BACK ANALYSIS OF VECTOR LOSS EFFECT TO DETERMINE THRESHOLD USING SLOPE STABILITY RADAR DATA CASE STUDY OF FAILURE IN OPEN PIT COAL MINE[1]

Alden Sinai Yudono[1)], Dwi Prio Utomo[1)], Luckman Hakim[1)], Ignatius Putra[1)], Deaz Dewantara[2)], and Tri Haryanta[2)]

1)Geotechnical Support Service PT GroundProbe Indonesia.
2)Site Geotechnical Team PT Pamapersada Nusantara.

ABSTRAK

Pemantauan kestabilan lereng suatu tambang terbuka adalah salah satu cara yang dapat dilakukan untuk mengelola risiko dari potensi longsor. Slope Stability Radar (SSR) adalah teknologi/alat yang dapat digunakan untuk memantau kestabilan lereng dengan menyajikan data secara real time. SSR menggunakan prinsip line-of-sight dalam menghitung besaran pergerakan lereng yang dapat menghasilkan vector loss pada nilai pengukurannya. Vector loss adalah persentase besaran deformasi tereduksi akibat arah pergerakan lereng memiliki selisih sudut terhadap arah pengukuran radar. Dalam pengelolaan longsor terdapat nilai ambang batas yang diterapkan untuk mengkategorikan perilaku deformasi batuan. Penelitian ini dilakukan untuk mengkaji pengaruh vector loss terhadap nilai ambang batas yang diterapkan pada tambang terbuka batubara dengan menggunakan 20 data longsor pada periode 3 April 2021 – 9 Mei 2021 yang dideteksi oleh SSR pada Pit A di area High-Wall Timur dan L Barat, serta Pit B di area High-Wall Barat.

Nilai ambang batas yang diterapkan saat ini mencakup kategori “Aman” pada nilai kecepatan deformasi 0 - 50 mm/hari, “Waspada” pada nilai kecepatan deformasi 50 mm/hari – 120 mm/hari, dan “Evakuasi” pada nilai kecepatan deformasi lebih dari 120 mm/hari. Hasil perhitungan data SSR menunjukkan bahwa tingkat kecepatan deformasi saat terjadinya longsor berada pada rentang data 28.77 – 202.53 mm/hari dan tingkat kecepatan deformasi terkoreksi vector loss saat terjadinya longsor berada pada rentang data 49.43 – 367.44 mm/hari.

Berdasarkan hasil perhitungan, maka nilai ambang batas pada kategori “Evakuasi” yang sebelumnya berada pada nilai deformasi lebih dari 120 mm/hari dapat dioptimalkan menjadi lebih dari 50 mm/hari untuk area High-Wall Timur dan Low-Wall Barat pada Pit A, serta area High-Wall Barat untuk Pit B. Nilai ambang batas untuk SSR dapat menggunakan nilai lebih dari 30 mm/hari untuk area High-Wall Barat pada Pit B, lebih dari 40 mm/hari untuk area Low-Wall Barat pada Pit A, dan lebih dari 50 mm/hari untuk area High-Wall Timur pada Pit A.

Kata Kunci*: vector loss, Slope Stability Radar, threshold.*

ABSTRACT

Slope stability monitoring in open pit mines is one of method that can be used to manage the potential of slope risk failures. Slope Stability Radar (SSR) is a technology/tool that can be used to monitor slope stability by provides real time data. SSR using the line-of-sight principle to calculate the magnitude of slope movement that will generates a vector loss on its measurements. Vector loss is the percentage of reduced deformation due to the direction of the movement of the slope forming an angle difference to the direction of the radar measurement. In slope failure management, slope stability threshold is used to categorize/classify the rock deformation behaviour. The aims of this research are to analyse the effect of vector loss on the

threshold that applied in open pit coal mines using 20 failures data from the period of April 3 - May 9, 2021, which detected by radar in Pit A at the East High-Wall and West Low-Wall areas, also in the Pit B at the West High-Wall area.
The current threshold applied include the "Safe" category with velocity of deformation at a range of 0 – 50 mm/day, "Warning" at velocity of deformation at a range of 50 mm/day – 120 mm/day, and "Evacuation" with velocity of deformation more than 120 mm/day. The analysis result of SSR data calculation shows that the rate of velocity when slope failures is in the range of data from 28.77 – 202.53 mm/day and the rate of velocity corrected by vector loss is in the range of data from 49.43 – 367.44 mm/day.
Based on the calculation, the threshold for the "Evacuation" category which was previously more than 120 mm/day can be optimized to be more than 50 mm/day for the East High-Wall and West Low-Wall areas in Pit A, as well as the West High-Wall area for Pit B. The threshold for SSR could be set using more than 30 mm/day for the West High-Wall area in Pit B, more than 40 mm/day for the West Low-Wall area in Pit A, and more than 50 mm/day for the East High-Wall area in Pit A.

