Developing a Digital Twin: A Semi-Brittle Slope Failure Case Study from Pueblo Viejo Gold Mine

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ABSTRACT: Technological improvements in geotechnical mapping, modelling and monitoring now allow a digital twin to be developed and maintained in parallel with mining operations. That is, the routine use of aerial photogrammetry, semi-automatic rock mass characterization, three-dimensional slope stability modelling and ground-based interferometric synthetic aperture radar monitoring allow near real-time comparison of modelled and realized ground conditions. This is critical for reconciling the effectiveness of geotechnical models for predicting future slope stability (or instability). This paper presents a semi-brittle slope failure case study from Pueblo Viejo gold mine which was managed using a digital twin approach. The near real-time comparison of the three-dimensional model with observed slope conditions allowed critical structures to be added to the geotechnical model as mining progressed. This led to the identification of a high risk area that would not have been identified if the digital twin was not implemented & maintained during mining.

Keywords: Slope stability analysis, photogrammetry, radar monitoring, digital twin.

1 INTRODUCTION

Pueblo Viejo gold mine is located approximately 80 km north of Santo Domingo, in the Dominican Republic, on the island of Hispaniola in the Caribbean archipelago. The mine is located at an altitude of approximately 300 to 500 m above sea level. The Pueblo Viejo district has a tropical climate with the nearby cities of Cotuí and Bonao receiving 1843 mm and 1956 mm of average annual rainfall (Bar et al., 2021).

Gold mineralization in the Pueblo Viejo district, Dominican Republic, is spatially and temporally related to a series of Early Cretaceous volcanic domes (Nelson, 2000). Two principal deposits (Moore and Monte Negro) and a number of smaller deposits including Cumba, Mejita, Banco V, Arroyo Hondo I and II have contributed ore since surface mining commenced in 1975. The geological setting is structurally complex with several phases of thrust faulting and hydrothermal alteration. Due to the complex ground conditions and tropical setting, several instabilities and geotechnical challenges have occurred and were retrospectively reviewed for incorporation into future designs (Bar et al. 2022a; Bar et a. 2022b; Cobián et al. 2022).

To proactively manage geotechnical risk at Pueblo Viejo, a digital twin was developed and maintained in parallel with mining operations. The purpose of a digital twin in surface mining is to develop a reliable prediction of future pit slope behavior through the ongoing mapping, monitoring and updating of slope stability models at various time scales, including but not limited to: three month or quarterly plans, successive pushbacks and life-of-mine (LoM) plans.

The digital twin produced at Pueblo Viejo mine incorporated routine:

- **Mapping**: including the acquisition and analysis of structures mapped from in-pit face mapping and aerial photogrammetry as excavations progressed.
- **Modelling**: including the development and updating of three-dimensional (3D) limit equilibrium (LE) slope stability models to predict and reconcile slope performance.
- **Monitoring**: including the acquisition and review of real time, ground-based, interferometric synthetic aperture radar (Gb-InSAR) with full pit coverage for safety and model validation.

This paper presents an overview of the general concepts used for a digital twin (mapping, modelling and monitoring) and its role in managing a semi-brittle slope failure in pushback 15 of Moore Pit. The slope failure was 20 m high (two benches). This failure would not have been identified had the digital twin not been implemented and maintained during mining operations.

Figure 1. Aerial photograph of Moore Pit Pushback 15 looking South. Highly anisotropic Carbonaceous Sediments (UCS and LCS) in the upper (shallow) slopes, overlying various tuffs (FDT and QBT). Red polygon indicates the location of the actual failure.

2 DEVELOPMENT OF A DIGITAL TWIN FOR MOORE PIT

Pushback 15 is located on the southern side of Moore Pit and comprises highly anisotropic Carbonaceous Sediments (UCS and LCS) in the upper slope, which overlies various tuffs (FDT and QBT) which are generally stronger. The initial Moore Pit pushback 15 design was analyzed using 3D and two-dimensional (2D) LE analysis based on the material properties summarized in Table 1. Pore pressures were simulated using a phreatic surface 5 to 10 m below the topographic surface and H_u coefficients derived from monitoring data (vibrating wire piezometers) in the area.

