuse the onset of processes leading to a collapse of the slope and could lead to unacceptable railway track configurations.

The system proposed in this study aims to provide timely warning for landslide experts to intensify observations of the Ripley Landslide.

As noted above, the annual displacement cycle is characterized by a most active period between September and May, with total horizontal displacements between 60 and 80 mm in the north area and up to about 100 mm in the south area. The total elevation change is about −20 mm in the north and up to about −70 mm in the south area, with maximum measured horizontal velocities (as per the 7-day running average) of about 0.6 mm/day. Displacements outside of the active periods or increases in annual deformations or deformation rates could indicate a change in the slope deformation mechanism that could be associated with a change in risk. Deviations from the annual displacement cycle should be communicated to a ground hazards expert for analysis.

Transport Canada has published Rules Respecting Track Safety, which include the maximum tolerances for deviations of the railway track geometry from its intended configuration (Transport Canada 2011). These tolerances depend on the class of the track, which are associated with operating speed limits. Across the Ripley Landslide, normal freight speeds can exceed 64 km/h, which makes this section a Class 4 track. Hendry et al. (2013) show

Table 3 Summary of the dispersion of horizontal velocity measurements

Values in mm/day	Percentile		Difference	
	0.5 %	99.5 %	Minimum	Maximum
GPS 1—daily record	−1.07	1.49	−7.98	8.46
GPS 1—7-day running average	−0.19	0.24	−1.10	1.07
GPS 1—21-day running average	−0.09	0.06	−0.30	0.36
GPS 2—daily record	−0.92	1.06	−1.03	1.37
GPS 2—7-day running average	−0.19	0.16	−0.20	0.16
GPS 2—21-day running average	−0.05	0.08	−0.05	0.09
GPS 3—daily record	−0.72	1.04	−1.36	1.51
GPS 3—7-day running average	−0.15	0.18	−0.24	0.22
GPS 3—21-day running average	−0.07	0.06	−0.08	0.07
SAA—daily average	−0.22	0.21	−0.88	0.58
SAA—24-h running average	−0.53	0.53	−0.75	0.78
SAA—3-day running average	−0.19	0.19	−0.28	0.28
SAA—7-day running average	−0.07	0.07	−0.10	0.10

based on track geometry measurements that track alignment is most influenced by the deformation of the Ripley Landslide. The alignment is evaluated as the mid-point offset of an 18.9 m (62 foot) chord. For a Class 4 track, deviations in alignment exceeding 38 mm require a slow order to be issued and repairs to be carried out within 72 h (Transport Canada 2011). The 12.5 mm/day threshold proposed by Bunce and Chadwick (2012) for warning trains is one-third of this threshold, and the total magnitude is comparable if this movement rate was sustained, given the time frame for correction of the defect. Hendry et al. (2013) analysed the relationship between the displacement of the Ripley Landslide as measured by the GPS and the deviation in track alignment. They showed annual track alignment deviations mostly between 5 and 20 mm, with one measurement reaching 25 mm. This suggested that maximum track alignment variations are significantly smaller than the cumulative landslide displacement. Hendry et al. (2013) attributed this difference to landslide deformations being accommodated by a large section of track. Moreover, they concluded that the current velocity of the landslide is effectively managed with normal maintenance practices, from the point of view of railway operations.

Considering a Class 4 track (maximum alignment deviation threshold of 38 mm), annual average displacement of 70 and 90 mm in the northern and southern sections of the landslide, and alignment deviations of 20 mm, the landslide displacement (MD) required to reach the Class 4 track deviation maximum threshold can be approximated as

$$\mathrm{MD}(\mathrm{mm}) = \frac{D(\mathrm{mm}) \times 38\,\mathrm{mm}}{20\,\mathrm{mm}}, \tag{4}$$

where D is the annual landslide displacement (northern or southern sections). Solving for the value of MD suggests that landslide displacements of about 130 and 170 mm in the northern and southern areas of the landslide, respectively, could lead to excessive deformations for Class 4 tracks.

Note that this approach assumes a linear relationship between landslide displacement and deviation in track alignment. Adopting this simplified approach was justified by the translational kinematics of the landslide, where the soil mass is sliding along a sub-horizontal shear surface. There is uncertainty associated with this simplification; however, it allows for estimating landslide deformations required to reach excessive track deviations and based on measurements in situ.