***Keywords**: vector loss, Slope Stability Radar, threshold.*

A. INTRODUCTION

The management of risk to personnel, equipment and continued production associated with slope instability is one of the key roles of geotechnical aspect in open pit mines. Slope stability monitoring tools can be used as part of a risk management program. The slope stability monitoring tool will work optimally in its application if it has a threshold that is used as a reference for action taking according to the hazard category based on the rock mass characteristics. Slope Stability Radar (SSR) is a technology/tool that can be used to monitor slope stability by presenting data in real-time with sub-millimeter of accuracy.
This paper aims to evaluate whether the current threshold is still relevant to use by conducting a back analysis using monitoring data from Slope Stability Radar (SSR). It is also expected to obtain a threshold that is appropriate for the monitored slope conditions by conducting a back analysis.
The geometry of the pit is one of the factors that affect the results of measurements using SSR where the angle formed between the direction of measurement and the direction of movement is a deduction from the actual movement where this condition is called vector loss. The approximate magnitude of the actual movement can be determined by using the back analysis method, and the corrected result can then be analyzed further to be used as a threshold.

B. METHODOLOGY

This study uses slope monitoring data by Slope Stability Radar – XT (SSR – XT) in cases of failures that occurred in one of Indonesia's coal mines. Figure 1 shows how Slope Stability Radar – XT (SSR – XT) acquire data of the slope. The analysis for determining the threshold is using the back analysis method based on the data characteristics of each failure that was successfully detected by radar. The analysis results will be calculated based on the vector loss from the line-of-sight of radar for each failure location to obtain a correction or the actual value of the maximum velocity at the time of the failure. The detailed geometry parameters of the slopes, such as slope dip and the presence of geological structures that affect the slope stability radar's line-of-sight, are not discussed in detail in this study.
SSR slope monitoring concept is based on radar interferometry technique (Noon, 2003). Interferometry is a method to measure displacement of an object/wall by calculating the small phase change of successive reflected signal. The SSR will transmit an electromagnetic signal to the slope surface and receive back the reflected signal successively as shown on figure 2. Each

reflected signal received by the radar has its own signal phase. Phase shift between successive transmissions used to determine displacement. The sets of deformation data for each scan in a monitoring period will produce a deformation plot which is the accumulation of magnitude slope movement in each scan. The plots of deformation data can be further analysed based on the deformation data's trend, velocity, inverse velocity, and velocity ratio.

Figure 1. SSR scanning based on line-of-sight.

There is a simple relationship between the direction of slope movement and the direction of the SSR can measure. All radar systems that use differential interferometry to calculate deformations can only measure deformations in the direction of the radar beam. SSR only measures movement towards or away from the dish, along the line-of-sight, it cannot measure sideways movement. All line-of-sight measurement tools can potentially measure less movement than actually occurs due to the geometry of the target and the instrument. This applies to all radar and laser monitoring technology. 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 diagram in figure 3 explains the issue.

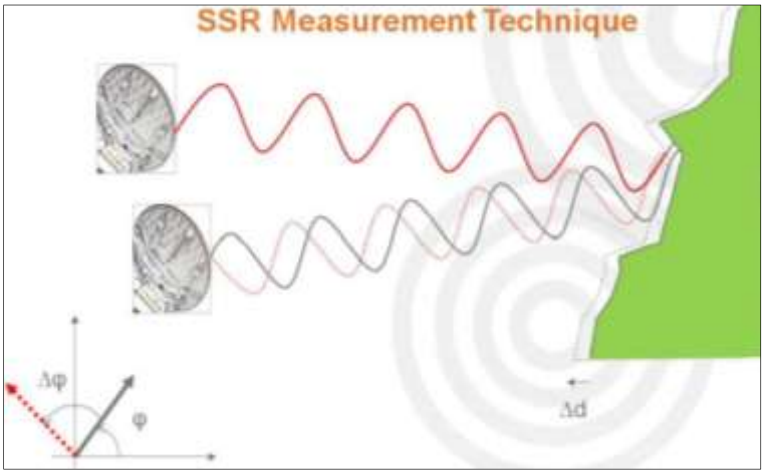

Figure 2. SSR measurement technique using interferometry method.

Figure 4 looks down on an SSR at positioned to monitor a wall. Assume the wall has moved uniformly (S) in the direction shown as $\mathbf{d_{WALL}}$, with the amount of movement represented by the length of the arrow. When the SSR dish is pointing directly in line with the movement, along the line-of-sight as at position (A), then the full effect of the movement will be measurable. However, when the dish has rotated and points at position, the line-of-sight is now at an angle (θ), to (B) the movement. The movement is made up of the component shown in orange, in line with the $\mathbf{d_{WALL}}$ radar signal, and the component shown in brown, perpendicular to the radar signal. Only $\mathbf{d_{LOS}}$**,** the component of the movement along the line-of-sight, can be measured. As the angle between the line-of-sight and the deformation increases toward 90°, the measurement is less sensitive to the deformation. This phenomenon called sensitivity. Sensitivity is the reduction in measurable deformation caused by the line-of-sight being at an angle to the actual movement.

