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Integrated Drone-Based Stope Geometry Reconciliation and Stability Assessment at the Dannemora Mine

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Abstract

This paper describes an integrated approach that combines drone-based 3D stope surveys, updated geotechnical data, in-situ stress measurements and numerical modelling to assess stope geometry, stress concentrations and backfill performance at the Dannemora underground iron ore mine. An initial study established a mine-wide geotechnical model; empirical assessments indicated that many existing and planned stopes plot outside the nominally "stable" zone of published stability charts, despite generally favourable historical stope performance. This discrepancy motivated the development of a mine-scale FLAC3D model and acquisition of detailed drone-based 3D stope surveys to test the actual stability of the stopes and to verify backfill behaviour. The drone surveys demonstrate discrepancies between planned and achieved stope geometries, particularly in width and backfill surface elevation and confirm that tailings backfill occupies a substantial portion of the existing voids with little evidence of large-scale caving. These geometries were used to refine the numerical model and check consistency between modelled behaviour and observed stope performance.The integrated dataset shows that, although empirical methods place many stope walls outside nominal stability envelopes, numerical modelling and drone-based reconciliation indicate generally stable behaviour when supported by high rock mass quality, systematic backfilling and appropriate sequencing. The paper outlines implications for stope design and sequencing and how drone surveys can be integrated to provide ongoing stability verification and design refinement.

Keywords

Dannemora Mine, Stope stability, Drone photogrammetry, Backfill, Numerical modelling.

1 Introduction

Dannemora Mine in southern Sweden has operated intermittently since at least 1481 and most recently between 2012 and 2015, with existing stopes extending from surface to ~450 depth and remaining mineralisation modelled and explored to ~750m. The future operation will use open stoping with systematic backfilling in steeply dipping, relatively narrow iron orebodies at depth within a high-quality but stressed rock mass. Figure 1 shows the existing and planned stopes. The analyses form part of a feasibility study update focused on the Botenhäll–Norrnäs and Konstäng mining areas, where existing open stopes, tailings backfill and critical infrastructure interact. Study assessments showed that several planned stopes, including those in the deeper Schaktmalmen, Svea and Diamanten 2 orebodies, do not plot within the empirically "stable" region of commonly used stability charts (Potvin, 1988; Clark and Pakalnis, 1997; Capes and Milne, 2008), even though existing stopes at the

site with similar or larger spans have remained stable. This prompted a more detailed, site-specific stability evaluation. Geotechnical behaviour is critical because, in all but one orebody (Diamanten 2), mining is beneath existing infrastructure in a brownfield footprint where in-situ stresses approach historical levels, and high extraction ratiosand large hydraulic radii raise the potential for dilution, local instabilities and stress-driven pillar damage (Clark and Pakalnis, 1997; Capes and Milne, 2008), with direct implications for safety and project economics. Empirical stability databases (Potvin, 1988; Clark and Pakalnis, 1997; Capes and Milne, 2008) contain relatively few cases combining large hydraulic radii, very good rock mass quality and systematic backfilling, as at Dannemora, and the initial design relied on converted RMR–Q relations and regional stress compilations with limited local verification. Existing stope and backfill geometries in Botenhäll, Norrnäs and Konstäng were only approximately known from conventional survey, limiting model calibration. To address these gaps, the 2024 study combined updated geotechnical logging and laboratory testing, LVDT-based overcoring stress measurements (Stress Measurement Company Oy, 2023) and drone-based 3D photogrammetric stope surveys (AMKVO, 2023) with the mine-scale FLAC3D (Itasca, 2019) model developed during the study.

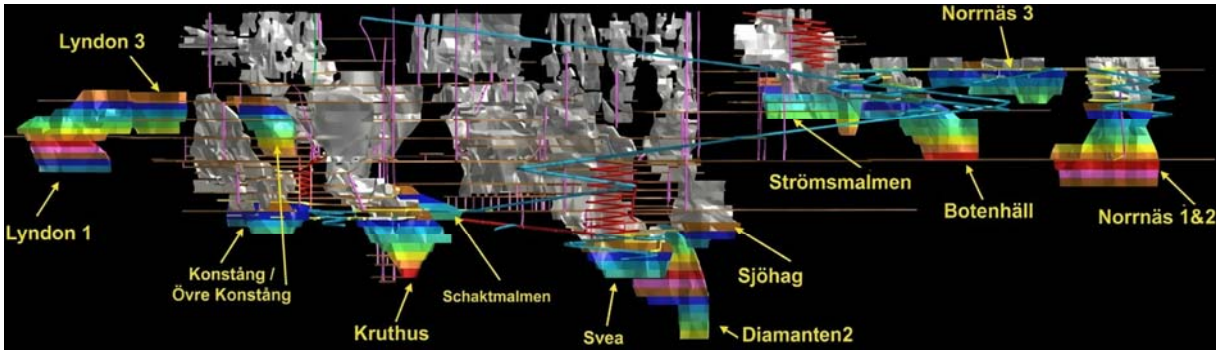


Fig. 1 Long profile view of the Dannemora mine, looking West (grey = existing stopes, multi-colour = planned stopes).

