

Applications of InSAR for Early Indication of Mine Slope Instability: Back Analysis of Satellite Displacement Data

Josef Bourgeois *National Institute for Occupational Safety and Health, Spokane, USA*

Sean Warren *National Institute for Occupational Safety and Health, Spokane, USA*

Samir Sbai *National Institute for Occupational Safety and Health, Spokane, USA*

Jacqueline Salzer *SkyGeo Inc., Sausalito, USA*

Armel Meda *SkyGeo Inc., Sausalito, USA*

Tye Lasich *Kinross Gold Corporation, Elko, USA*

Abstract

Conventional ground-based instrumented displacement monitoring can be labor intensive and time consuming, particularly when monitoring a large or complex mine environment. Satellite-based Interferometric Synthetic Aperture Radar (InSAR) provides a safe, economical monitoring option in providing coverage of large areas and critical interests of mine sites. In April 2023, researchers at the National Institute for Occupational Safety and Health (NIOSH) collaborated with SkyGeo Inc. and industry partners of the Highwall Safety project to back analyze recent slope failures in Nevada and identify whether there were early indicators of instability leading up to the events. This paper presents the results of each back analysis and outlines a path forward on continuation of this work throughout the duration of the NIOSH Highwall Safety project. This research coincides with the development of a comprehensive slope failure evaluation database as discussed by NIOSH at Slope Stability 2022 in Tucson, Arizona.

1 Introduction

Two past slope failures that occurred at the Bald Mountain Mine, an open pit gold mine complex located in White Pine County, Nevada, and operated by Kinross Gold Corporation, were back-analyzed using Interferometric Synthetic Aperture Radar (InSAR) to determine whether the monitoring method could identify early indicators of instability leading up to the events. Both events were analyzed using two independent Sentinel-1 descending satellite datasets. The first slope failure that was back-analyzed occurred at the East wall of Top Pit in December 2014 while the second occurred at the North wall of Saga Pit in January 2023. Sentinel-1 data is available at this location starting in November 2014 and continues to be operational, providing the opportunity to

Point your camera for the
QR Code on the side and save
the event on your calendar.



realization



organization



evaluate the displacement patterns associated with both events and relate them to activities and observations on-site.

2 Background

2.1 Use of InSAR Monitoring in the Mining Industry

Successful use of satellite-based InSAR has been proven in multiple industries and has been increasingly utilized to monitor open pit mines (Hadjimitsis, Papadaki et al. 2013, Athayde Pinto, Paradella et al. 2015, Colombo 2015, Paradella, Ferretti et al. 2015, Raventos and Sanchez 2018, Carla, Intrieri et al. 2019, F. Gama, Mura et al. 2020, López-Vinielles, Ezquerro et al. 2020, Sertabipoğlu, Özer et al. 2020, Tang, Motagh et al. 2020, Bar and Dixon 2021, Gong, Lei et al. 2021, Moon and Lee 2021, Lee, Moon et al. 2022). Results are typically provided as periodical reports with the ability to visualize movement data in online portals and/or spatial formats for use in common software packages, such as ArcMap and Google Earth. Current use of InSAR in the mining industry is predominantly by larger mine operations. Williams, Ross et al. (2021) provides a detailed example of successful InSAR back-analysis of the Manefay failure in the United States. InSAR could be used at smaller mines and quarries at relatively low economic costs compared to ground-based radar monitoring.

When compared to ground-based monitoring systems, satellite-based InSAR presents advantages including the ability to monitor large areas with up to 1-2 millimeters of precision as well as the ability to analyze historical data (Williams, Ross et al. 2021). Additionally, this type of monitoring can be done remotely by use of satellite data without the need to install equipment in the mine, providing a safety benefit to its use. These advantages presented by InSAR monitoring are being explored by researchers and collaborators of the Highwall Safety project, which is being conducted by the National Institute for Occupational Safety and Health (NIOSH), to mitigate the impact of large-scale slope failure by catching the ground movement earlier on and better characterizing its size and shape for improved safety and mine management.