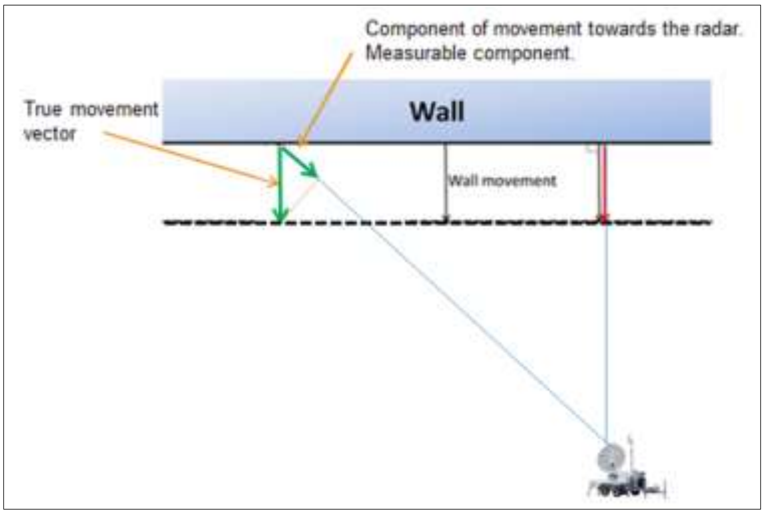

Figure 3. Component of wall movement vector

In a worst scenario, when the movement is actually at 90° to the line-of-sight, in the direction shown by the brown arrows in figure 4, then no movement at all can be detected. If the movement direction is more than 90° to the line-of-sight, then the SSR measures the line-of-sight component of the deformation in the opposite direction. In that case the wall is moving away from the SSR. Always consider the direction of likely movement, a small-measured movement may indicate a larger movement in a different direction. Sensitivity can also be important vertically in SSR measures across a pit. At the entire figure 5 (S) (A) movement is measurable. At the measurable deformation shown in orange is reduced because the (B) line-of-sight is not aligned with actual movement shown in blue.

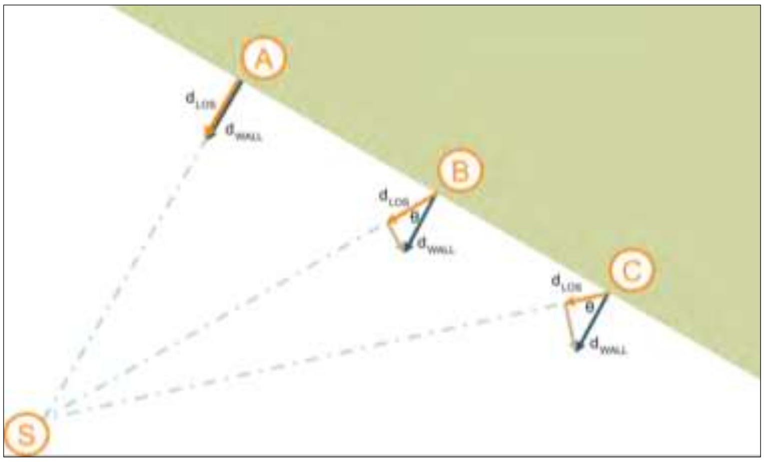

Figure 4. Horizontal sensitivity.

The measureable movement is smaller than the complete movement by a factor of **cos θ**, as described by equation (1). This equation (1) can be used to calculate both horizontal and vertical sensitivity. The result of the final calculation will be the true direction of the SSR when measured and obtain the corrected magnitude.

$$d_{WALL} = d_{LOS} \times \cos \theta \quad (1)$$

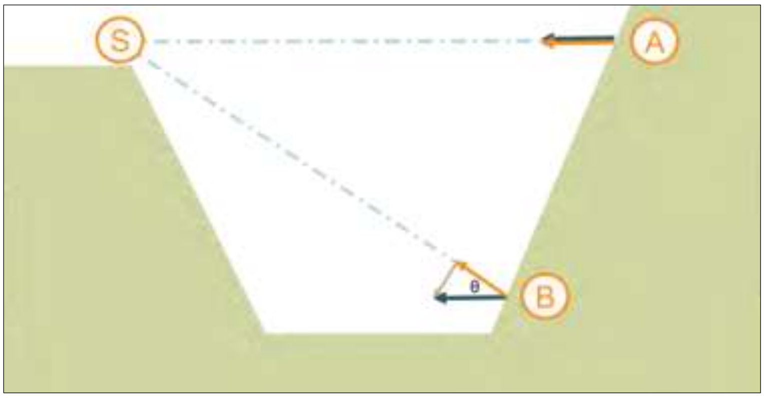

Figure 5. Vertical sensitivity.