As shown in Figure 2, most of the pushback had a Factor of Safety (FoS) above 1.2, which is the minimum required static FoS according to the site acceptance criteria. One *lower* FoS slip surface (FoS = 1.07) was predicted in the UCS and LCS units. It was decided that such a potential hazard could be managed at an operational level, without a substantial slope redesign. However, from both a safety and economic risk management perspective, this required a digital twin approach during excavation. The digital twin was designed to include:

- Mapping of structural and rock mass conditions using aerial photogrammetry, and supplemented by face mapping where safely accessible for every 20 m of vertical advance.
- 3D LE model updates as local geomechanical conditions were mapped and projected.
- Targeted monitoring using ground-based radar systems. Two overlapping IDS ArcSAR systems were deployed, in conjunction with a 24/7 monitoring and response protocol to facilitate the evacuation of personnel and equipment prior to any collapse (Bar et al. 2022c).

Table 1. Material Properties.

Material		UCS: Upper Carbonaceous Sediments	LCS: Lower Carbonaceous Sediments	FDT: Fine Dacitic Tuff	QBT: Quartz Bearing Tuff
Unit Weight	[kN/m^3]	26	27	28	28
UCS	[MPa]	8	14	30	30
GSI	[-]	37	48	50	60
m_i	[-]	12	8	8	10
Damage Factor, D	[-]	0.0 - 0.7	0.0 - 0.7	0.0 - 0.7	0.0 - 0.7
Pore Pressure, H_u	[-]	0.56	0.69	0.75	0.64
Persistent Fractures*	[-]	Bedding	Bedding	Faults	Faults
c' (fractures)	[kPa]	6	8	7	7
ϕ' (fractures)	[°]	18	16	17	17
Fracture Orientation	[-]	SW	SW	NW	NW
Dip / Dip Direction	[°]	33/235	33/235	13/328	13/328
Persistence	Bedding is continuous, faults are typically persistent for 25 to 50 m.				