2.2 NIOSH Highwall Safety Project

In October of 2021, the Geomechanics Team at NIOSH Spokane Mining Research Division (SMRD) started the Highwall Safety project, which will run until 2026. This project is a continuation of a pilot project conducted by Warren, Chambers et al. (2021) where one of the main goals is to quantify the performance of available criterion for rockfall catchment bench design in a variety of bench configurations and optimize said criterion based on field calibration. During the development of the project proposal, it was requested to add a research objective focused on improving slope performance monitoring capabilities at open pit and quarry sites by working with vendors on existing

Point your camera for the
QR Code on the side and save
the event on your calendar.



monitoring technologies and expanding their use in the mining industry. As a starting point, researchers at NIOSH collaborated with SkyGeo Inc. to back-analyze slope failures at partnering mine sites using InSAR to help spread awareness of the technology and its applications for improved mine site monitoring. This paper presents the results of the first round of InSAR back-analysis at Bald Mountain Mine with the goal of continuing the campaign at other mine sites in the United States throughout the duration of the Highwall Safety project.

2.3 SkyGeo Inc. & InSAR Processing Approach.

SkyGeo is a supplier of products and services derived from InSAR data, including operational monitoring for open pit mines. Based on their broad experience monitoring and investigating ongoing slope instabilities, SkyGeo has developed a catalogue of typical patterns potentially associated with on-site risks. The collaboration with their customers and on-site teams is a key element for understanding patterns in the data and was also key to achieve the outcomes presented in this paper.

SkyGeo performs InSAR processing using proprietary small baseline subset (SBAS) and Persistent Scatterer (PS) algorithms. The combination of algorithms enables them to accurately map displacement dynamics occurring over different temporal and spatial scales. For both cases presented in this paper, a historical baseline analysis was conducted on the site using two independent stacks of SAR imagery acquired by the standard resolution Sentinel-1 satellite.

Due to the locations of the failures and orientation of the walls on which they occurred, only descending orbit datasets were processed (see sections 3.1.1 and 3.2.1). The two datasets have incidence angles of 34 and 44 degrees. Due to topographic and geometric effects, descending orbits provide better coverage on the area that failed, and a higher sensitivity to displacements therefore increasing the likelihood of detecting any precursors. The ascending orbit datasets were excluded since they would provide no coverage of the failure areas in question.

3 Bald Mountain Mine Back-Analysis Case Studies

3.1 Case Study 1 – December 2014 Top Pit

3.1.1 Satellite Dataset

The December 2014 event followed the beginning of satellite acquisitions over the failure area by only a month. Therefore, the pre-failure data availability is limited. The images processed into displacements estimates are shown in Figure 1.

Point your camera for the QR Code on the side and save the event on your calendar.





Figure 1. Sentinel-1 satellites used to analyze Top pit East wall slope failure.

3.1.2 Event Information and InSAR Analysis

The Top pit East wall slope failure occurred on December 21, 2014. At that time, only 1 out of the 96 prisms on the East wall caught movement prior to failure. Furthermore, a storm event that took place December 20th caused a gap in the prism data prior to the failure. Figure 2 shows a side-by-side of the failure area, as mapped after the event, and prism locations.

