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A proactive approach to slope failure alarming by utilising velocity ratio as a parameter to deal with line-of-sight concerns for a Slope Stability Radar™

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Abstract

The Slope Stability Radar (SSR)™ is a popular tool for monitoring slopes in mining operations due to its ability to obtain sub-millimetre precision using the interferometry method. However, the effectiveness of the SSR also depends on its position with respect to the pit geometry and angle of incidence, as it only measures slope movement in the line-of-sight of the radar.

The conventional alarm system based on deformation and velocity thresholds can be affected by geometry and angle of incidence, leading to alarms being triggered at different times, even in the same deformation area that is being monitored. In order to address this limitation, the authors propose utilising the velocity ratio (VR) to reduce the impact of vector losses and improve alarm accuracy. The VR is a dimensionless number resulting from the comparison of two movement rates, reference against the current, and estimates of how a wall is moving in the present versus in the past.

For this study, the parameters of deformation, velocity, and VR were extracted from six sensor samples during the linear deformation phase. The statistical analysis revealed that the standard deviation of VR exhibited the lowest value compared to deformation and velocity. These findings highlight the advantages of employing VR alarms, as they simplify the determination of a single threshold value. This streamlined approach is particularly advantageous in cases where varying magnitudes of velocity are observed across different sections of a slope. On the contrary, utilising basic velocity analysis to achieve similar warning times across different slope sections would necessitate the use of varying thresholds, leading to increased complexity in alarm definition.

This approach with VR has the potential to improve the site's geotechnical decision-making process, as it enables real-time monitoring of slope stability with greater accuracy and reduces the risk associated with the 'unknowns' related to catastrophic slope failures.

Keywords: *open pit, Slope Stability Radar, line-of-sight, alarm, velocity ratio*

1 Introduction

The Slope Stability Radar (SSR)™ is a popular tool for monitoring slopes in mining operations due to its ability to obtain sub-millimetre precision using the interferometry method. However, the effectiveness of the SSR also depends on its position with respect to the pit geometry and angle of incidence, as it only measures slope movement in the line-of-sight (LOS) of the radar. As a result, there is a potential for underestimating the true magnitude of slope deformation, thereby impacting alarm threshold exceedance, which commonly relies on the conventional alarm system based on deformation and velocity thresholds. This can result in alarms being triggered at different times, even within the same deformation area. Setting the threshold value excessively high introduces the risk of missed alarms during critical events, while setting it too low may lead to persistent false alarms. The objective of this paper is to propose the utilisation of velocity ratio (VR) to reduce the impact of vector losses and improve the accuracy of alarms. By implementing this approach, it is anticipated that the impact of the SSR's limitations can be minimised, resulting in more precise and reliable alarm triggers. The paper further explores the SSR alarm system, presents case studies of SSR operation in various mines, and critically evaluates the limitations associated with these alarm systems.

2 SSR monitoring system

The SSR remotely scans rock slopes to continuously measure any surface movement and can be used to detect and alert users of wall movements with sub-millimetre precision (Noon et al. 2001). It utilises the interferometry method to measure deformation by collecting data of the phase difference calculation. The SSR transmits a signal to the wall, which is then reflected. Each reflected signal received by the radar has its own wave phase value. The SSR determines the magnitude and direction of the monitored slope deformation by comparing the phase measurement in each footprint (pixel) with the previous scan. The wall may then move up to several millimetres prior to failure or any other major instability phenomena. The deformation dataset for each scan in a monitoring period will form a deformation graph, which is the accumulation value of slope movement on each scan. The deformation data plot can be further analysed based on trends of deformation, velocity, inverse velocity and VR, which interpret as the rock slope behaviour.

3 Correlation between line-of-sight and vector loss

As an interferometry-monitoring tool, the effectiveness of measurement using SSR depends on the LOS. The LOS tools can potentially measure less movement than occurs due to the geometry of the target and the instrument. The greater the difference between the vector impact angle of the measurement tool and the movement of the wall, the less movement magnitude will be detected. The loss of the real magnitude due to the incidence angle between those two properties is called vector loss. Hence, to obtain an effective measure using the SSR, one should consider the deployment position in terms of pit size and shape as well as the angle of incidence relative to the actual direction of slope movement (Sharon & Eberhardt 2020). Figure 1 shows the correlation between the true movement and the vector component of the movement by SSR LOS.

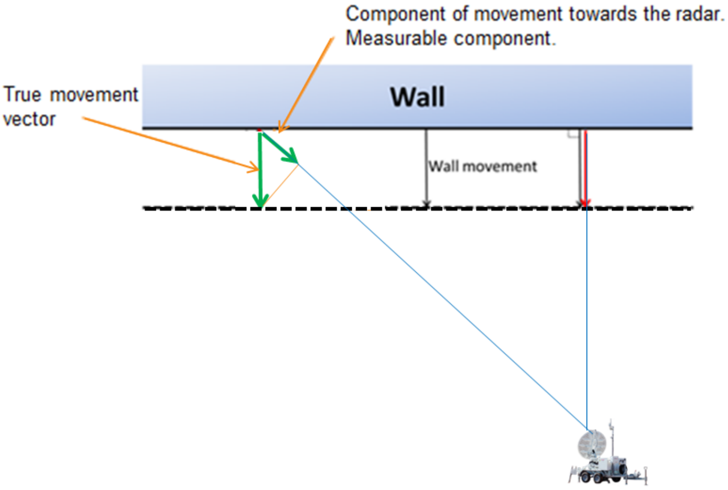


Figure 1 Vector loss generated by the incidence angle between the true direction of movement and the component direction of the movement measured by the SSR (GroundProbe 2019)

4 SSR alarm system

The SSR system is equipped with alarm features that activate when specified thresholds are surpassed. It provides various types of alarms that can be applied with thresholds designed to trigger in a sequence leading up to collapse. To ensure effective slope monitoring, alarms and notifications need to be properly configured within the system. By default, the alarms are not pre-configured, making it the user's responsibility to establish the appropriate settings to trigger them. The alarms of the SSR are determined by thresholds and configurations defined by the user and require manual configuration, as they are not automatically enabled by the software.