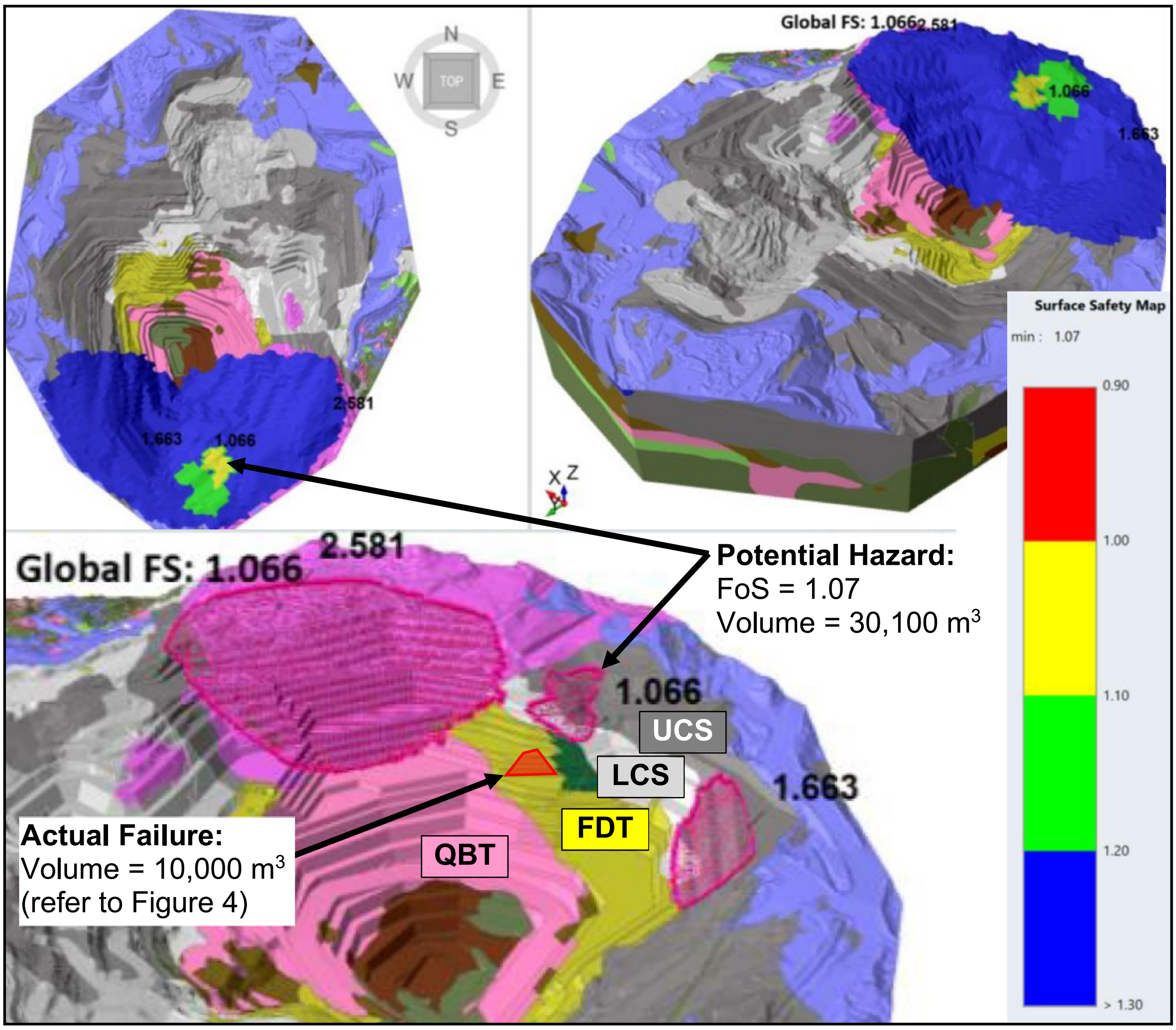

Figure 2. Moore Pit Pushback 15 Initial Design – 3D LE modelling results indicating generally stable conditions (i.e. FoS > 1.2). A *low* FoS (1.066) slip surface was predicted within the UCS and LCS units. Top Left: Plan View map showing FoS contours, Top Right: Perspective view looking South-East showing FoS contours. Bottom: *Lowest* FoS Slip Surfaces and Key Materials. Looking South-East.

2.1 PHOTOGRAMMETRIC 3D MODELS FOR MAPPING AND DISPLACEMENT MEASUREMENTS

Photogrammetric 3D models from drone imagery are generally acquired on a monthly basis at Pueblo Viejo mine. Face mapping is completed where safely accessible for every 20 m of vertical advance. The site geotechnical engineers map and reconcile structural features using 3GSM's ShapeMetrix UAV software. All mapped structures are then saved in a central database.

Photogrammetric 3D models for Moore Pit were developed on a fortnightly basis due to the potential hazard identified in the UCS and LCS units from initial slope stability modelling, Figure 2. Several hundred geological structures were mapped using photogrammetry and confirmed the regional anisotropy orientation (33°/235°) in the Carbonaceous Sediments. Mapping further identified a set of low-angle faults and shears within the FDT, with dip and dip direction of 13°/328°, as shown in Figure 3 and documented in Table 1. These structures had not previously been identified at the time the initial 3D LE model was developed and were used to predict the semi-brittle failure realized in this unit.

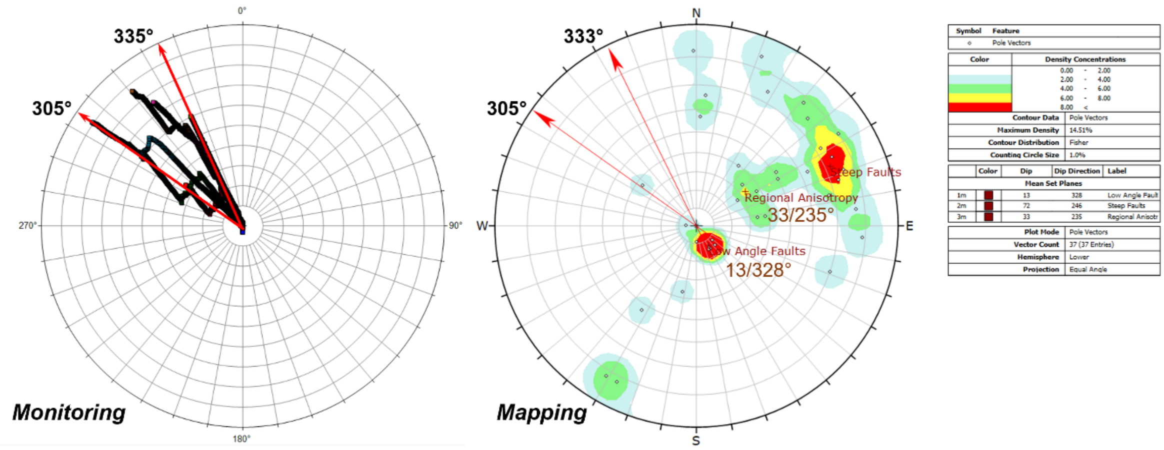

Figure 3. Stereographic Projections indicating co-alignment of low angle faults with the direction of movement. Left: Displacement vector directions: 305-335° from IDS Guardian software. Right: Mapping data with low angle fault orientations with mean dip and dip direction of 13°/328°.

Data from photogrammetry mapping was also used to generate displacement maps for the predicted semi-brittle failure. Data from subsequent acquisitions was contoured to show displacement over time. The displacement maps were then used to estimate and verify the sub-vertical structures bounding the wedge-type failure. This information is summarized in Figure 4, and was used to reconcile and update the digital twin 3D model.

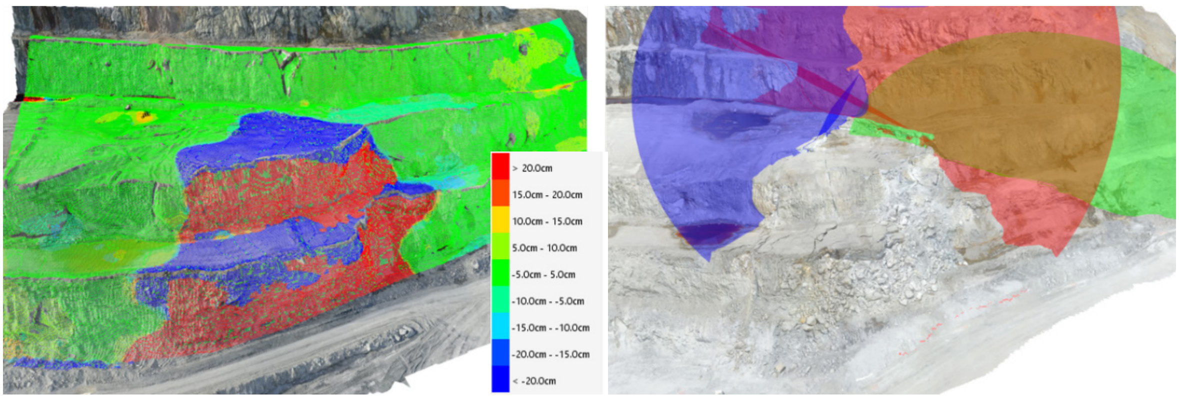

Figure 4. Left: displacement map generated from a comparison of photogrammetric 3D models (red indicates outward movement and blue indicates downward movement). Right: Main geological faults mapped and modelled (extrapolated) from the same 3D model. Orientations: Blue Fault: 51°/294°, Red Fault: 57°/356°.

2.2 DISPLACEMENT MEASUREMENTS FROM RADAR MONITORING

Full pit monitoring is available at Pueblo Viejo where four IDS IBIS radars are set up to monitor all operating areas. All measurements of movement area are processed and displayed into a single map view. Displacement vectors are then calculated on overlapping areas, Figure 5. For each overlapping pixel covered by two radars, one single 2D or 3D displacement vector is visualized, depending on the number of radars monitoring the target area. For accurate measurements of displacement and direction of movement (i.e. to calculate movement displacement vectors) at least two radar systems are required to reconstruct a pseudo 3D displacement vector by combining interferometric displacements measured from different positions in space (Severin et al. 2014; Leoni et al. 2016).