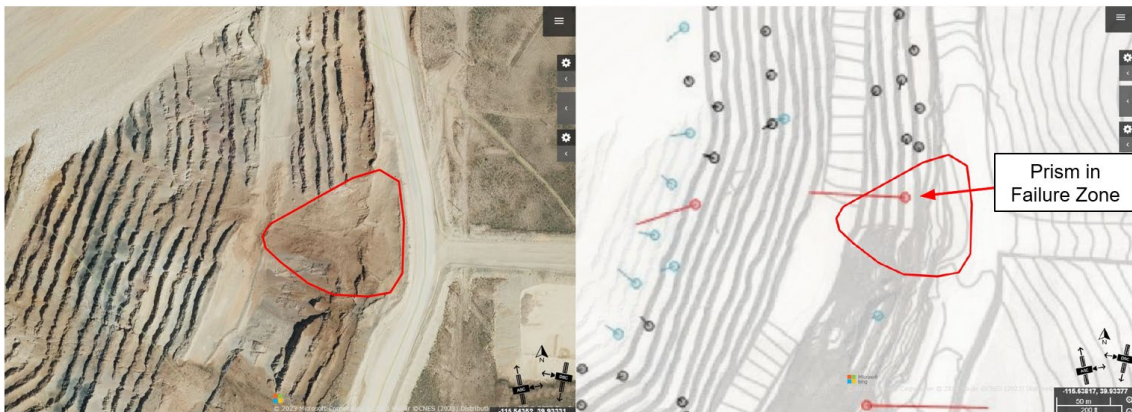


Figure 2. Top pit East wall failure area (red outline) and prism location.

There was no significant displacement measured by the prism in the failure zone until after December 9th, 2014 (Figure 3) which is the date of the last Sentinel-1 descending 71 pre-failure acquisition. This provided an opportunity to see if InSAR could pick up displacement prior to the prism. Figure 4 shows the InSAR differential line-of-sight displacements from November 15, 2014 to December 9th, 2014. Negative displacement (orange-red) indicates movement away from the satellite's line of sight while positive indicates movement towards the satellite's line of sight.

Point your camera for the QR Code on the side and save the event on your calendar.



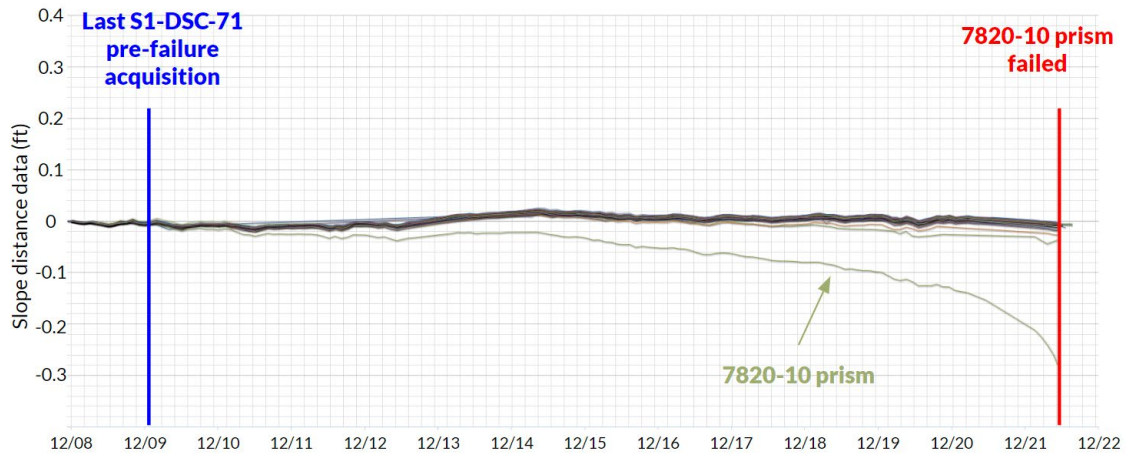


Figure 3. Timeline of 7820-10 prism located in Top pit East wall failure area showing displacement after December 9, 2014 and failure on December 21, 2014.