2 Background

2.1 Study Context

The updated rock mechanics assessment defined geotechnical domains and rock mass quality using historical RMR logging, mapping and new logging and testing (Bieniawski, 1973; Barton et al., 1974; NGI, 2015; Schlofeldt and Carter, 2018). Weighted mean RMR89 values generally fall in the "good" to "very good" range, with derived Q values indicating conditions favourable for large open stopes; re-logging and mapping show generally high RQD, with only thinner zones of reduced quality near mapped weakness zones and contacts. On this basis, the rock mass is modelled as a continuum in the mine-scale FLAC3D analyses, while recognising that jointing controls local overbreak and small-scale instabilities. Empirical assessment using the modified Stability Graph and related tools showed many planned and existing stope walls plotting outside the nominally stable region (e.g. Potvin, 1988; Clark and Pakalnis, 1997), suggesting a higher probability of instability than observed in practice at Dannemora. The empirical charts were therefore treated as conservative screening tools rather than hard design limits. A mine-scale FLAC3D model was developed to assess stope and pillar performance and interactions in the Kruthus–Konstäng–Upper Konstäng–Schaktmalmen area, where critical pillars and infrastructure coincide. The main existing stope geometries and qualitative performance classes are summarised conceptually in Table 1.

Table 1. Summary of existing Dannemora stopes (orebody, approximate dimensions, qualitative stability).

Orebody	Max. height (m)	Max. width (m)	Strike length (m)	Performance
Botenhäll	~75	~40	~94	Stable
Diamanten	~243	~60	~241	Stable
Källarmalmen	~196	~64	~189	Stable
Konstäng	~242	~120	~239	Stable; minor local hangingwall failures
Kruthus	~267	~109	~159	Stable
Norrnäs 1 & 2	~105	~36	~168	Stable
Sjöhag	~474	~48	~152	Stable
Strömsmalmen	~170	~39	~302	Stable
Svea	~333	~78	~213	Stable

The study highlighted limitations in the historical geotechnical database, including reliance on converted RMR–Q relationships, sparse large-scale structural data and coarse representation of as-mined stope and backfill geometries. Because many existing stopes plot outside the empirical "stable" zone yet have performed well, additional geotechnical logging, stress measurements and drone surveys were undertaken in Botenhäll, Norrnäs and Konstäng to provide a stronger basis for numerical modelling. This discrepancy led to a programme of additional geotechnical logging and testing, LVDT-based overcoring stress measurements and drone-based 3D surveys of key existing stopes and backfill in Botenhäll, Norrnäs and Konstäng. The resulting dataset provides a stronger basis for numerical modelling and checking whether the apparent empirical "over-span" at Dannemora is consistent with actual stress–strength conditions and observed behaviour.

3 Geotechnical Data and Methods

3.1 Geotechnical inputs overview

The updated dataset combines historical and new geotechnical logging, mapping and laboratory testing to characterise rock mass and intact properties in each orebody and domain. Re-logging using RMR89, Barton's Q-system and GSI corrected biases in historical RMR datasets and provided consistent rock mass inputs for numerical modelling; converted Q values were checked against directly logged Q and found to be consistent, supporting continued use of corrected RMR as the primary classification. Laboratory testing from 2021–2024 campaigns comprised UCS (with deformation), multistage triaxial compression, Brazilian tensile and direct shear tests on ore and waste, with rigorous validation. The combined dataset confirms high intact strengths across most orebodies and broadly appropriate design values. In-situ stresses were characterised using LVDT-based overcoring at levels L145 and L251, and inverse modelling yields stress gradients consistent with regional Fennoscandian data (Stephansson et al., 1986), which have been adopted in the numerical modelling.