C. RESULT AND DISCUSSION

1. EXISTING THRESHOLD

Slope stability monitoring tools are one part of risk management in mining activities. This management program is designed to focus on providing early warning of an impending slope failure so that personal risk to mining staff is minimized while mine production is maximized by reducing downtime of the mine (Kumar and Rathee, 2017). For this reason, it is necessary to have a deformation threshold that functions as a critical limit with certain categories to assist the person in charge of making decisions. Table 1 shows the current threshold used in slope risk management in Pit A and Pit B. There are 3 categories in the current threshold. These are safe, warning, and evacuation. The safe category is at a deformation velocity between 0 – 50 mm/day while continuing to monitor periodically and make stabilization efforts. The warning category is at a deformation velocity between 50 – 120 mm/day, which requires hourly monitoring and applying signs in areas that are potentially affected by the failure. The evacuation category is at a deformation velocity more than 120 mm/day and evacuation must be carried out immediately. This study is to find out whether the current thresholds are still relevant to be applied or not by using monitoring data from the Slope Stability Radar (SSR).

Table 1. Existing deformation threshold applied.

Category	Safe	Warning	Evacuation
Velocity of deformation	0 – 50 mm/day	50 – 120 mm/day	>120 mm/day
Action	• Monitor periodically • Make stabilization effort	• Hourly monitoring • Apply warning sign	• Immediately evacuation to muster point

This study was conducted in Pit A and Pit B in the period of 3 April 2021 – 9 May 2021, where the failure events occurred. A total of 6 failure events occurred in the West Low-Wall area and 8 failure events occurred in the East High-Wall area of Pit A. Pit B contained 6 failure events that occurred in the West High-Wall area. The failure with the lowest maximum velocity of failure occurred in the West High-Wall area of Pit B with 28.77 mm/day and the failure with the highest maximum velocity of failure occurred over the West Low-Wall area of Pit A with 202.53 mm/day. Referring to the threshold that is currently used, a failure event with a maximum velocity of failure at 28.77 mm/day should be in the safe category. Figure 6 shows the maximum velocity of failure events, and the x axis represents the time of occurrences.

2. EFFECT OF PIT GEOMETRY

SSR is using the line-of-sight method to monitor, hence the condition of pit geometry will affect the result of the data. If assumed that the movement direction of a slope is in the same direction as the slope face, then the magnitude of the movement will be reduced if it is not measured from the direction and position that is parallel to the movement. The percentage of reduction in measurable deformation caused by the line-of-sight being at an angle to the actual movement is called vector loss. Figure 7 and figure 8 are the front view and plan view of Pit A and Pit B which shows the failure events area. F01 – F20 in figure 7 and figure 8 shows the point where failure occurs and the arrow at each point represent the direction of movement where the direction is parallel to the slope face.

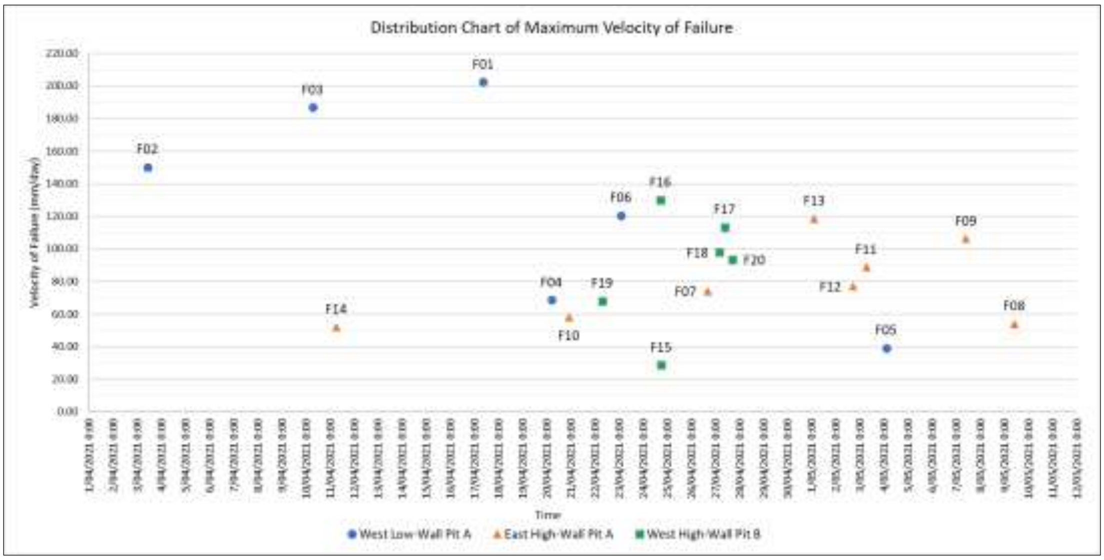

Figure 6. Failure events over the Pit A and Pit B.