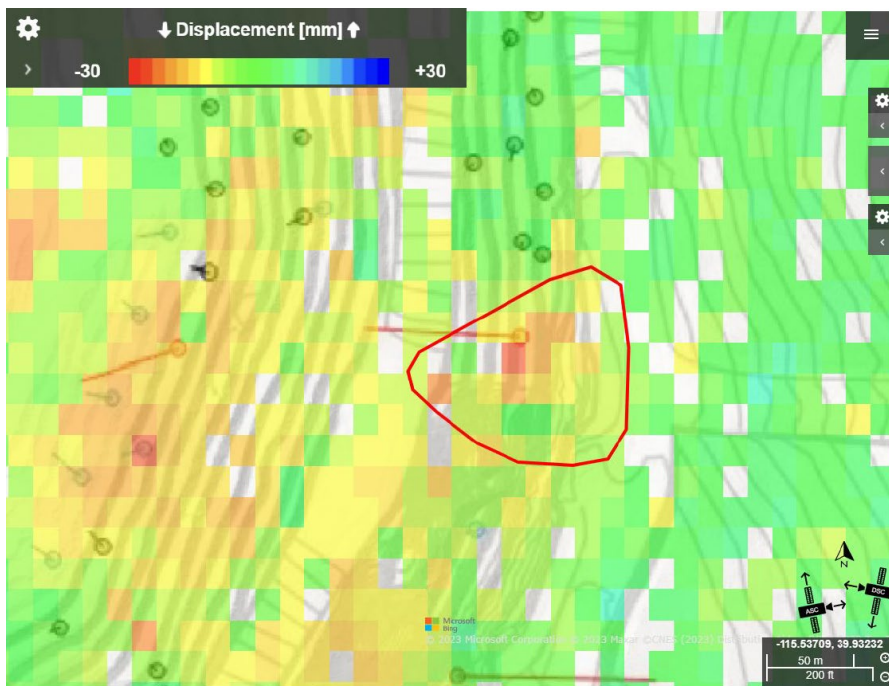


Figure 4. Sentinel 1 descending 71 data of Top pit East wall failure area with prism locations showing differential line of sight displacements from November 15, 2014 to December 9, 2014.

Point your camera for the QR Code on the side and save the event on your calendar.



The displacements estimated with InSAR shown in Figure 4 show up to -30 millimeters in the 24 days leading up to December 9th, 2014. The direction of the movement indicates a downslope direction. This displacement occurs at the location of the prism that measured movement after December 9th, 2014 showing that InSAR detected displacement before the prism.

3.2 Case Study 2 – January 2023 Saga Pit

3.2.1 Satellite Dataset

For the January 2023 event, the same satellite orbits were selected for processing as for the 2014 failure in Top pit. The last images prior to the failure were not included due to heavy snow cover, which negatively impacts the quality of the results. The time line of images used as well as the timing of the failure is shown in Figure 5.

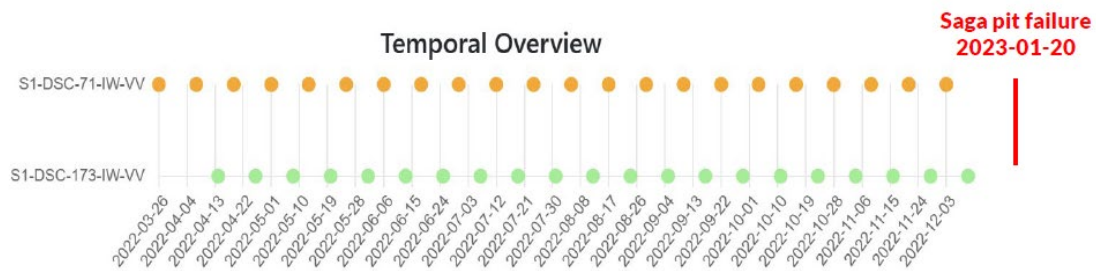


Figure 5. Sentinel-1 satellite orbits and acquisitions used to analyze Saga pit North wall slope failure.