GroundProbe's MonitorIQ software allows the application of six different types of alarms, including deformation alarm, velocity alarm, inverse velocity alarm, VR alarm, coherence alarm and tracking alarm (GroundProbe 2021). These alarms are referred to as stackable alarms, which can be aligned with a site's geotechnical triggered action response plan (TARP) as described in Figure 2. A TARP is a policy of planned responses to trigger events. The purpose of a TARP is to define a range of trigger levels and the associated response protocols to be initiated in the event of a trigger level being exceeded (Saunders et al. 2016).

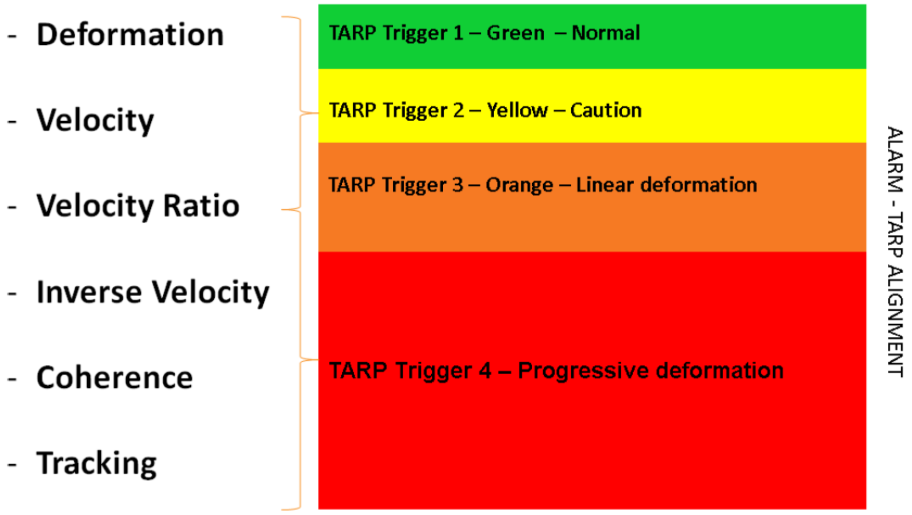


Figure 2 **Alignment of stackable alarms with TARP triggers levels (Saunders et al. 2016)**

Deformation and velocity alarms are commonly used and easily comprehensible alarm types during the initial stages of a monitoring campaign. They are effective in detecting and providing notifications of new areas of instability. When an increased level of risk is identified (indicated by a linear deformation trend), GroundProbe's other MonitorIQ stackable alarms can be applied. The alarm thresholds can be determined through a back-analysis of historical data captured by the SSR, which includes records of previous failure events. It is important to remember that this type of empirical approach by itself may be unreliable due to the small sample size and variability in failure mechanisms (Saunders et al. 2016). Back-analysis of failure events can arguably be used to determine preliminary alarm thresholds, but knowing that no two collapses will ever be the same suggests that a more diligent, multi-layered approach is required.

The conventional alarm system based on deformation and velocity thresholds can be affected by geometry and angle of incidence, leading to alarms being triggered at different times, even in the same deformation area. When a linear deformation trend is identified, the velocity is noted, and a new velocity (or VR) alarm can be set. The aim of this alarm is to alert the user of the onset of a progressive deformation trend.

- Deformation alarm

  This alarm uses cumulative deformation with or without a set time window. In some situations, a deformation alarm may not be the most appropriate approach. In many cases, it shows that it may have been useful to consider setting a velocity alarm rather than only considering cumulative deformation.

- Velocity alarm

  Velocity refers to the rate of wall movement towards or away from the SSR, defined as the distance the wall moves per unit of time. The use of velocity alarms is to indicate a change in the deformation trend. The software performs velocity calculations based on a calculation period defined by the user, and on a scan-by-scan basis. It is important to note that brittle collapses can occur within shorter time periods, and rapid velocity changes can have significant implications.

- VR alarm

  The VR is determined by dividing the velocity calculated at a specific time by the velocity calculated at a reference time. The major advantage of VR is that it indicates a change regardless of the magnitude of the deformations being monitored. Since this alarm is a ratio, it is dimensionless and useful to indicate the onset of a progressive-type deformation. This alarm is only applicable after the deformation has been observed by the radar, not for slope with a stable condition.

5 Discussion

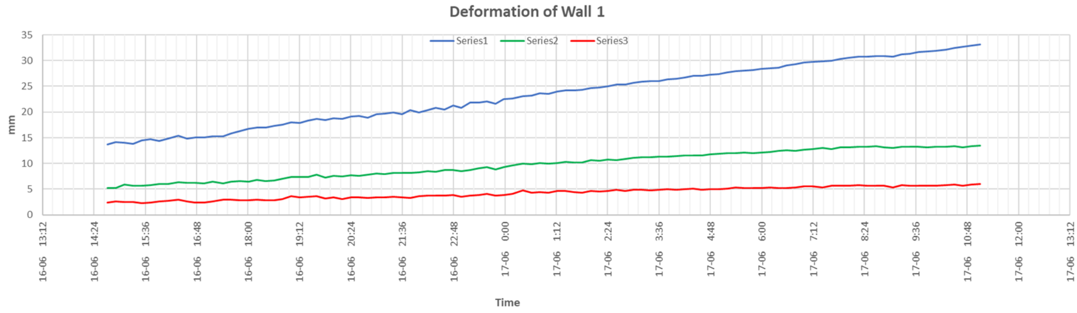
With a monitoring tool using the LOS principle, the magnitude of deformation and velocity decreases due to the impact of pit geometry on the LOS direction. The deformation and velocity magnitude will be optimal if the positions between the SSR and the monitoring point are facing each other. However, the magnitude will decrease, as there is a difference in the angle formed between the direction of movement and the measurement.

The decrease in the magnitude of deformation and velocity makes the conventional alarm, created using both parameters, being a bias in magnitude. In the same failure event, the magnitude of deformation and velocity at different control points will indicate a different magnitude. If a threshold is set on a conventional alarm, the point with a higher incidence angle from the SSR will trigger the alarm last, as its magnitude reaches the threshold much later due to the loss in magnitude from the LOS.