Figure 5 displays the radar velocity data and pseudo 3D displacement vectors calculated for the semi-brittle slope failure in Moore Pit. Movement in this area of the pit initially began to accelerate approximately 23 hours prior to collapse. At this point in time, mine operations were notified and the area controlled.

During failure, average velocities of 4 and 8 mm/h were recorded, 4 and 1 hours prior to collapse, respectively. Accelerations of 10 mm/h^2 were observed 1 hour prior to collapse. The resultant failure was approximately 10,000 m^3 in size (26,500 t).

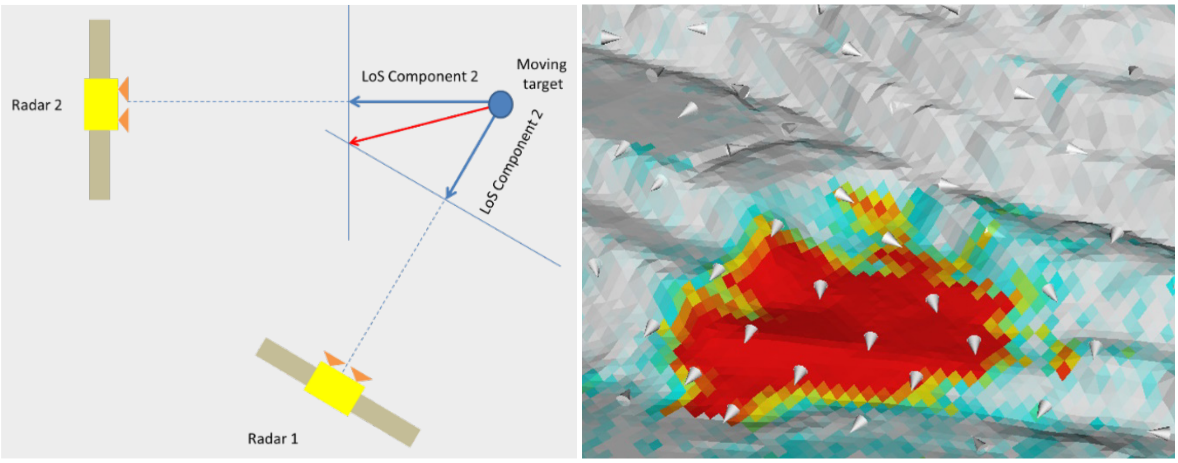

Figure 5. Left: Concept of radar system geometry with two radars and one moving target. Measurement of different components from different LoS and direction of displacement vector on the horizontal plane. Right: Vectors from semi-brittle failure indicating direction of movement (consistently toward the NW: 305-335° within failure) and contouring indicating velocity (red contours indicate ≥2 mm/h LoS toward radar).

3 DISCUSSION AND SUMMARY OF DIGITAL TWIN PROCESS

The slope that was initially designed and analyzed using 3D LE slope stability modelling identified a *low* FoS (FoS ~ 1.07) area in the UCS and LCS units. The volume of the slip surface associated with this FoS was approximately 80,000 m^3. The design provided a digital twin approach that was implemented during mining operations. The digital twin required routine mapping and constant monitoring and reconciliation of as built conditions with predicted slope performance based on the 3D LE model.

Routine mapping identified additional structures not included in the original 3D LE model. Reconciliation of these newly measured structures and actual displacement allowed stability predictions to be refined to safely manage an additional semi-brittle wedge-failure exposed through mining operations in Moore Pit in the FDT unit. The identified failure volume was approximately 10,000m^3; it has been pro-actively and effectively managed using the mapping, modelling and monitoring systems required by the digital twin methodology. The newly identified structures will be included in the next realization of the digital twin model.

In its current form the digital twin process remains a relatively manual process, but will be continued to be implemented by Pueblo Viejo based one the value identified in this case study. It is envisaged with ongoing improvements in technology and software integration, the digital twin process for geotechnical risk identification and reconciliation will be automated by 2030.

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