3.2 Numerical modelling framework

Stope and pillar stability are evaluated primarily using a mine-scale FLAC3D model that includes all planned and existing stopes and key infrastructure, with refined zoning around Kruthus, Konstäng, Upper Konstäng, Lyndon 1, Lyndon 3 and Schaktmalmen. Because existing open and backfilled stopes, and multiple orebodies interact over large lateral and vertical extents, a single mine-scale model was adopted to capture stress changes, confinement and pillar load sharing, before moving to more detailed orebody-scale analyses. The model employs a Mohr-Coulomb constitutive law fitted to Hoek–Brown rock mass envelopes derived from updated intact strength and GSI (Hoek *et al*., 2002) and represents backfill as an elastic material with moderate stiffness. Mining is simulated in stages following the planned extraction sequence; outputs include plasticity zones and strength–stress ratios around stopes, pillars and infrastructure. Empirical stability charts were used to flag stopes outside nominal stable regions and to identify walls and ore bodies requiring closer scrutiny (Potvin, 1988; Clark and Pakalnis, 1997; Capes and Milne, 2008). In the present work, they provide context for why the detailed FLAC3D analyses and drone surveys were undertaken, namely, to test whether nominally "over-spanned" stopes are in fact stable. In a subsequent phase, local ore body-scale discontinuum models will be developed for selected areas to examine joint-controlled mechanisms and support performance where the mine-scale continuum model stresses are a large proportion of the rock mass or pillar strength.

4 Drone-Based 3D Photogrammetric Stope Survey

4.1 Data acquisition, processing and registration

Drone-based close-range photogrammetry was used to capture high-resolution 3D geometries of selected existing stopes at Botenhäll, Norrnäs and Konstäng. Overlapping image sets from safe vantage points in stopes and connecting drifts were processed using a standard photogrammetric workflow and registered to the mine survey grid, producing dense point clouds and meshes for comparison with historic stope wireframes. For Botenhäll and Norrnäs, cross-sections through stope wireframes and survey meshes show the correspondence between modelled extents, mined voids and backfill surfaces, while at Konstäng, 3D views illustrate the relationship between existing stope voids, fill meshes and planned Upper Konstäng stopes (Fig. 2). These reconciled geometries were used to refine the geotechnical block model and the FLAC3D mesh in the focus area, replacing idealised shapes.