3. BACK ANALYSIS

To determine the appropriate threshold for the current movement conditions, it is necessary to do a back analysis of the maximum velocity of failure from the failure data that was resulted by the SSR measurement. However, before the velocity data is used, it is necessary to make corrections to the effect of vector loss on the reduction of the velocity. Table 2 shows the data of the maximum velocity of failure and the difference between the vertical and horizontal angles from the line-of-sight of the SSR to the direction of movement. The data in table 2 then calculated using equation (1) that used to correct the velocity by the difference in the horizontal and vertical angle. Table 3 shows the velocity that has been corrected for vector loss. By comparing the velocity in table 2 and table 3, the magnitude of the loss angle is directly proportional to the increase in the vector loss.

Table 2. Maximum velocity of failure events and its magnitude of the loss angle.

#	Code	Max. velocity of failure (mm/day)	θ Hor. (deg.)	θ Ver. (deg.)	#	Code	Max. velocity of failure (mm/day)	θ Hor. (deg.)	θ Ver. (deg.)
1	F01	202.53	43.16	1.74	11	F11	88.83	5.44	1.82
2	F02	150.13	56.55	0.34	12	F12	76.96	0.53	2.40
3	F03	186.92	56.55	0.34	13	F13	118.73	2.62	2.56
4	F04	68.60	58.21	2.06	14	F14	52.08	73.40	8.72
5	F05	39.28	52.41	3.05	15	F15	28.77	54.37	2.32
6	F06	120.48	1.74	0.94	16	F16	130.13	55.30	1.28

7	F07	74.21	23.16	11.83	17	F17	113.39	53.67	1.28
8	F08	54.00	21.80	8.77	18	F18	97.98	26.65	2.34
9	F09	106.32	19.07	8.34	19	F19	68.04	48.61	4.56
10	F10	58.26	15.50	0.65	20	F20	93.33	23.82	4.42

According to the calculations, the maximum velocity of failure with the most occurrences is in the range of 51 – 150 mm/day, with 12 landslide events in that range. The highest magnitude for maximum velocity of failure is 367.44 mm/day, while the lowest magnitude is 49.43 mm/day. The distribution of the maximum velocity of failure based on their range is depicted in figure 9, while the corrected maximum velocity of failure is shown in figure 10. By combining the information from table 3 and figure 10, it shows that the lowest velocity in the West Low-Wall Pit A area is 64.48 mm/day, the lowest velocity in the East High-Wall Pit A area is 58.84 mm/day, and the lowest velocity of failure in the West High-Wall Pit B area is 49.43 mm/day. By approaching the corrected lowest maximum velocity where the magnitude is around 50 mm/day, then the velocity at 50 mm/day can be recommended as a threshold for evacuation where the previous threshold was at > 120 mm/day. This recommendation threshold applies to Pit A in the West Low-Wall and East High-Wall areas, and also to Pit B in the West High-Wall area. Figure 10 also shows the threshold line, which is at 50 mm/day where most of the failures occur at velocities above that number.

Table 3. Corrected maximum velocity of failure and the percentage of vector loss.

#	Code	Max. velocity of failure (corrected) (mm/day)	Loss velocity	#	Code	Max. velocity of failure (corrected) (mm/day)	Loss velocity
1	F01	367.44	44.88%	11	F11	89.28	0.50%
2	F02	272.37	44.88%	12	F12	77.03	0.09%
3	F03	255.39	26.81%	13	F13	118.9	0.20%
4	F04	130.31	47.35%	14	F14	179.32	70.95%
5	F05	64.48	39.08%	15	F15	49.43	41.79%
6	F06	120.55	0.05%	16	F16	228.65	43.08%
7	F07	82.46	10.01%	17	F17	191.45	40.77%
8	F08	58.84	8.23%	18	F18	168.34	41.79%
9	F09	113.69	6.48%	19	F19	103.04	33.96%
10	F10	60.46	3.64%	20	F20	102.33	8.79%