3.2.2 Event Information and InSAR Analysis

The Saga pit North wall slope failure occurred on January 20, 2023. The failure area as well as displacement rate estimated by InSAR between July 30, 2022 and December 5, 2022 is shown in Figure 6. A negative displacement rate (red colors) indicates movement of the ground away from the satellite, when projected onto the satellite line of sight. The white dashed area in Figure 6 highlights a clear spatial anomaly in the failure area along the crest of the pit with displacement rates reaching up to -100 millimeters a year. It's important to note that there is no InSAR coverage below the crest due to mining activity.

Point your camera for the QR Code on the side and save the event on your calendar.





Figure 6. Displacement rates estimated from Sentinel-1 descending orbit 71 data for the period July 30, 2022 to December 5, 2022. Background: pre-failure optical image of the Saga pit North Wall. Red outline: failure area. White outline: group of InSAR points showing an increase in displacement rate preceding the failure.

Focusing in on some of the points with higher displacement on the crest allowed researchers to better follow trends of displacement rates as well as determine when the data started to become inconsistent prior to failure as shown in Figure 7. When investigating the individual points shown in Figure 7, movement is seen along the crest of the slope beginning in July, 2022 and an acceleration is observed in November, 2022.

Point your camera for the QR Code on the side and save the event on your calendar.



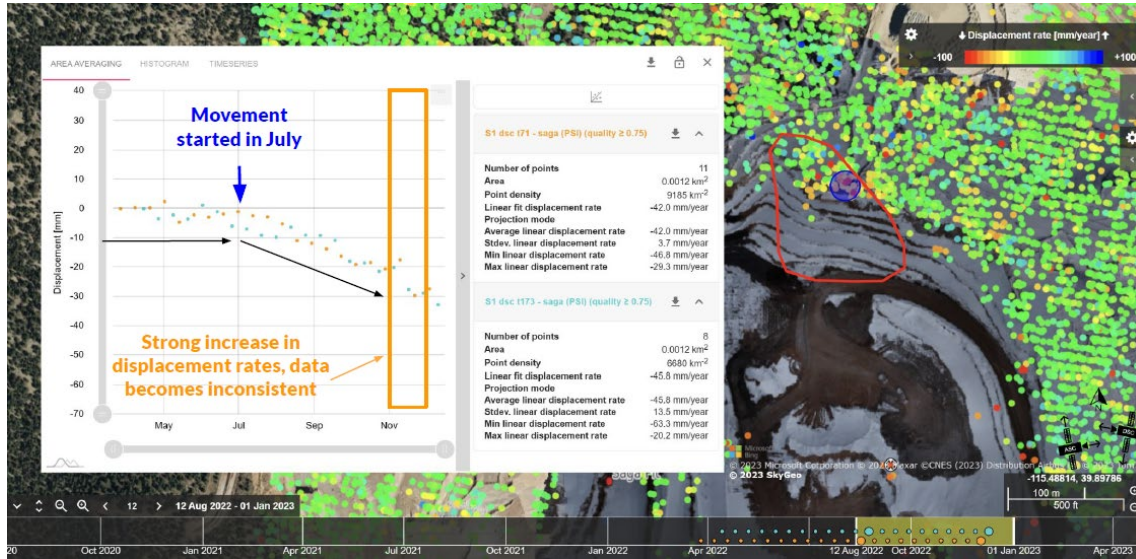


Figure 7. Sentinel-1 descending 71 and Sentinel 1 descending 173 data of Saga pit North wall failure area showing displacement map and average time series of the crest points within the blue shaded circle selected for analysis.

4 Discussion of Results

4.1 Case Study 1 – December 2014 Top Pit

While there was limited Sentinel 1 data available prior to the December, 2014 Top pit failure, as shown in Figure 1, some insight was gained by evaluating differential displacement maps generated by SkyGeo Inc., revealing movement up until December 9, 2014, which was not caught by the prism. Due to the timing of the satellite acquisitions, the displacements mapped by the satellite do not capture the acceleration as seen in the prism in the 3 days leading up to the failure. However, the spatial displacement anomaly mapped via satellite in the earlier stage of the development of the instability could have been raised as an area of concern if InSAR monitoring was in place at the time, enabling the team on site to take precautionary measures, such as limit access to the pit, or optimize their ground based monitoring, e.g. relocating a ground-based radar unit from a different pit. Moving forward, in cases like this, use of InSAR in the slope monitoring program can help fill gaps in displacement data where installation of prisms is not feasible and can complement data being gathered by prisms.

Point your camera for the QR Code on the side and save the event on your calendar.



4.2 Case Study 2 – January 2023 Saga Pit

When comparing the satellite data availability for the two case studies, the catalog of historical Sentinel-1 data is more extensive for the January 2023 failure in the Saga pit. Both two descending datasets used consistently showed a long-term displacement pattern in the failure area as well as shorter term acceleration which could have been raised as a concern if InSAR monitoring was in place at the time.

For this event, a longer time period of data is available prior to the failure. This enabled SkyGeo Inc. to provide additional insights into the event, such as the point in time where there was an onset of instability, and correlating it to operational activities, such as the mining of new benches at the time. The early identification of the formation of instabilities could potentially enable remediation measures that are only feasible while the displacement rates are minor, such as the installation of a stabilizing berm.

A case study like this provides a good example in the importance of integrating both ground-based radar and satellite InSAR data as the InSAR data can detect displacements above the mine crest where most of the detachment zone may be located. An additional example of this type of situation and the benefit of combining both ground-based radar and satellite InSAR data within a mine monitoring program is outlined in Carlà, Farina et al. (2018).

5 Conclusions

This paper represents a first step in the NIOSH Highwall Safety project's InSAR back-analysis campaign to spread awareness of the technology and its applications for improved mine site monitoring. Moving forward, the NIOSH research team will continue to partner with mining operations and companies that provide displacement monitoring services to provide a collection of case studies for increased knowledge sharing to ultimately benefit the mining industry. Finally, the case studies gathered as part of the InSAR back-analysis campaign will be integrated as appropriate into a slope incident database (Sbai, Bourgeois et al. 2022), a collaborative effort between NIOSH and the University of Arizona's Geotechnical Center of Excellence (GCE), which aims to act as a tool that progresses the development of trigger action response plans through utilization of machine learning to improve predictive slope failure modeling.

6 Disclaimers

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH, CDC.

Point your camera for the
QR Code on the side and save
the event on your calendar.



realization



organization



7 References

- Athayde Pinto, C. de, W. R. Paradella, J. C. Mura, F. F. Gama, A. Ribeiro dos Santos, G. G. Silva and M. E. Hartwig (2015). "Applying persistent scatterer interferometry for surface displacement mapping in the Azul open pit manganese mine (Amazon region) with TerraSAR-X StripMap data." *Journal of Applied Remote Sensing* 9(1).
- Bar, N. and R. Dixon (2021). "Unveiling unknowns: Practical application of InSAR for slope performance monitoring and risk management across multiple surface mines." *Engineering Geology* 293.
- Carlà, T., P. Farina, E. Intrieri, H. Ketizmen and N. Casagli (2018). "Integration of ground-based radar and satellite InSAR data for the analysis of an unexpected slope failure in an open-pit mine." *Engineering Geology* 235: 39-52.
- Carla, T., E. Intrieri, F. Raspini, F. Bardi, P. Farina, A. Ferretti, D. Colombo, F. Novali and N. Casagli (2019). "Perspectives on the prediction of catastrophic slope failures from satellite InSAR." *Sci Rep* 9(1): 14137.
- Colombo, D. (2015). Surface displacement monitoring - Using satellite InSAR for mining operations. 24th International Mining Congress and Exhibition of Turkey. Antalya, Turkey, TMMOB Maden Muhendisleri Odasi.
- Gama, F., J. C. Mura, W. R. Paradella and C. G. de Oliveira (2020). "Deformations Prior to the Brumadinho Dam Collapse Revealed by Sentinel-1 InSAR Data Using SBAS and PSI Techniques." *Remote Sensing* 12(21).
- Gong, C., S. Lei, Z. Bian, Y. Tian, Z. Zhang, H. Guo, H. Zhang and W. Cheng (2021). "Using time series InSAR to assess the deformation activity of open-pit mine dump site in severe cold area." *Journal of Soils and Sediments* 21(11): 3717-3732.
- Hadjimitsis, D. G., E. Papadaki, A. Tripolitsiotis, C. Steiakakis, Z. Agioutantis, S. Mertikas, P. Partsinevelos, P. Schilizzi, K. Themistocleous, S. Michaelides and G. Papadavid (2013). Land movement monitoring at the Mavropigi lignite mine using spaceborne D-InSAR. First International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2013).
- Lee, H., J. Moon and H. Lee (2022). "Activity of Okgye Limestone Mine in South Korea Observed by InSAR Coherence and PSInSAR Techniques." *Remote Sensing* 14(24).
- López-Vinielles, J., P. Ezquerro, J. A. Fernández-Merodo, M. Béjar-Pizarro, O. Monserrat, A. Barra, P. Blanco, J. García-Robles, A. Filatov, J. C. García-Davalillo, R. Sarro, J. Mulas, R. M. Mateos, J. M. Azañón, J. P. Galve and G. Herrera (2020). "Remote analysis of an open-pit slope failure: Las Cruces case study, Spain." *Landslides* 17(9): 2173-2188.
- Moon, J. and H. Lee (2021). "Analysis of Activity in an Open-Pit Mine by Using InSAR Coherence-Based Normalized Difference Activity Index." *Remote Sensing* 13(9).
- Paradella, W. R., A. Ferretti, J. C. Mura, D. Colombo, F. F. Gama, A. Tamburini, A. R. Santos, F. Novali, M. Galo, P. O. Camargo, A. Q. Silva, G. G. Silva, A. Silva and L. L. Gomes (2015). "Mapping surface deformation in open pit iron mines of Carajás Province (Amazon Region) using an integrated SAR analysis." *Engineering Geology* 193: 61-78.
- Raventos, J. and C. Sanchez (2018). The use of InSAR for monitoring slope stability of rock masses. TuniRock2018. Hammamet, Tunisia, Tunisian Society for Rock Mechanics.
- Sbai, S., J. Bourgeois, S. Warren and C. Stopka (2022). Development of a comprehensive slope failure evaluation database for open pit mines. International Slope Stability 2022 Symposium. Tucson, Arizona, University of Arizona's Geotechnical Center of Excellence.
- Sertabipoğlu, Z., Ü. Özer and H. Tunçdemir (2020). "Assessment of slope instability with effects





April 14 to 19, 2024 

Fundação Dom Cabral 
Nova Lima, Minas Gerais, Brazil

- of critical displacement by using InSAR and FEM." *Arabian Journal of Geosciences* 13(4).
- Tang, W., M. Motagh and W. Zhan (2020). "Monitoring active open-pit mine stability in the Rhenish coalfields of Germany using a coherence-based SBAS method." *International Journal of Applied Earth Observation and Geoinformation* 93.
- Warren, S., D. Chambers, C. Stopka and J. Armstrong (2021). Rockfall catch bench design guidelines - revisited. *Minexchange: 2021 SME Annual Conference & Expo*, Virtual, Society for Mining, Metallurgy & Exploration.
- Williams, C., B. Ross, M. Zebker, J. Leighton, M. Gaida, J. Morkeh and M. Robotham (2021). "Assessment of the Available Historic RADARSAT-2 Synthetic Aperture Radar Data Prior to the Manefay Slide at the Bingham Canyon Mine Using Modern InSAR Techniques." *Rock Mechanics and Rock Engineering* 54(7): 3469-3489.

Point your camera for the
QR Code on the side and save
the event on your calendar.



realization



organization