A proactive approach that can be taken to solve this problem is the use of a VR alarm. A VR alarm is used as an early warning of a linear deformation turning into a progressive phase in which this alarm compares the velocity that begins to increase with a period of velocity already specified during the linear phase (Saunders et al. 2016). Since the result of the VR is the value of the velocity comparison, then the VR has no dimension. This paper attempts to show that by using the properties of the VR at a different control point on a failure event, the minimum difference magnitude of VR will be obtained, because the VR is not affected by the geometry of the pit.

In this paper, a back-analysis is conducted using six samples showing the linear phase of deformation that have both a deformation and a velocity alarm on them. The back-analysis of the linear phase on these samples is required in order to observe the characteristics of conventional alarms (deformation and velocity alarms). This paper also presents a back-analysis using another failure case to be applied to the VR alarm and compares it with the conventional alarm.

Figure 3 shows six charts of the analysed samples, where the charts are in the linear deformation phase. No collapse is experienced with these samples. Each data series represents a control point on the body of the common deformation area. However, it can be seen that the magnitude of each selected deformation point is different. The blue line indicates the magnitude that is least affected by the angle of incidence. Hence, the magnitude still tends to be higher than the other lines. Remember that the greater the difference between the vector impact angle of the measurement tool and the movement of the wall, the less movement magnitude will be detected, and vice versa. The green line indicates the intermediate affected, and the red line is the largest affected by the angle of incidence which impacted it. The red line has a significant vector loss which makes it have a lower magnitude.



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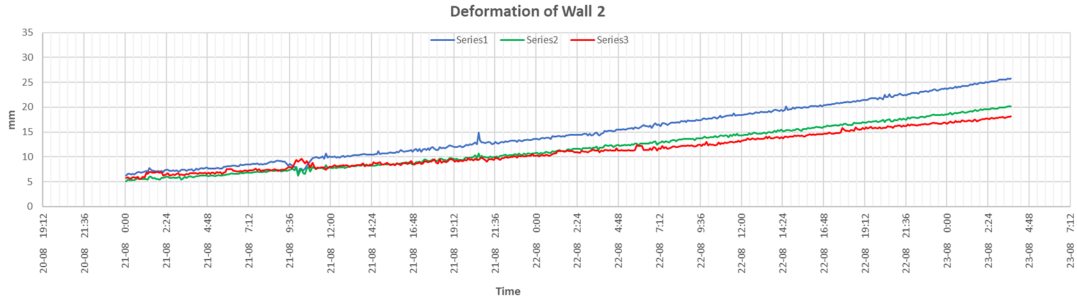

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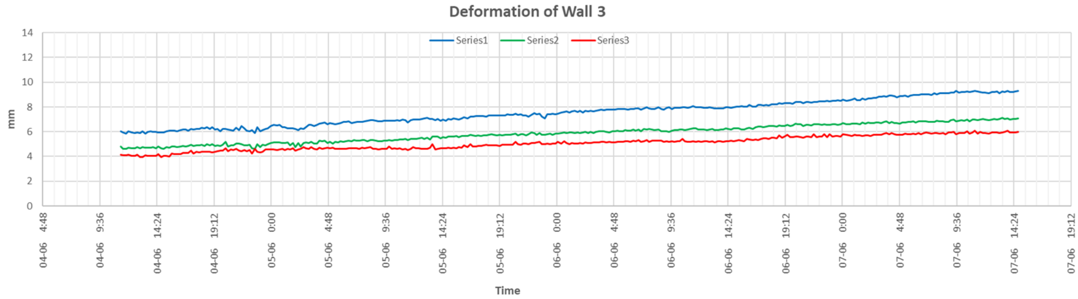
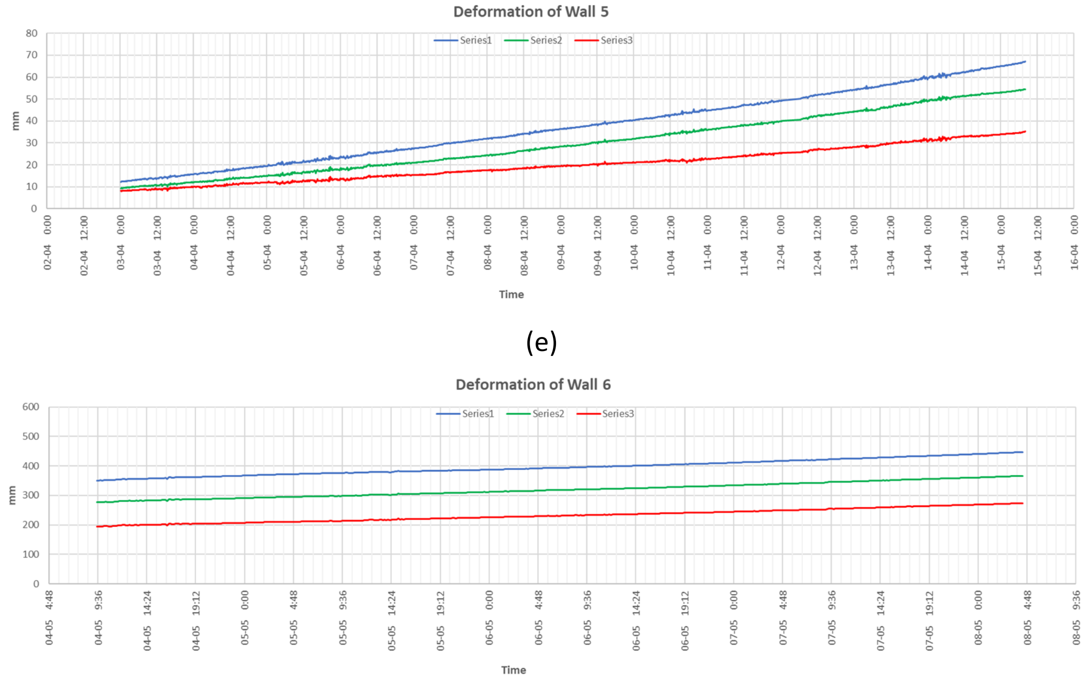


(c)

(d)

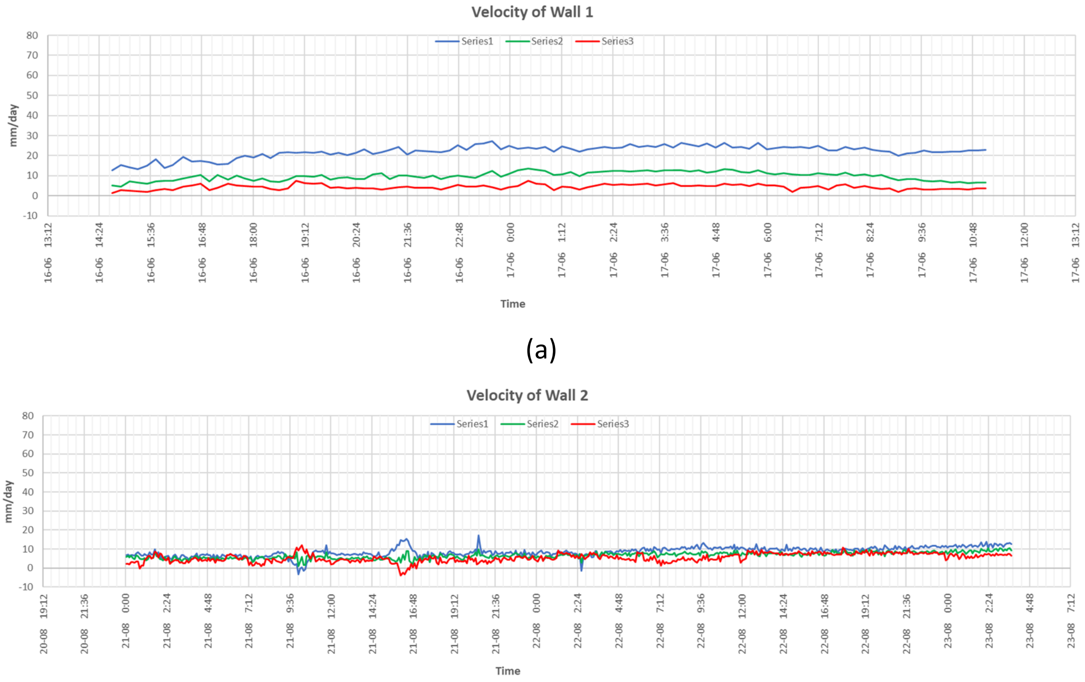


(e)

(f)

Figure 3 The deformation charts of the six samples. The blue line indicates the magnitude that is least affected by the angle of incidence. The green line indicates the intermediately affected, and the red line is the largest affected by the angle of incidence. Please note that the positive magnitude represents the movement towards to the SSR

The velocity, which is the result of the calculation of deformation compared to a certain period of time, also shows a different magnitude on the linear phase shown in Figure 4. Creating an alarm using both parameters will lead to difficulty in determining its threshold. If using a threshold based on the largest magnitude, the point with less magnitude will potentially not trigger the alarm. If the threshold is used with the smallest magnitude value, there will be a lot of unwanted or false alarms.



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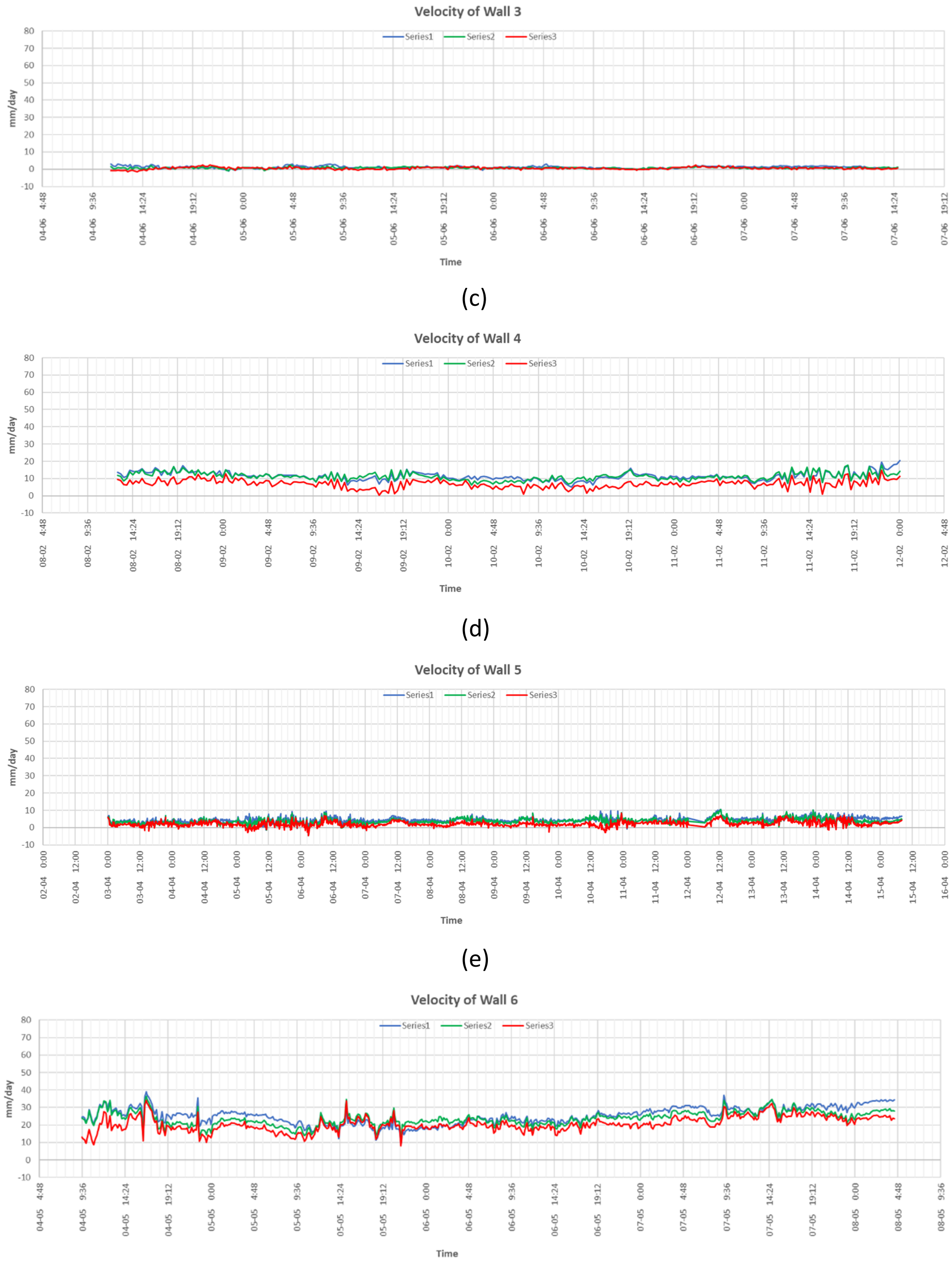