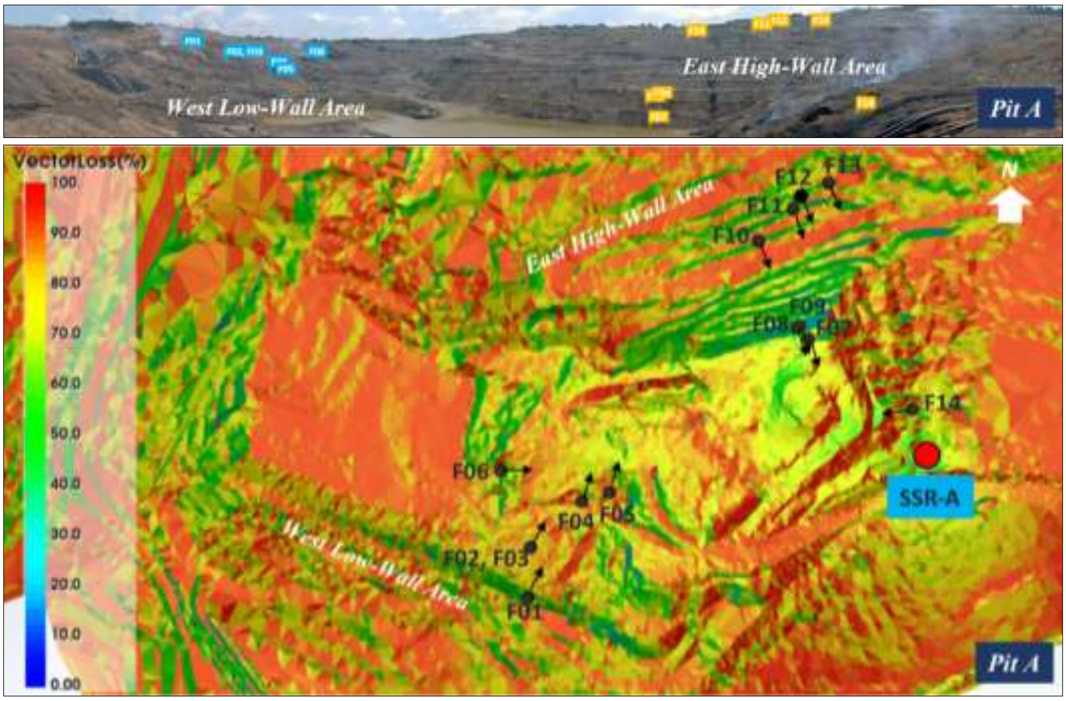

Figure 7. Front view photograph and view of Pit A that shows position of each failure event.

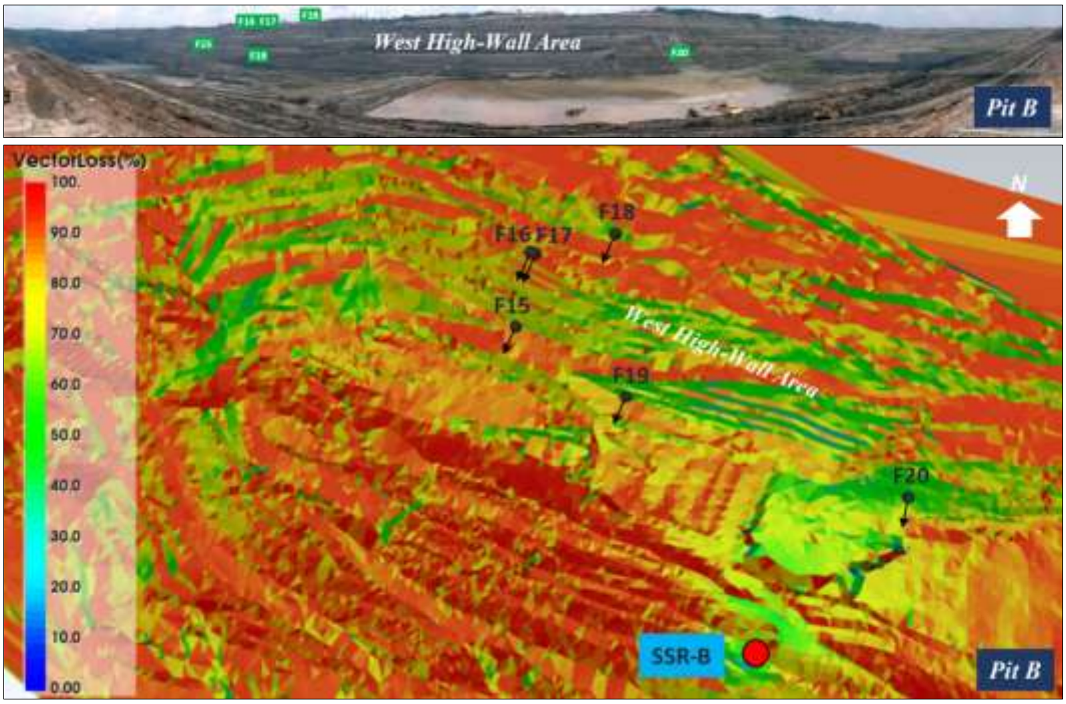

Figure 8. Front view photograph and view of Pit B that shows position of each failure event.