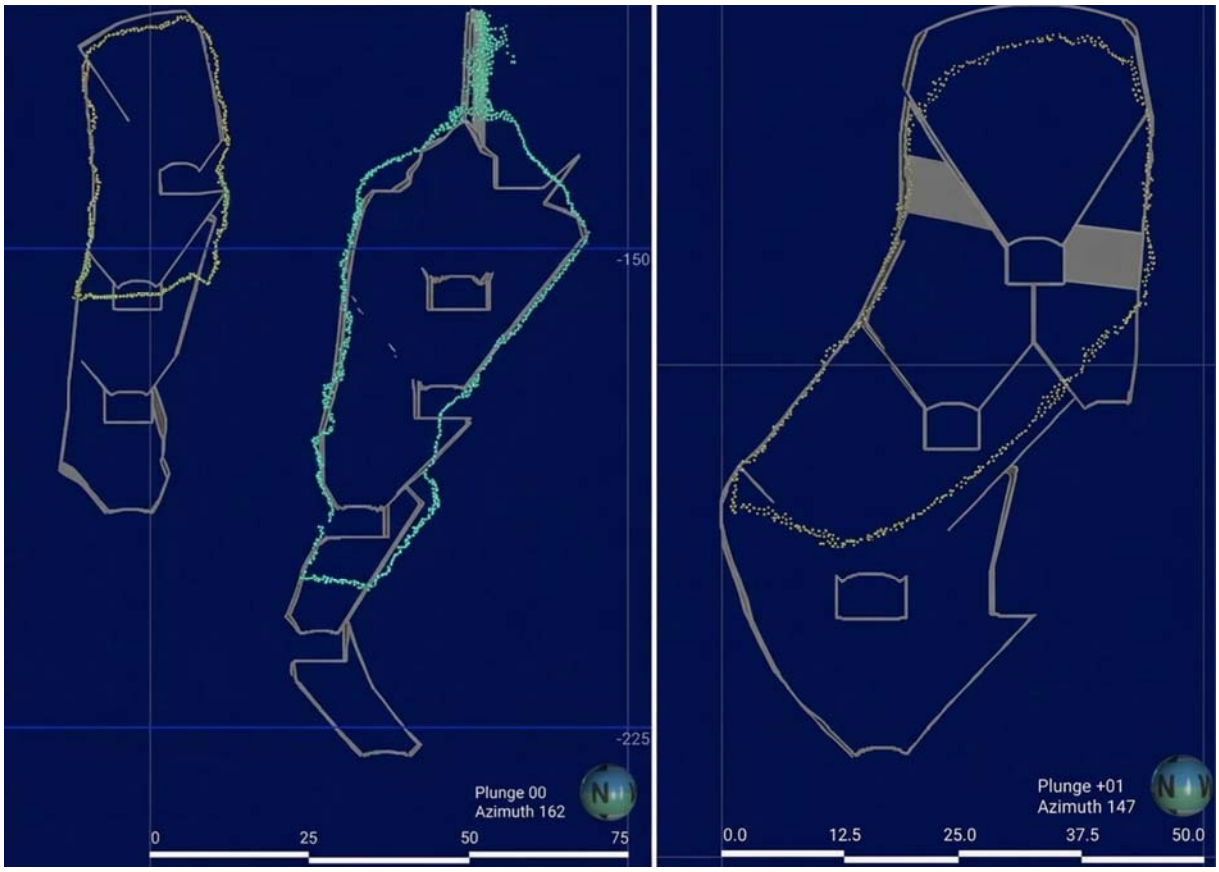


Fig. 2 Cross section through the existing stope wireframes (grey) and recent stope surveys for Norrnäs 1 &2 – Left Image (cyan and dark green) and Botenhäll – Right Image (olive green). The base of the survey point is where the ore bodies have been backfilled.

5 Results: Stope Geometry Reconciliation

5.1 Overbreak, underbreak and geometry differences

In the Botenhäll–Norrnäs area, cross-sections comparing historicalstope wireframes with drone-derived meshes showno evidence of large-scale caving or major backfill collapse.At Konstäng, reconciled stope voids show a poor correlation with the historical stope wireframe, with the surveyed hangingwall located higher than previously interpreted and the overall void significantly larger than depicted in the legacy model (Fig. 3). Tailings placed between 2012 and 2015 infill most of the existing stope, encroaching into the orebody now referred to as Upper Konstäng. The dominant interpretation is that a larger volume of material was mined from Konstäng than indicated by the historical wireframes, and that the current void size primarily reflects production rather than post-mining caving. This is supported by the 2015 tailings surface: the 3D point cloud shows mostly fine-grained tailings and only a few blocks above this horizon, implying the void geometry has been essentially unchanged since backfilling ceased. The lower Konstäng orebody appears to have been undercut and has likely been of approximately its current size since 1982, consistent with historical records of mining of a Konstäng “pillar” down to level −350 m using 37 tonnes of explosives (SSAB, 1982). These findings confirm that both the lower Konstäng and part of Upper Konstäng have long-standing, larger-than-recorded voids, and the updated FLAC3D model therefore incorporates the drone-derived void and fill geometries to better represent actual stress paths and boundary conditions for the critical Konstäng–Upper Konstäng–Kruthus pillar system.

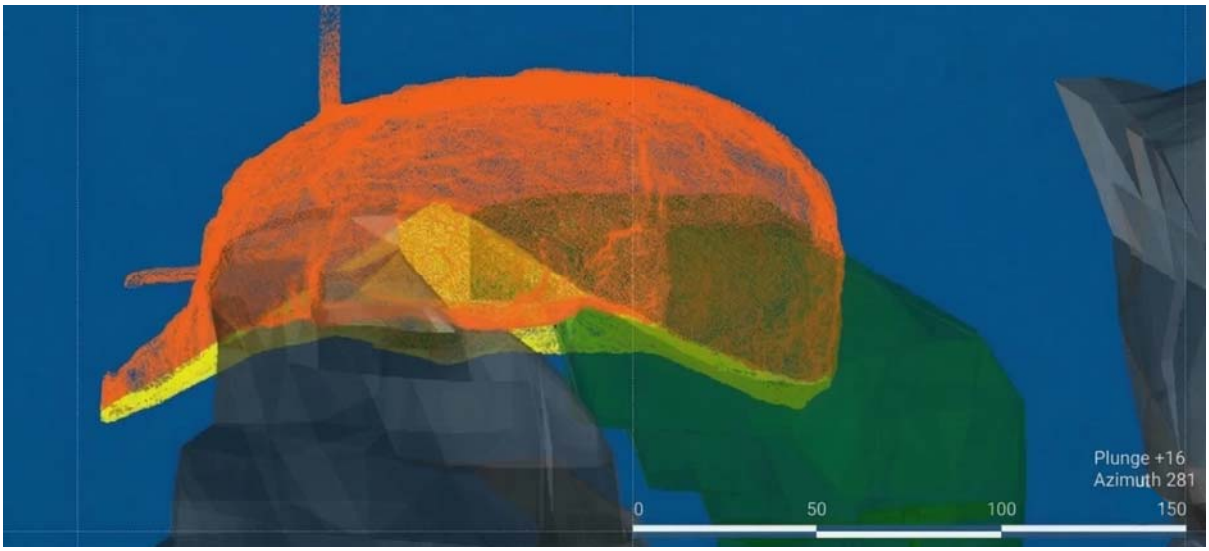


Fig. 3 Example drone-derived stope geometry at Konstäng, showing existing orebody wireframe (grey), surveyed stope void (orange), tailings fill (yellow) and planned Upper Konstäng stopes (green) in mine coordinates.

The surveys delineate backfill extents and surfaces, especially in the Konstäng stopes, where separate meshes for void and fill show that tailings backfill occupies a substantial proportion of the existing stope volume. Backfill surfaces are relatively smooth and gently sloping at stope scale, with no evidence of large, detached blocks or major caving structures, suggesting that long-term behaviour has been dominated by the intact rock mass and stress field rather than progressive backfill collapse, and that blocks observed on the backfill surface most likely detached during drilling or production blasting, rather than reflecting inherent stope instability. In Botenhäll and Norrnäs, the base of the surveyed voids defines the backfill elevations in the examined stopes and constrains fill thicknesses. These observations support representing backfill as an elastic medium in the numerical model and confirm that systematic backfilling has underpinned the favourable stability record of stopes that appear "over-spanned" when judged solely against generic empirical charts.

6 Numerical Stability Assessment with Reconciled Geometries

The mine-scale FLAC3D model, updated to incorporate drone-derived void and backfill, shows inelastic zones confined to a ~2 mshell around excavation boundaries of nominal 40 m diameter and no large-scale failure zones inconsistent with observed stope conditions. Strength–stress ratio plots indicate that critical pillars, including the pillar between Konstäng, Upper Konstäng and Kruthus, show elevated utilisation during Upper Konstäng extraction but retain acceptable factors of safety under the proposed sequencing and backfill strategy. The numerical model provides a direct test of the apparent contradiction between empirical chart positions and observed performance: stopes and pillars outside nominal stability envelopes can be stable when site-specific rock mass properties, in-situ stresses, detailed geometries and presence of backfill are accounted for explicitly. The drone surveys are critical in this respect, as they ensure that modelled spans, stope contacts and backfill extents reflect actual, rather than idealised, conditions. Backfill plays a central role in both the numerical interpretation and the reconciled field evidence: existing stopes marginal on a purely empirical basis have remained intact when systematically backfilled, and model simulations show that backfill reduces stress concentrations. Sensitivity analysis confirms that removing backfill significantly increases plasticity and reduces strength–stress ratios in some pillars, whereas reasonable variations in assumed backfill stiffness do not materially alter qualitative stability conclusions.

7 Discussion

The combined empirical, drone and numerical work at Dannemora shows that reliance on stability charts alone would lead to an unduly conservative view of stope stability, because many existing and planned stopes fall outside the nominal "stable" zone despite demonstrably good performance. Empirical tools are therefore best used as a first-pass screen to identify stopes requiring detailed analysis, not as strict design limits. Numerical modelling constrained by reconciled geometries and updated geotechnical inputs provides a more appropriate basis for assessing stope and pillar stability at Dannemora, particularly in the Kruthus–Konstäng–Schaktmalmen area where extraction is closely

coupled to critical infrastructure. The updated FLAC3D model shows that plasticity is confined to limited zones around excavations and strength–stress ratios in key pillars and infrastructure remain acceptable. The drone surveys are central, confirming that existing "over-spanned" stopes have remained stable and provide the actual void and backfill shapes against which model outputs can be judged. Operationally, integrating drone surveys into mine planning provides an efficient means of monitoring stope geometries and backfill performance, and feeding reconciled data back into numerical assessments to support ongoing stability verification and design.

8 Conclusions

An integrated geotechnical assessment has been developed for the Dannemora underground iron ore mine, combining updated rock mass and intact strength datasets, in-situ stress measurements, drone-based 3D stope surveys and mine-scale FLAC3D modelling. Empirical stability charts indicate that many existing and planned stopes plot outside nominal generic stability limits, but reconciled geometries and numerical modelling show that these stopes and pillars are stable under the site-specific conditions present at Dannemora when supported by systematic backfilling and appropriate sequencing. Drone-derived geometries constrain as-mined stope and backfill shapes, and the updated FLAC3D model indicates generally stable stopes, pillars and critical infrastructure under the proposed mine plan. These findings support the planned stoping strategy and highlight the importance of combining empirical screening with drone-based reconciliation and numerical modelling; integrating these tools into the Ground Control Management Plan will enable ongoing stability verification and effective risk management over the life of mine.

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