(c)

(d)

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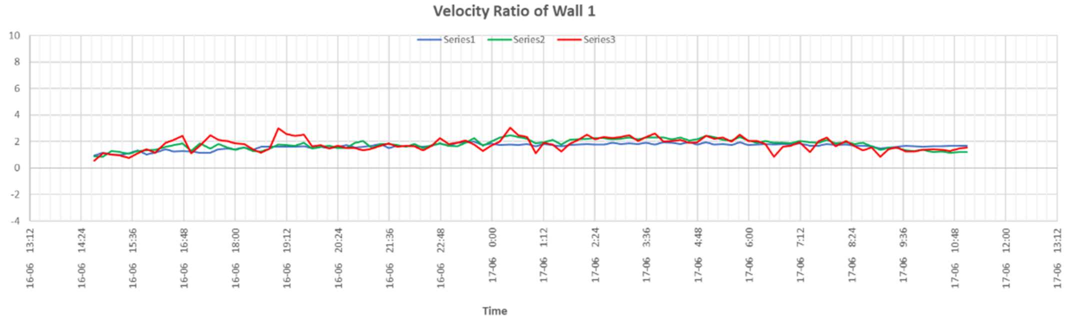
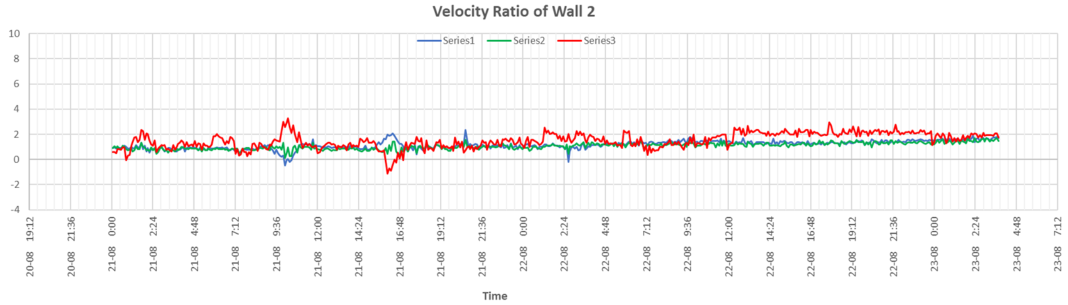
(f)

Figure 4 **In the linear phase, the velocity chart will show a relatively horizontal trend. However, creating an alarm using velocity is still difficult due to its wide variation of values (due to the selected time window)**

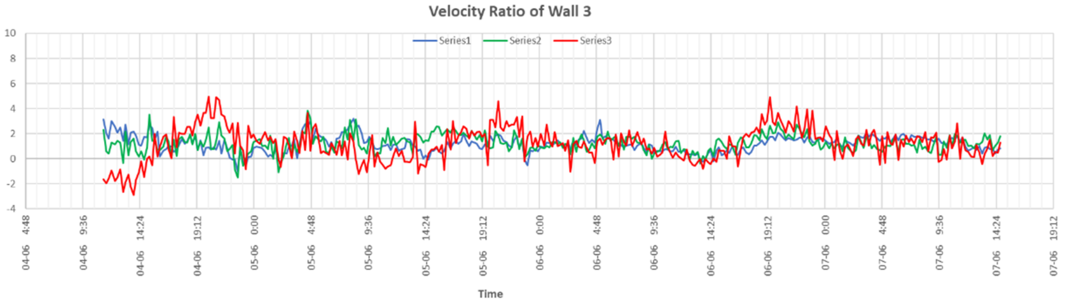
The VR has a different character than the previous two parameters. The magnitude of the VR is the result of the comparison between the specific velocity and the period of velocity previously determined in the linear phase. Hence, if the magnitude of the VR is close to 1, it means that the continuing deformation is still in the linear phase, as shown in Figure 5. The increasing VR magnitude indicates the ongoing linear deformation is changing towards progressive deformation.


Velocity Ratio of Wall 1
Series1
Series2
Series3
10
8
6
4
2
0
-2
-4
16-06 13:12
16-06 14:24
16-06 15:36
16-06 16:48
16-06 18:00
16-06 19:12
16-06 20:24
16-06 21:36
16-06 22:48
17-06 0:00
17-06 1:12
17-06 2:24
17-06 3:36
17-06 4:48
17-06 6:00
17-06 7:12
17-06 8:24
17-06 9:36
17-06 10:48
17-06 12:00
17-06 13:12
Time

(a)


Velocity Ratio of Wall 2
Series1
Series2
Series3
10
8
6
4
2
0
-2
-4
20-08 19:12
20-08 21:36
21-08 0:00
21-08 2:24
21-08 4:48
21-08 7:12
21-08 9:36
21-08 12:00
21-08 14:24
21-08 16:48
21-08 19:12
21-08 21:36
22-08 0:00
22-08 2:24
22-08 4:48
22-08 7:12
22-08 9:36
22-08 12:00
22-08 14:24
22-08 16:48
22-08 19:12
22-08 21:36
23-08 0:00
23-08 2:24
23-08 4:48
23-08 7:12
Time

(b)


Velocity Ratio of Wall 3
Series1
Series2
Series3
10
8
6
4
2
0
-2
-4
04-06 4:48
04-06 9:36
04-06 14:24
04-06 19:12
05-06 0:00
05-06 4:48
05-06 9:36
05-06 14:24
05-06 19:12
06-06 0:00
06-06 4:48
06-06 9:36
06-06 14:24
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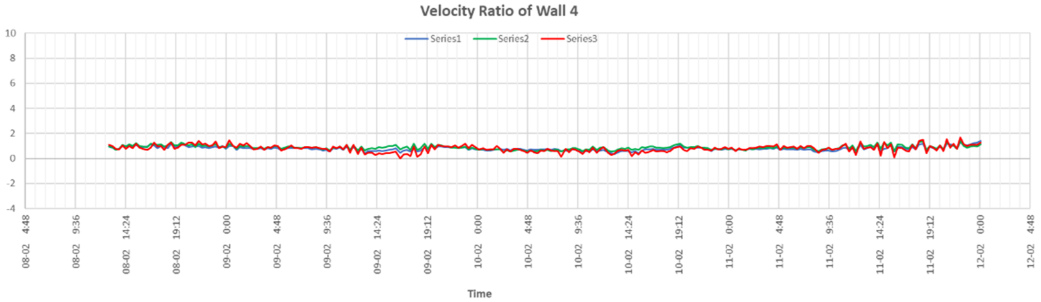
07-06 9:36
07-06 14:24
07-06 19:12
Time

(c)


Velocity Ratio of Wall 4
Series1
Series2
Series3
10
8
6
4
2
0
-2
-4
08-02 4:48
08-02 9:36
08-02 14:24
08-02 19:12
09-02 0:00
09-02 4:48
09-02 9:36
09-02 14:24
09-02 19:12
10-02 0:00
10-02 4:48
10-02 9:36
10-02 14:24
10-02 19:12
11-02 0:00
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11-02 19:12
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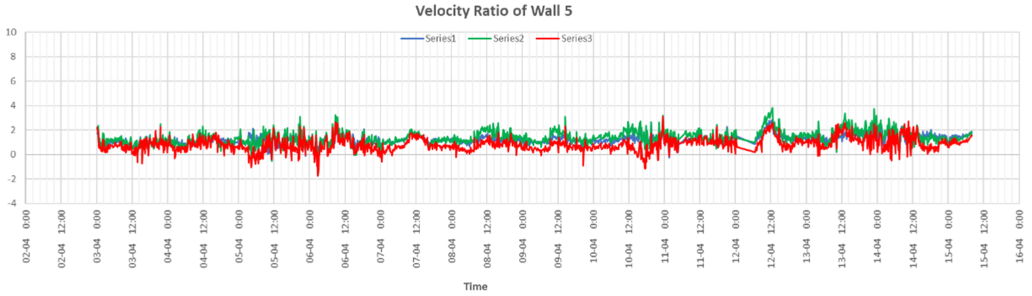
12-02 4:48
Time

(d)


Velocity Ratio of Wall 5
Series1
Series2
Series3
10
8
6
4
2
0
-2
-4
02-04 0:00
02-04 12:00
03-04 0:00
03-04 12:00
04-04 0:00
04-04 12:00
05-04 0:00
05-04 12:00
06-04 0:00
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13-04 0:00
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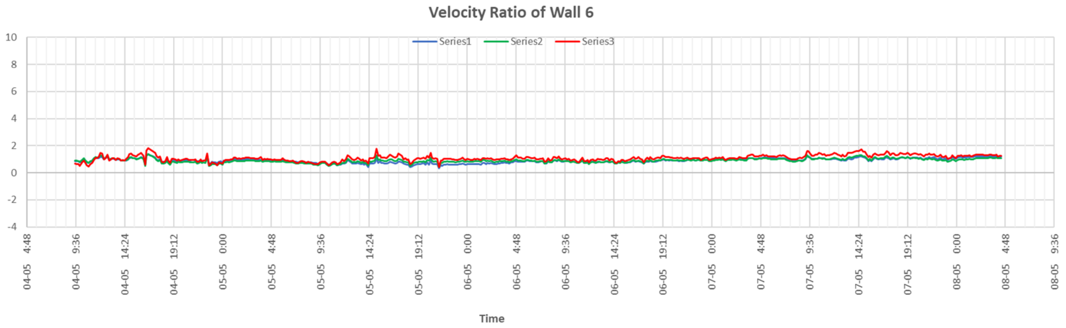
16-04 0:00
Time

(e)



(f)

Figure 5 If the VR magnitude is close to 1, it means that the deformation is still in the linear phase. The magnitude of the increasing VR indicates the ongoing linear deformation is increasing towards progressive deformation

6 Results

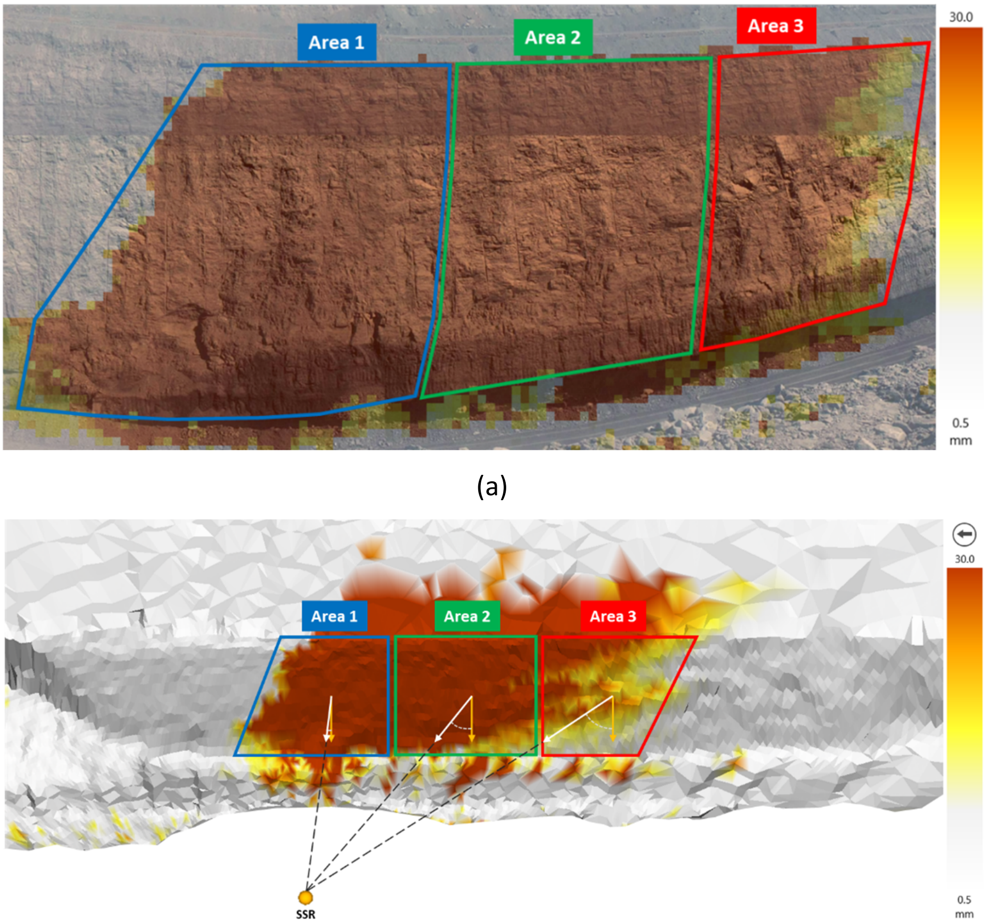
Compared with deformation and velocity, VR shows a narrower range of values, which means the data variation is the minimum. Unlike the two other parameters that have a wide data range and a lot of data variation, VR can simplify the threshold values used in alarm configurations.

Table 1 shows the mean and standard deviation values of each data category. Compared to deformation and velocity, the standard deviation value on the VR is the lowest (0.20–0.96) of the three data categories (deformation: 1.28–82.16 mm; velocity: 0.64–7.75 mm/day). This low data variance will simplify the determination of the alarm threshold. In deformation alarms, the values of different deformations on the same deformed area will make it difficult to configure the alarm. The VR alarm makes the determination of thresholds simpler, because the data variation values are the least and the user will receive a similar time warning.

Table 1 Comparing the mean and standard deviation values of deformation, velocity and VR, it is observed that VR has the lowest mean and standard deviation values. It means that the VR has the least variance in the data

Data	Deformation (mm)		Velocity (mm/day)		Velocity ratio (VR)	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Wall 1	12.46	10.12	12.10	7.75	1.73	0.39
Wall 2	13.39	2.41	6.91	2.50	1.24	0.47
Wall 3	6.16	1.28	0.83	0.64	1.19	0.96
Wall 4	111.26	33.66	9.88	3.15	0.82	0.22
Wall 5	28.93	9.60	3.47	1.77	1.13	0.56
Wall 6	316.05	82.16	23.21	4.79	0.96	0.20

After describing the characteristics of the deformation, velocity and VR trend by back-analysis, back-analysis using the monitoring data that has already failed was also conducted to test whether the VR alarm could simplify the threshold value or obtain a different result. An area was deformed with elongated dimensions. The deformation area was divided into three areas, as shown in Figure 6, where the incidence angle of Area 1 is about 8° and has the smallest impact of the vector loss. The incidence angle of Area 2 is about 48° and has an intermediate impact of vector loss, while the incidence angle of Area 3 is about 72° and has the greatest impact of the vector loss.



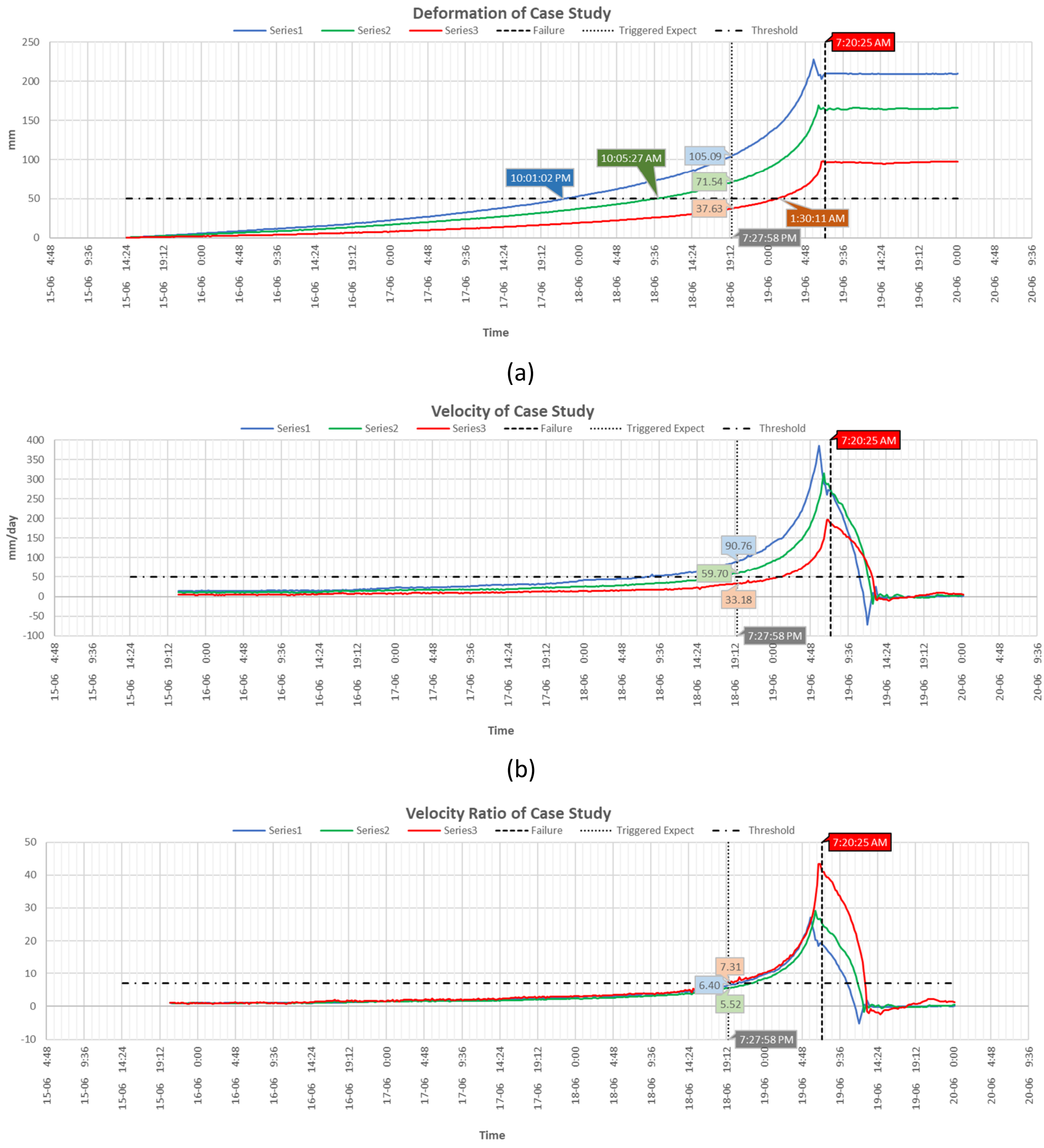
(a)

(b)

Figure 6 **(a) Front view of deformation area divided into three areas; (b) The top–down view of the deformation with their movement component. Area 1 has the smallest impact of the vector loss, Area 2 has the intermediate impact, and Area 3 has the greatest impact**

Based on SSR data as shown in Figure 7, the failure occurred at 7:20:29 am If the alarm is required to be triggered approximately 12 hours before the failure occurrence, the deformation data indicates different threshold values, where in Area 1 (Series 1) the threshold value must be set at 105.09 mm, Area 2 (Series 2) at 71.54 mm, and in Area 3 (Series 3) at 33.18 mm as shown in Table 2. The velocity chart also shows similar characters, where Area 1 should have a threshold of 90.76 mm/day, Area 2 at 59.70 mm/day, and Area 3 at 33.18 mm/day.

Using these conventional alarm threshold become a complex task due to the necessity of using different thresholds with a wide and significant variance of their value, also have to divide the specific deformation area. On the other hand, the alarm in Area 1 will be triggered first and continue to trigger until it reaches the other threshold area, where it will be triggered together until it fails. A significant concern arises when employing uniform threshold values throughout the entire area, as this can potentially lead to missed alarms.



(a)

(b)

(c)

Figure 7 **(a) Deformation chart, which generally shows the wide difference of threshold if the user requires setting the alarm for approximately 12 hours before failure, (b) velocity chart which also shows similar characteristics where the threshold still shows a wide variance of value, and (c) VR shows the similar value with a lower variance of the threshold**

Unlike the conventional alarm, which has a wide and significant variance of the threshold magnitude, the VR graph in Figure 6c shows similar values and a narrow variance in the 12 hours before the failure, where Area 1 has a value of 6.40, Area 2 is 5.52, and Area 3 is 7.31. Since the VR magnitude has a low impact from the incidence angle, they show similar value with a narrow variance. From the back-analysis obtained, Area 3 has the highest acceleration rate of the three areas, regardless of the LOS magnitude. The low variance observed in the VR values simplifies and facilitates the process of determining thresholds.

Table 2 The VR alarm indicates that its threshold value has a low variation compared to other types of alarms

Alarm type	Threshold			Alarm triggered
	Area 1	Area 2	Area 3	
Deformation (mm)	105.09	71.54	37.63	12 hours before failure
Velocity (mm/day)	90.76	59.70	33.18	12 hours before failure
Velocity ratio	6.40	5.52	7.31	12 hours before failure

Table 3 illustrates that the VR alarm consistently triggers within a narrow time frame of less than a three-hour difference. In contrast, the deformation alarm exhibits a time difference of approximately 14 hours, and the velocity alarm shows a time difference of about nine hours. Please note that geotechnical conditions always have a specific character and parameters. These alarm back analyses were only applied in this specific case and may not be considered a generic alarm that can be applied to other situations.

Table 3 The VR alarm indicates a similar alarm time triggered compared with the other alarm type

Alarm type	Alarm triggered			Threshold
	Area 1	Area 2	Area 3	
Deformation (mm)	22:01:02 June 17	10:05:27 June 18	01:30:11 June 19	50 mm
Velocity (mm/day)	07:00:52 June 18	17:01:50 June 18	01:18:50 June 19	50 mm/day
Velocity ratio	19:27:07 June 18	19:03:07 June 18	21:15:07 June 18	7

7 Conclusion

The SSR is widely recognised as an extensively utilised and sophisticated monitoring tool in open pit mines globally. However, it presents a limitation due to its reliance on the LOS method. As a result, there is a potential for underestimating the true magnitude of slope deformation, thereby impacting alarm triggering, which commonly relies on deformation and velocity thresholds. Setting the threshold value excessively high introduces the risk of missed alarms during critical events, while setting it too low may lead to persistent false alarms.

The objective of this study was to investigate the extent of variability in deformation, velocity and VR graphs across multiple control points within a common deformed area. The findings reveal significant disparities in the magnitudes of LOS deformation, indicating noteworthy variations despite the proximity of the control points within the common deformed area. The analysis demonstrates minimal deviations in the VR graph when compared to the deformation and velocity graphs. This observation suggests that the VR value is comparatively less affected by LOS effects, making it a valuable addition to the set of thresholds used for slope failure alarms.

The configuration of alarms in SSR monitoring should not be treated as a ‘set and forget’ procedure. Adopting a proactive approach is crucial when establishing alarm settings to effectively mitigate the risk of missed failure events. Specifically, when the slope exhibits linear or steady-state deformation, it is recommended that VR alarms be incorporated alongside other alarm thresholds. This comprehensive approach helps minimise the potential underestimation of deformation magnitudes and enhances the accuracy and reliability of slope stability monitoring.

Acknowledgement

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