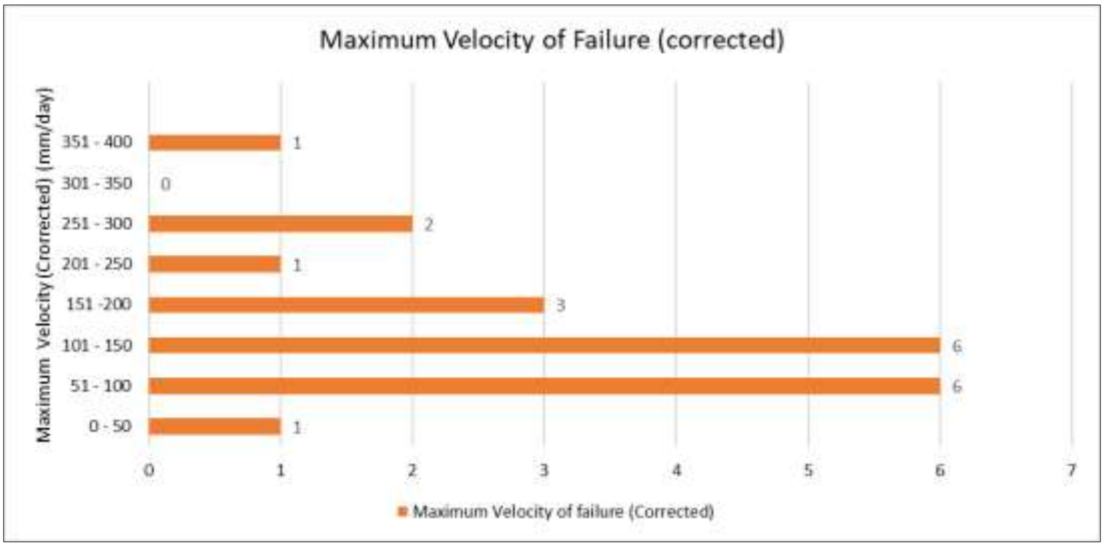

Figure 9. Corrected maximum velocity of failure events that divided by specific range.

The recommended threshold for the evacuation is the velocity magnitude that has been corrected. So that it can be applied to other monitoring tools that monitor the same area. As a best practice in monitoring using SSR, the measured (uncorrected) of maximum velocity of failure can be used as a threshold for monitoring using SSR. Using the data in table 2, the lowest maximum velocity of failure in the West Low-Wall area of Pit A is 39.28 mm/day, in the East High-Wall area of Pit A is 54.00 mm/day, and in the West High-Wall area of Pit B is 28.77 mm/day. By approaching the velocity in each of these areas, it can be recommended that the threshold for monitoring using SSR in the West Low-Wall area of Pit A is 40 mm/day, in the East High-Wall area of Pit A is 50 mm/day, and in the West High-Wall area of Pit B is 30 mm/day, as can be seen in figure 11.

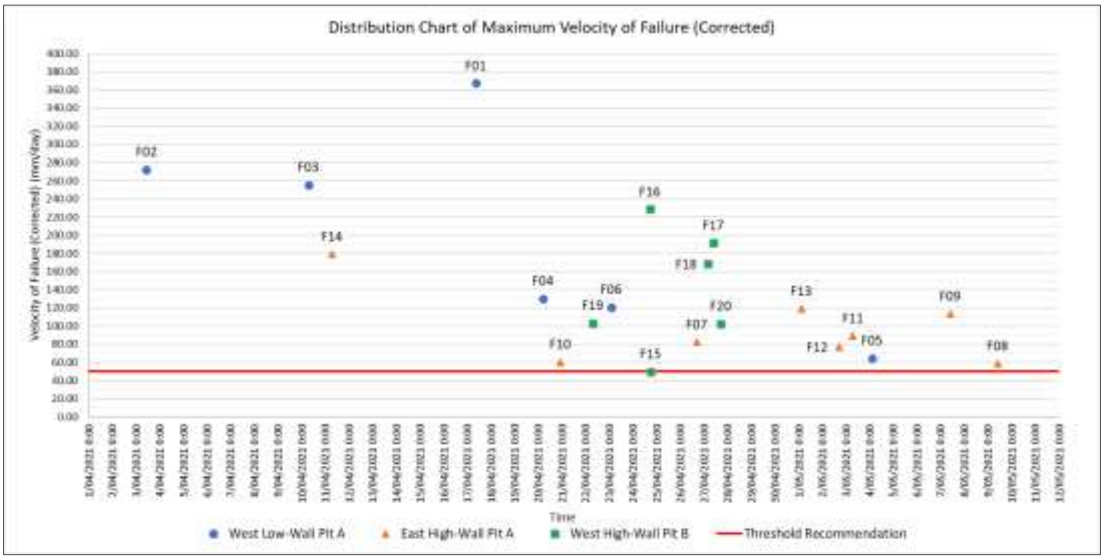

Figure 10. Distribution of corrected maximum velocity of failure events and the threshold recommendation.