Maximum measured horizontal velocities of about 0.6 mm/day correspond to short-term rate calculations using both GPS and SAA measurements. Sustained increases in velocities above this value could reflect a progressive acceleration of the slope with the potential to lead to a sudden collapse of the Ripley Landslide. Bunce and Chadwick (2012) suggest that if the GPS indicates movement in excess of a threshold value of 12.5 mm in any 24-h period trains be directed to proceed across the landslide at a slow enough speed such they can stop within half their sight distance. In addition, we suggest that an early warning system also utilize criteria consisting of a velocity threshold that, if exceeded, triggers a request for close observation of slope behaviour by a landslide expert. Such a warning would require a short-term velocity calculation, near real-time, and with minimum scatter. The dispersion values presented in Table 3 show that 99 % of the SAA daily-average measurements fall within ±0.22 mm of the estimated trend. The SAA daily average was considered a good compromise between data scatter and required averaging time (24 h). The scatter was considered acceptable when compared with the maximum accelerations measured (0.6 mm/day). However, this scatter needs to be considered when formulating the warning criteria in order to minimize unnecessary warnings. In this regard, a threshold between 1 and 1.5 mm/day is suggested as appropriate.

With the above considerations, an early warning system for the Ripley Landslide is proposed in Table 4. In the top section of this table, thresholds are set to identify deviations from annual displacement trends that might accuse evolution of the landslide mechanisms towards a more unstable state. Proposed protocols, given these thresholds are exceeded, correspond to intensification in landslide monitoring and observation to assess the implementation of risk mitigation strategies. This includes sustained accelerations over 1.5 mm/day. The intensified monitoring if this rate is exceeded aims at identifying potential rapid accelerations of the landslide that would require avoidance of the area and preparedness to deal with its consequences. This section of the table deals with the safety of operations.

The lower section of Table 4 deals with the serviceability of the railway track with regard to the landslide movement. These thresholds aim at identifying potential deviations of the track beyond Class 4 standards. The associated protocols aim at timely inspections of the track if excessive deviations are suspected.

The proposed warning system has been tested with monitoring data between 1 May 2014 and 24 August 2015. Figure 13 presents the SAA cumulative horizontal displacement and daily-average horizontal displacement rates for this period. Horizontal velocities, cumulative horizontal displacement, and annual displacement were all below the criteria. The only noticeable feature was the start of acceleration in 2015 (July 10), which is early compared to most other annual observations. It is believed that the dry conditions in the area during this period of time might have lead to an earlier decrease in river level, thereby removing the river buttressing effect on the landslide and triggering its acceleration at an earlier date. Cumulative displacements and accelerations are being closely monitored by the GPS and SAA systems to detect any longer change in annual trends.

Table 4 Proposed early warning system and associated protocols

Scenario	Proposed Protocols
No change	Continue monitoring
Change in annual displacement cycle: Annual horizontal displacement - GPS 1 or GPS 2 > 90 mm - SAA > 100 mm - GPS 3 > 130 mm Annual elevation change - GPS 1 or GPS 2 > 40 mm - GPS 3 > 90 mm Annual horizontal displacement between May and September > 25 mm SAA daily-average horizontal velocity > 1.5 mm/day	The change in annual landslide displacement cycle might be related to a change in deformation mechanism and variation of the risk associated with the landslide. Sustained velocities above previously observed or sustained landslide acceleration could suggest a potential sudden collapse of the slope. - Continue monitoring - Communicate change in landslide behaviour to ground hazards expert - Assess risk level and mitigation options - Implement risk mitigation options if necessary
Displacement related to track geometry: Cumulative horizontal deformation - GPS 1, GPS 2 or SAA > 130 mm - GPS 3 > 170 mm	Horizontal displacements above these thresholds could potentially cause deviations of the alignment of the railway track beyond Class 4. - Communicate information to ground hazards expert - Implement management strategies if necessary

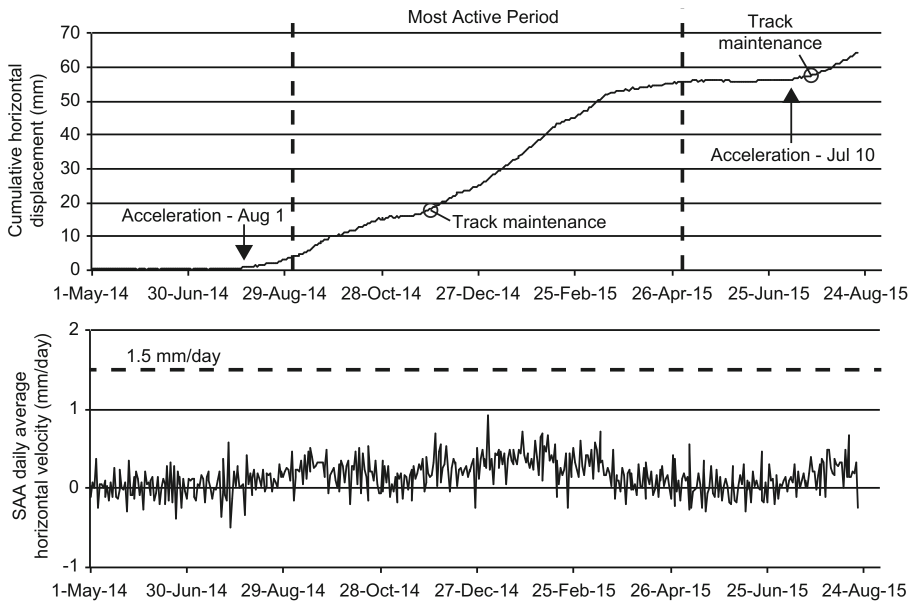

Fig. 13 SAA cumulative horizontal displacement and daily-average horizontal rate between 1 May 2014 and 24 August 2015

Figure 13 also shows track maintenance during this period of time. It has to be noted that maintenance records indicate that corrected sections were limited, 10–20 m long, and that each maintenance date corresponds to different locations of different tracks. Cumulative landslide displacements starting on these dates can be used to assess when track deflections increase towards thresholds for Class 4 track at these locations.

5 Conclusions

The Ripley Landslide is a very slow soil slide moving on a fully developed, sub-horizontal, basal shear surface. Its significance is associated with the presence of two important railway lines along its toe. Displacement of the Ripley Landslide is being monitored through several approaches, including a GPS monitoring system that provides real-time measurements of the position of three locations on the surface of the landslide and a SAA that provides real-time slope displacement with depth at one location. The monitoring system shows an annual cycle of slope deformations most active between September and May. Annual horizontal displacements range between 60 and 80 mm in the north area of the slope to about 100 mm in the south area of the slope. Elevation changes range between 25 and 80 mm for the north and south areas, respectively. The average horizontal velocities during the active displacement period are between 0.2 and 0.35 mm/day, with maximum velocities of up to 0.6 mm/day.

It was illustrated how the GPS lost information for some periods, but generally allows for consistent measurements of the annual displacement cycle and is judged to be adequate for monitoring long-term behaviour of the landslide as well as excessive displacements in short periods of time. The SAA provides more continuous measurement of displacements and a finer resolution that allows for short-term velocity monitoring of the landslide. However, the amount of deformation of the slope will shear the SAA casing; therefore, it is expected to only provide reliable measurements for 3 years before replacement is necessary. In this regard, the SAA is not an adequate tool for monitoring long-term landslide behaviour. The GPS and SAA systems are complementary and together provide another option for managing the risks associated with the Ripley Landslide.

An early warning system was developed for the landslide based on displacement monitoring. The system aims to identify deviations from annual displacement trends that might accuse evolution of the landslide mechanisms towards a more unstable state that could eventually lead to a collapse of the slope, and identify potential deviations of the track that could compromise its serviceability. The limitations of the system are associated with the short lifespan of the SAA casings at this location (3 years), and the need for constant power and remote data transfer. Although this last one is common to many monitoring systems, the lifespan of the SAA casing can represent a sensitive cost. It is important to note that the system considers a simple linear relationship between landslide displacement and track deformation. It is likely that the relationship between these evolves following further disaggregation of the slope-forming materials. This will require continuous updating in light of newly acquired displacement information. The system, however, provides a robust approach that considers safety and serviceability of railway operations. It was tested for recently acquired data, showing detailed and continuous landslide displacement measurements that allowed for trends and displacement rates to be assessed with no false warnings triggered.

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