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Understanding surface subsidence from a block cave by comparing InSAR data with 3D numerical modeling

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Abstract

All mining operations have an inherent risk of instability related to rock excavations. For underground mines, the risk can be extended to the surface in the form of surface subsidence. Mining companies routinely use deformation monitoring to manage the geotechnical risks associated with the mining process. It can be challenging to monitor the extent and magnitude of subsidence with deformation-monitoring methods used for surface or underground mines. If a mine transitions from a surface mine to an underground mine, the existing monitoring techniques can be used to monitor small-scale effects of caving on the pit walls. It would be unrealistic, however, to measure the effects of subsidence using similar techniques for the whole area of influence. Numerical modeling is widely used to predict the effects of subsidence, based on small data sets available to calibrate the model. Now, satellite-based, interferometric synthetic aperture radar (InSAR) can be used to monitor deformation and subsidence over a wide range of areas. The technology has progressed to where measurements can be obtained every five to ten days. This is an efficient technique for covering large, slow-moving areas in comparison to the results obtained from numerical modeling. The data obtained can also be used to calibrate the numerical model to obtain better future predictions of subsidence. Today, the combination of satellite-based radar and numerical modeling has become an invaluable tool for monitoring and predicting the effects of subsidence. In this paper, a visual demonstration of results of movements from an active mine site should contribute to the understanding of how satellite-based radar data and numerical modeling can be used to show the effects of subsidence.

1 Introduction

As our world evolves to rely more and more on technology, the demand for metals has been increasing. With this ever-increasing need for mineral resources, mining operations worldwide are working to develop deeper and more complex mines to extract the high and lower grade ore. Many surface mine operations are transitioning to underground mines to obtain deeper and economically beneficial orebodies. Block caving is recognized as the most suitable underground mining method to use for bulk extraction of relatively large, deep, and lower grade ore bodies. Block caving, by definition, is a mass mining method in which a block of ore is undercut, followed by drawing of the broken ore (Brown 2007). As the ore continues to be drawn from the extraction level, the rock immediately above will start to gradually collapse into the void to replace the ore that has been removed. Continued extraction of the ore will result in further progressive failure of the underlying rock until the cave breaks through to surface. The initial breach is typically in the form of a circular pit, commonly referred to as a chimney cave breakthrough. The breakthrough is roughly centered over the mining area, although offsets may occur if geologic weaknesses are present (Van As et al. 2003). This effect is known as subsidence, which is a slow and gradual process that will take place over the life of mine.

Some of the significant hazards associated with the block caving method include but are not limited to uncontrolled collapses, air blasts, crown pillar failure, mud rushes, seismicity and rockburst as well as surface subsidence. Surface subsidence can have detrimental impacts on critical infrastructure, such as surface service roads, buildings, large ventilation fans, and waterways that are located in the zone of influence of subsidence. Thus, it is of utmost importance to better predict subsidence and to have a robust subsidence management plan based on monitoring and observations. Recent progress in the computer and software industry has provided geomechanical engineers with better tools to predict, measure, and monitor the subsidence over the life of mine.

This paper is based on the subsidence monitoring and modeling efforts at PT Freeport Indonesia (PTFI). To better manage the subsidence and prevent impacts to surface infrastructure, PTFI has been using advanced three-dimensional numerical modeling techniques to forecast subsidence impacts. Additionally, PTFI has implemented an extensive surface-monitoring program that includes a well-developed, rich microseismic array, a series of prisms, and the use of the Satellite-based Interferometric Synthetic Aperture Radar (InSAR).

The monitoring plan helps to validate and calibrate the numerical modelling predictions. The monitoring data also provides early detection and warning of subsidence impacts so appropriate action plans can be implemented to prevent the impact as per the PTFI Trigger Action Response Plan (TARP).

In this paper, the outputs from InSAR data are analyzed and compared with 3D numerical modeling predictions. This comparison is conducted as an ongoing process that feeds into the calibration of the numerical model.

2 Subsidence modeling

To better forecast subsidence impacts for its block caving operations, PTFI has created a detailed three-dimensional numerical model. The subsidence numerical model is used to simulate cave propagation and forecast surface subsidence following the mine plan and production schedule. The analysis was conducted using a coupled Discontinuum Finite Element (DFE) and Newtonian Cellular Automata (NCA) Model. This model simulates the physics of cave draw, cave flow, cave growth, rock mass damage and movements of faults as a coupled system to evolve cave shapes and estimate stress, strain and movement. In a DEF-NCA coupling mechanism, DEF replicates the stiffness changes in the cave that are a result of NCA-computed muck pile movements and cave shapes (Beck et al. 2011).

Analysis was performed on subsidence that will be induced by mining the Grasberg Block Cave (GBC) mine, Deep Mill Level Zone (DMLZ) mine and Deep Ore Zone (DOZ) mine. The model required various inputs to simulate ground conditions and the realistic mine plan in order to generate subsidence predictions as accurately as the resolution allows based on the input data. The model inputs are listed below:

- Mining geometries to the scale of drifts and drawbells from DMLZ, GBC and DOZ mines (Figure 1 and 2)
- Interpreted structure data spanning 13 km centered on the mine, including all regional and mine scale structures / discontinuities
- Interpreted geology data spanning 13 km centered on the mine, including intrusives, alterations and geotechnical domains
- Extraction sequence and schedules for all the relevant areas
- Constitutive model which includes the following:
  - Yield Surface, which is needed for realistic softening and dilatancy – key for simulating damage and rate of energy release (RER)
  - Calibrated plastic and strain potential, which is essential as the RER is heavily dependent on load re-distribution during yield

- Structures with valid frictional-cohesive constitutive formulation
- Strain, damage and seismicity data

- Stress field for GBC and DMLZ as specified in Table 1
- Material properties like UCS and GSI for each geotechnical domain as specified in Table 2
- Anisotropy to represent bedding

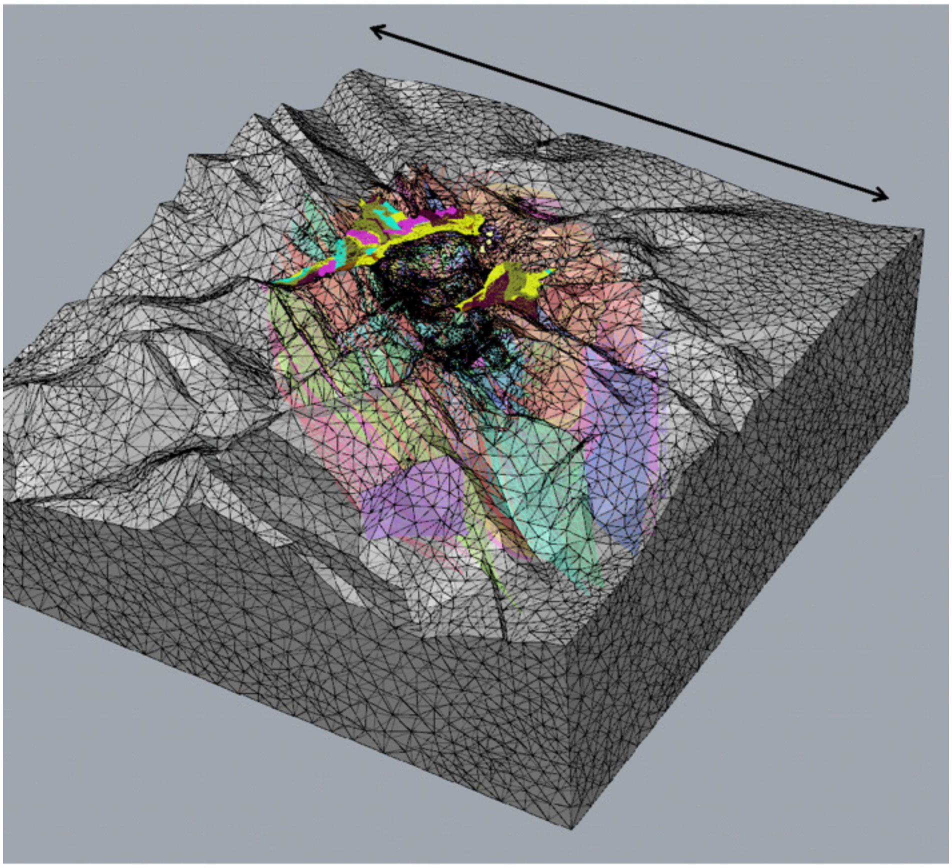

Figure 1 **Example of model area containing mine geometries, geological and structural data**

Table 1 **Subsidence model stress inputs**

Mine	Stress (MPa)	Trend	Plunge
GBC	$\sigma 1 = 76.95$	30°	84°
	$\sigma 2 = 62.70$	210°	6°
	$\sigma 3 = 42.75$	300°	0°
DMLZ	$\sigma 1 = 88.95$	224°	10°
	$\sigma 2 = 62.70$	347°	70°
	$\sigma 3 = 42.75$	130°	20°

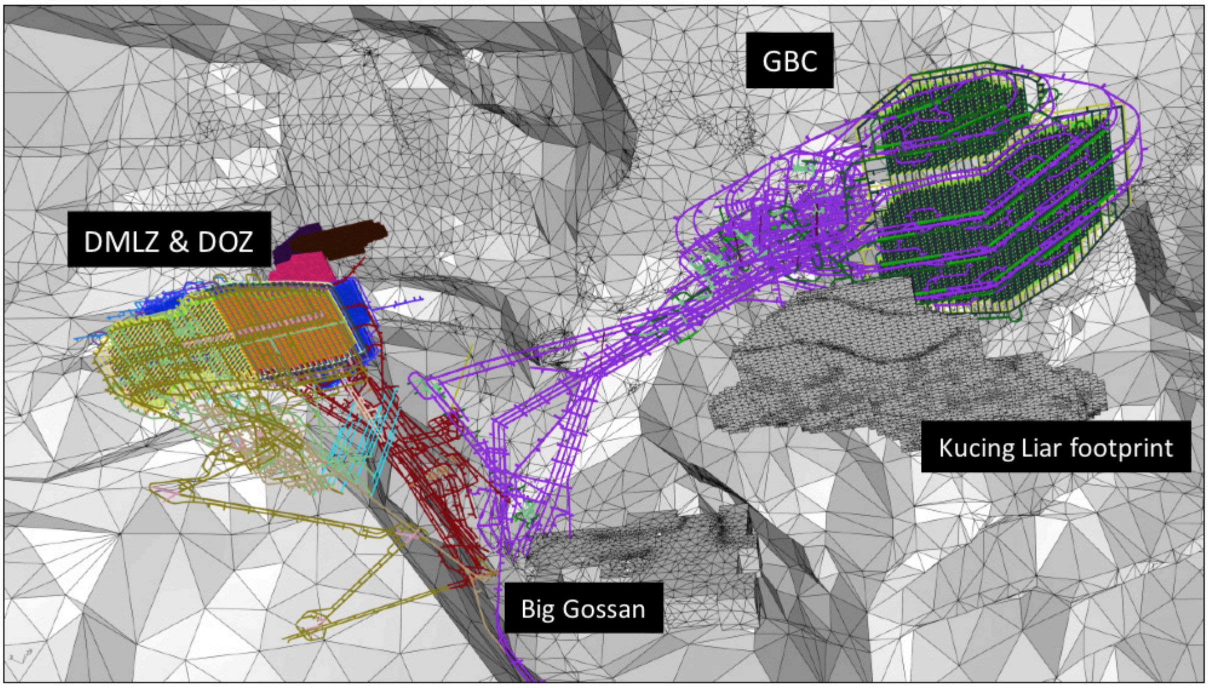

Figure 2 **Model geometry inputs**

Table 2 **Subsidence model material property inputs**

Geotechnical domain	UCS (MPa)	Young's modulus (GPa)	GSI	Density (g/cm³)
Potassic Undifferentiated	110	46	72	2.7
Phyllic Undifferentiated	100	68	61	2.8
Phyllic Undifferentiated	100	68	69	2.8
Sericite Pyrite	110	41	67	2.8
Sericite Pyrite	110	41	69	2.8
Heavy Sulfide Zone	130	96	60	3.5
Kali Undifferentiated	140	47	68	2.7
Kali Sericite-Pyrite	80	47	61	2.6
Broken Zone	40	20	39	2.7
Endoskarn	160	55	74	3.0
Tertiary Ertsberg Diorite	160	53	81	2.7
Exoskarn	135	68	69	3.0
Tertiary Fumai Marble	80	46	48	2.8
Tertiary Waripi Marble	95	46	58	2.8

3 Subsidence management strategy

The DFE-NCA model is a powerful tool used at PTFI to predict the timing and the extent of subsidence impacts. Subsidence prediction using three-dimensional numerical modelling is just one of the strategies used to manage subsidence at PTFI. Monitoring is another key component of subsidence management. The overall strategy used at PTFI to manage subsidence includes a four-stage approach as described below (Figure 3):

1. Initial appreciation: This is the initial classification to assess the level of interrogation required for the site investigation stage. In this stage, the sites of interest will be classified as 'low risk,' 'requires further investigation' or 'exceeding risk threshold.' These classifications are based on the amount of damage caused by strain forecasted from the numerical model.
2. Site Investigation: Site investigation is performed when indicated by the initial appreciation stage. Based on the initial results and available data, an observational program and actions to manage the expected cave induced deformation are recommended.
3. Engineering: Based on the site investigation stage, a risk assessment matrix is generated. The risk assessment matrix is accompanied by a risk mitigation plan based on the level of risk a particular site or infrastructure will experience.
4. Observation: Observation is the last stage to manage the impact of subsidence. At this stage, subsidence is monitored continuously and monitoring results are used to calibrate and update the model to improve future subsidence forecasts.

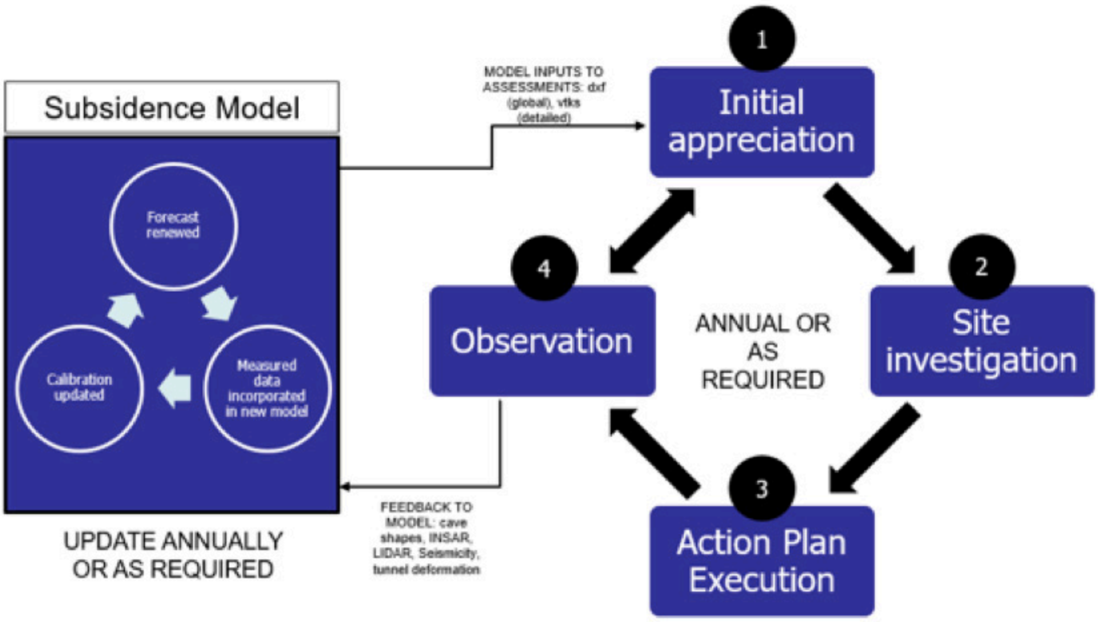

Figure 3 **Four-stage subsidence management strategy**

4 InSAR

Satellite-based Interferometric Synthetic Aperture Radar (InSAR) is a well-known, proven and industry accepted method used to measure subsidence. InSAR is widely considered as a best practice and an effective tool to manage subsidence risk. It has been successfully used at several underground mines and more recently at the Kiiruna mine and the LKAB Malmberget mine (Mäkitaavola et al. 2016; 2018) among others. InSAR provides broad coverage, high spatial density, and high precision to complement the existing monitoring technology (Chandarana et al. 2016). It is often used in addition to ground-based monitoring systems to monitor slope failures in open-pit mines or as a monitoring tool for surface subsidence caused by underground block cave mining. InSAR can detect small deformations over large areas with high accuracy. For example, it can detect deformations as low as 5 mm between two readings, and at a millimeter scale when multiple images are combined (Taylor et al. 2016). Surface-based monitoring technologies are ideal for small areas of measurement, like the slopes of an open-pit mine or stockpiles, but InSAR can detect risks across the entire mine site, including open pits, stockpiles, mine infrastructure, tailings, etc. InSAR provides extensive visual capacity and a broader range of coverage due to its distance from the earth's surface.

However, like any other monitoring technology, InSAR has its limitations as listed below (Taylor et al. 2016):

- Longer processing times required to deliver deformation measurements, making it difficult for mines to mitigate risks promptly.
- Dynamic and constantly changing surfaces of an active mine cause difficulties in obtaining successful measurements between image acquisitions.
- Extreme rates of slope deformations and subsidence at an active mine limit conventional InSAR from providing accurate measurements.

The limitations above do not limit mines from using the satellite-based deformation data for subsidence monitoring. Subsidence may result in prolonged initial movements, and these would be very easy for InSAR to capture. The slow processing times would not vastly influence the subsidence risk mitigation factor as the 3D numerical modeling would fill the gap with its predictions. Overall, using the satellite-based radar would serve as a beneficial tool to confirm the predictions from numerical modeling and fill in the gaps by providing data with sub-millimeter accuracy to calibrate the prediction models.

5 Data analysis

As mentioned previously, InSAR is a satellite-based radar that provides deformation data. The quality and quantity of the data collected from the radar are highly dependent on the angle of the satellite as it passes over the area of interest. The data coverage can also depend on the ascending and descending direction of the satellite. If the data from only an ascending or descending pass of the satellite is collected, the opposite side of the ground surface might be under the shadow, creating a gap in the data. PTFI uses a dual look (ascending and descending modes) to collect the InSAR data using the Terrasar-X (TSX) satellite with an 11-day time lag.

In the study of subsidence, the data gap generated in the InSAR data can be filled with near accurate modeling output data. Figure 4 shows the difference in the data images generated from InSAR data and an image from the subsidence model prediction. InSAR has a few limitations; one of which is its inability to capture rapidly moving areas due to the long-time intervals between data capture. In addition to missing data in fast-moving areas, InSAR is not able to capture areas under shadow due to the angle at which the satellite views the earth's surface. On the other hand, a model prediction does not have either of these two limitations. A model can give predictions for fast-moving areas and generate outputs for the entire region. In Figure 4a, the visible white areas indicate areas missed by InSAR due to the shadow created by the topography. Figure 4b is a direct comparison with Figure 4a from model output results.

An annual comparison of the InSAR data with modeling results from 2017 to 2019 is demonstrated in Figures 5-7. Due to the limitation of InSAR to measure areas with high displacement, a displacement scale of 0 cm to 40 cm is used. InSAR data available for this paper display deformation based on as-built surfaces within the 2017-2019 timeframe. Modeling results show an annual increment in the subsidence zones based on pre-mining topography, making it necessary to show a larger scale of deformation. Hence, a range of 0 cm to 500 cm and 0 cm to 300 cm is used to display the deformation for the years 2017, 2018 and 2019, respectively.

Figure 5 illustrates the data from the year 2017 for the subsidence above the DOZ mine. In this figure, the images show an increasing rate of subsidence moving towards the center, emphasizing the caved zone. Figure 5a has visible data only on the right side, whereas the left side does not have sufficient data due to the angle of the satellite capturing the data. Model results in Figure 5b highlight the area to the left that will experience the effects of subsidence. It also indicates the area in the center that should experience movement caused by the caving of the rock mass as ore is extracted underground. In this scenario, it is not possible to confirm the modeling predictions with the InSAR data, as the rate of movement is too high for InSAR. In the case of such high deformation, InSAR would not be able to differentiate between actual deformation and the change in surface topography. The white circles in Figures 5a and 5b show similar movement trends in the same location from both data sets, higher towards the center, and reducing as the distance from the caved zone increases.

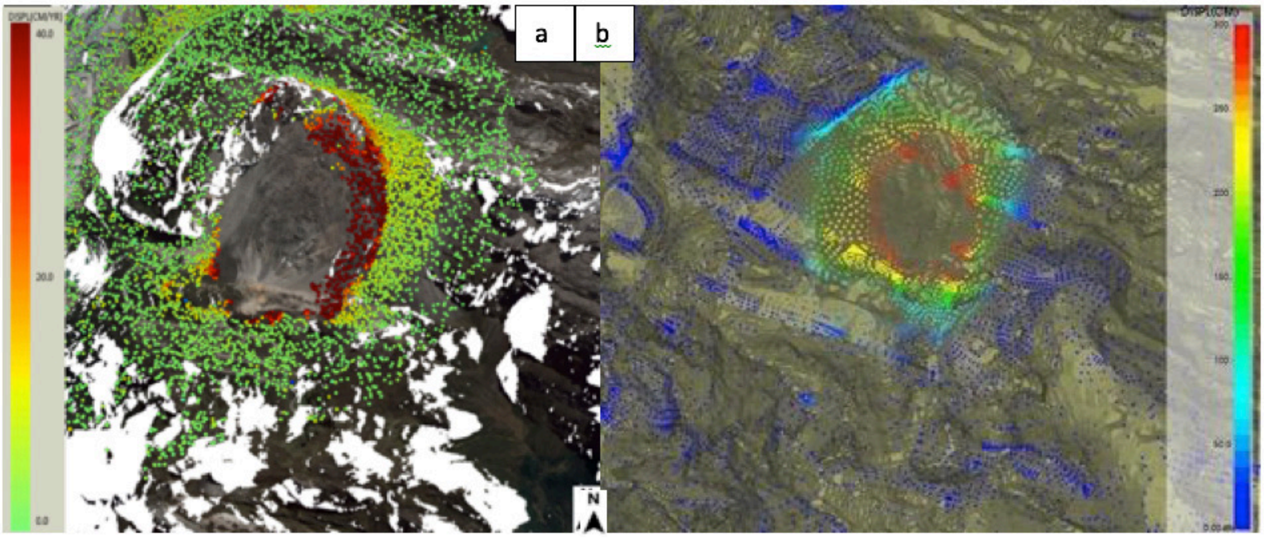

Figure 4 **a. InSAR image highlighting the area with missing data; b. image from modeling prediction showing a full set of data**

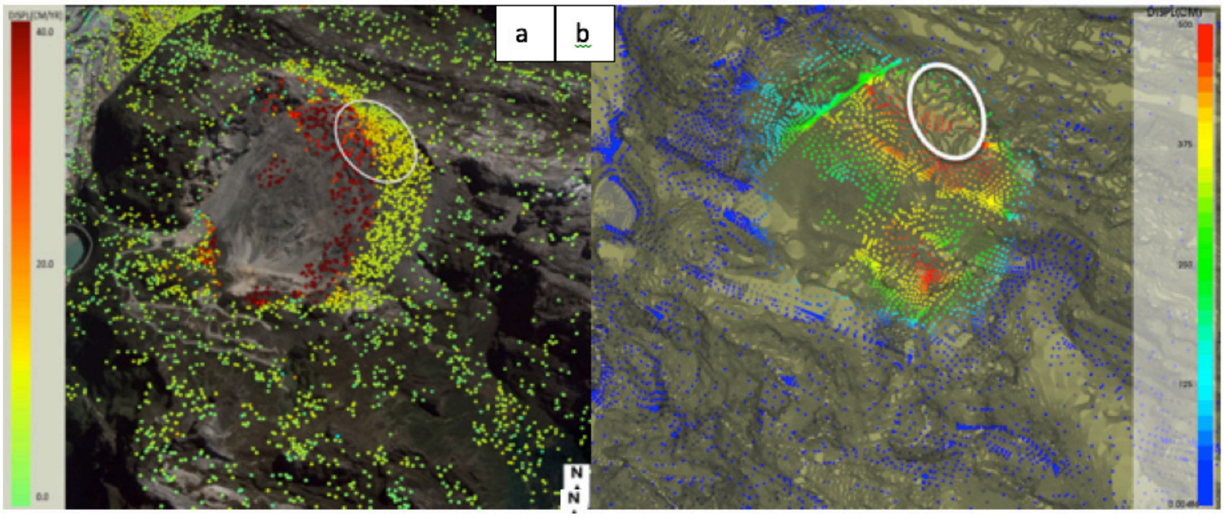

Figure 5 **a. Cumulative displacement from InSAR for 2017 b. Predicted annual displacement for 2017 based on the subsidence numerical model developed in 2019**

Figure 6 shows the data above the DOZ from InSAR and the model predictions for the year 2018. This image illustrates an increased rate of deformation in the center, defining the increased cave zone, as more ore is extracted underground. In the year 2018, InSAR captured a higher rate of deformation on the northern side as compared to data from 2017. The model output has a similar visual representation, in Figures 6a and 6b, respectively. The northern area of the image is at a much higher elevation than the southern side. As the rock mass caves, higher displacement is more prominent as it is easy for the rock mass to slide from a higher elevation while losing support beneath. Both the InSAR data and the modeling outputs show a similar trend in the areas highlighted with the white circles. Figure 6 also illustrates that the highest amount of surface subsidence is observed in the center of the caved zone, and the effects of subsidence decrease as the distance from the center of the cave increases.

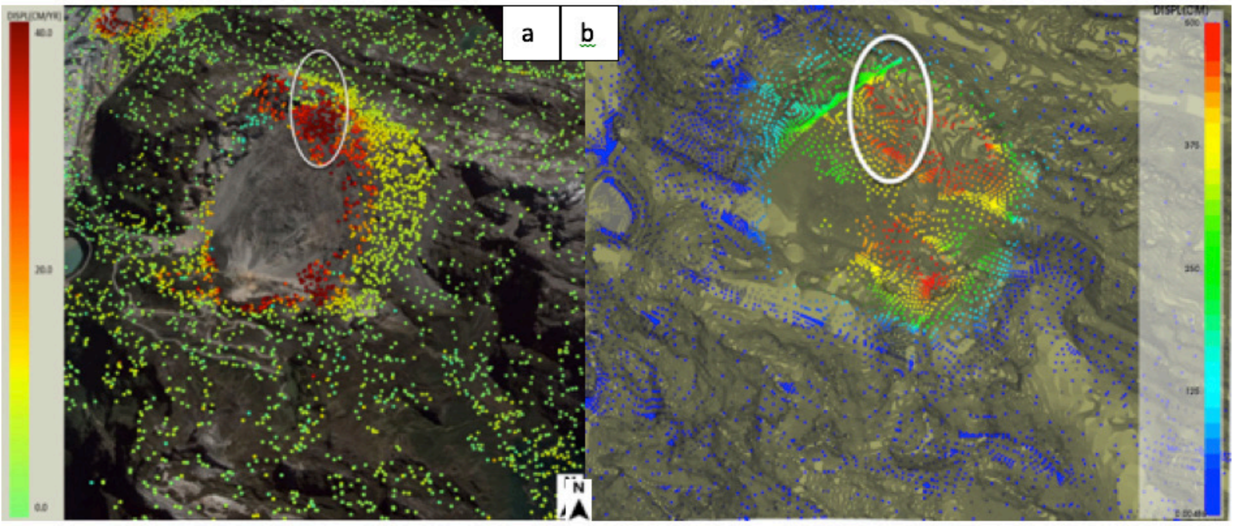

Figure 6 a. Cumulative displacement from InSAR for 2018 b. Predicted annual displacement for 2018 based on the subsidence numerical model developed in 2019

Figures 7a and 7b show the increasing subsidence effects for the year 2019. From these images, it can be easily observed how subsidence grows outwards from the center of the cave. As defined earlier, the cave first achieves its chimney breakthrough to the surface, and there is a further breakthrough of the rock mass surrounding the center throughout the life of mine. As the distance from the center of the mine increases, the effects of subsidence are decreased, as demonstrated in Figure 7b. Figure 7 highlights the direction of subsidence with an arrow. The low rate of extraction in DOZ reduced the high rates of deformation in the center of the mine. As there is a reduced rate of deformation in 2019, a smaller deformation scale is used in Figure 7b.

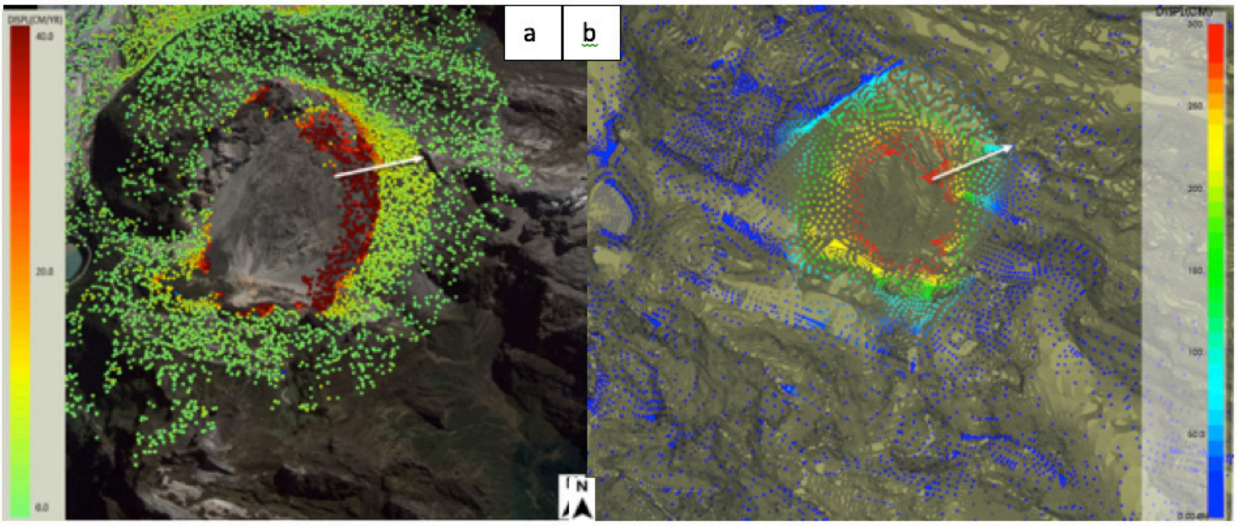

Figure 7 a. Cumulative displacement from InSAR for 2019 b. Predicted annual displacement for 2019 based on the numerical model developed in 2019

6 Conclusions

All the data presented in the paper demonstrate that InSAR monitoring and modeling are both valuable tools in understanding how subsidence may affect the area surrounding an active block caving mine. InSAR is a useful tool to observe the actual deformation from surface subsidence, but due to its limitations, it can be challenging to get the full overall picture especially in an area with a lot of vegetation. To fill in the gap and to prepare risk mitigation strategies, it is beneficial to use 3D subsidence numerical modeling. Subsidence modeling generates future predictions of subsidence based on the mining sequence and other input parameters like rock type, geology, etc. The modeling predictions can help plan risk mitigation strategies, whereas the InSAR data can be used to confirm the model results for the areas with available data. Similar to InSAR, 3D modeling has its challenges. The model can only make predictions based on the model inputs. In cases in which the model inputs are incorrect or the mine sequence changes, the data could generate less accurate predictions. This paper also demonstrates the similarities between the InSAR data and modeling outputs, showcasing the importance of combining the use of both tools at an active mine, where monitoring alone would limit the ability to develop risk mitigation strategies in advance.

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References

Beck, DA, Sharrock, G & Capes, G 2011, 'A coupled DFE-Newtonian Cellular Automata scheme for simulation of cave initiation, propagation and induced seismicity', 45th US Rock Mechanics / Geomechanics Symposium in San Francisco, CA, June 26–29, 2011.

Brown, ET 2007, 'Block Caving Geomechanics', JKMRC: Brisbane.

Chandarana, UP, Momayez, M & Taylor, KT 2016, 'Monitoring and Predicting Slope Instability: A Review of Current Practices From A Mining Perspective', International Journal of Research in Engineering and Technology, vol. 05, Issue 11, pp. 139-151.

Mäkitaavola, K, Stöckel, B-M, Savilahti, T, Sjöberg, J, Dudley, J, McParland, MA & Morin, R 2018, 'InSAR as a Practical Tool to Monitor and Understand Large-Scale mining-induced Ground Deformations in a Caving Environment', in Y Potvin & J Jakubec (eds), Proceedings of Caving 2018, Vancouver, Canada, pp. 661–674.

Mäkitaavola, K, Stöckel, B-M, Sjöberg, J, Hobbs, S, Ekman, J, Henschel, M & Wickramanayake, A 2016, 'Application of InSAR for monitoring deformations at the Kiirunavaara mine', in HS Mitri, S Shnorhokian, MK Kumral, A Sasmito & A Sainoki (eds), Proceedings of the 3rd International Symposium on Mine Safety, Science and Engineering, McGill University, Montreal, pp. 133–139.

Taylor, K, Ghuman, P & McCardle, A 2016, 'Operational Mine Monitoring with InSAR', in PM Dight (ed.), Proceedings of the First Asia Pacific Slope Stability in Mining Conference, Australian Center for Geomechanics, Perth, pp. 695-706.

Van As A, Davison J & Moss A 2003 'Subsidence definitions for block caving mines', Rio Tinto technical services.