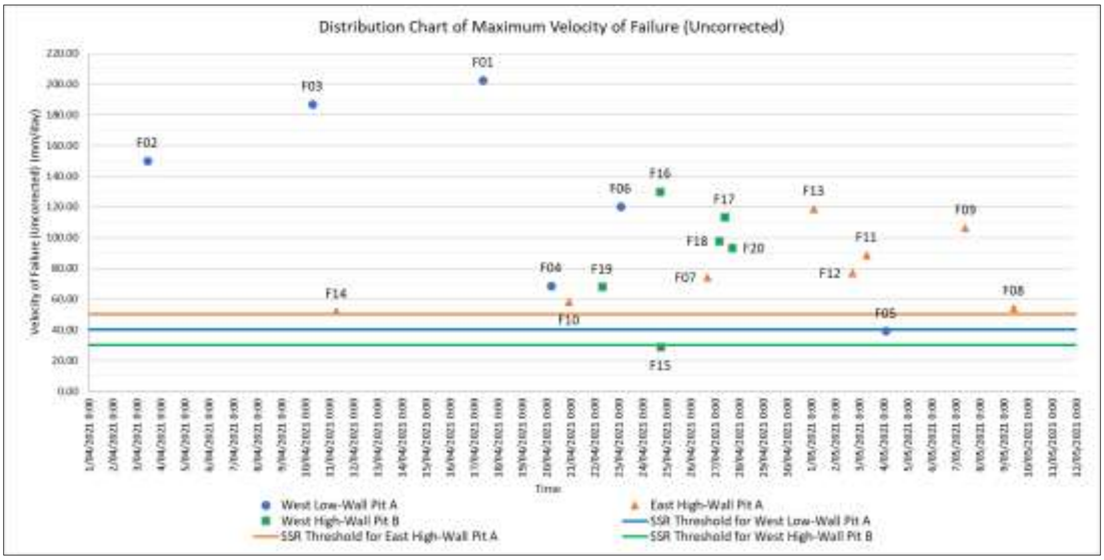

Figure 11. Distribution of uncorrected maximum velocity of failure events and the threshold recommendation for monitoring using SSR.

4. SSR AS MONITORING TOOL

In monitoring slope stability using SSR, pit geometry and the position of the SSR influence the measuring the movement. But this is by no means something insurmountable. SSR is a real-time monitoring tool that helps in managing the risk of slope stability by giving early warnings before failure occurs. We can create a critical limit using only SSR data without the need for back analysis. However, the threshold for monitoring results using SSR can only be applied to the SSR itself, and if it is to be applied to other monitoring tools, it is necessary to carry out back analysis using the method described above. This needs to be considered so as not to be misled in its application. After Bye's research on Osasan (2012), SSR has 93% of a success rate in detecting slope failures, whereas other method has the rate below 90%. Combining the SSR with other methods allows receiving almost 100% success rate. That study shows on table 4.

Table 4. Bye's monitoring type analysis (Osasan, 2012).

Monitoring type	Success rate
Visual monitoring only	32%
Prism/crack meter only	45%
Visual + prism/crack meter	63%
Visual + prism/crack meter + laser	86%
Radar only	93%
Visual + prism/crack meter + radar	97.5%
Visual + prism/crack meter + laser + radar	99%

D. CONCLUSION

According to the results of the back analysis, the geometry of the open pit has an impact on the measurement results, with the greater the angle formed between the direction of movement and the direction of measurement, the lower the value of the movement. The vector loss is 70.95% at point F14, with a horizontal angle difference of 73.40° and a vertical angle difference of 8.70°. On the other hand, a vector loss of 0.05% is obtained at point F06, which has a horizontal angle difference of 1.74° and a vertical angle difference of 0.94°. To overcome this, the threshold of actual movement needs to be optimized to accommodate the reduction magnitude caused by the effect of vector loss.

The maximum velocity of failure is in the data range of 28.77 – 202.53 mm/day, and the corrected magnitude of maximum velocity of failure after vector loss correction is in the range of 49.43 – 367.44 mm/day. Based on the results of these calculations, the "Evacuation" threshold category, which was previously set at more than 120 mm/day for the East High-Wall and West Low-Wall areas of Pit A, as well as the West High-Wall area of Pit B, can be optimize to more than 50 mm/day. The threshold used specifically for monitoring using SSR can apply a threshold category of the "Evacuation" of more than 30 mm/day for the West High-Wall area of Pit B, more than 40 mm/day for the West Low-Wall area of Pit A, and more than 50 mm/day for the East High-Wall area of Pit A.

ACKNOWLEDGEMENT

The authors thank PT Pamapersada Nusantara as owner of the data and gratefully acknowledge support everyone who helps in this work.

REFERENCES

GroundProbe Geotechnical Support Services, (2017): *SSR Geotechnical Training Modules*, Internal Document GroundProbe Geotechnical Support Services.

Harries, N., Noon, D., and Rowley, K. (2006): Case studies of slope stability radar used in open cut mines, *International Symposieum on Stability of Rock Slopes in Open Pit Mining and Civil Engineering*, 335 – 342.

Kumar, A., and Rathee, R. (2017): Monitoring and evaluationg of slope stability for setting out of critical limit at slope stability radar, *International Journal of Geo-Engineering*, **8**, 1 – 16.

Noon, D. (2003): Slope stability radar for monitoring mine walls, *Mining Risk Management Conference*, Sydney, NSW, 1 – 12.

Noon, D., and Harries, N. (2003): Slope stability radar for managing rock fall risk in open cut mines, *Sixth Large Open Pit Mining Conference*, Australian Institute of Mining and Metallurgy, Perth, 93 – 98.

Osasan, K.S. (2012): *Open-Cast Mine Slope Deformation And Failure Mechanisms Interpreted From Slope Radar Monitoring*. Ph.D. Thesis, Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg.