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A methodology for evaluating caving subsidence backfilling

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Abstract

Cave mining methods – including block, panel, and sublevel caving – produce surface subsidence as ore extraction causes the cave to propagate upwards. When a sufficient volume of ore is extracted, initial elastic deformation turns into surface cracking and eventually a subsidence crater forms. As mining continues, this crater increases in size, both vertically and laterally. Deposition of fill in the crater is an effective method to limit crater expansion and the associated deformation or cracking of the surrounding ground. This paper outlines a comprehensive methodology for the technical and economic assessment of subsidence control by filling, including fill sources, deposition methods and related requirements, possible benefits for control of water ingress, sulphide oxidation and closure, and possible risks such as early dilution and/or inrushes to the extraction level.

Keywords: *cave mining, subsidence, backfilling, column filling, tailings, acid rock drainage*

1 Introduction

Cave mining methods, including block caving, panel caving, and sublevel caving, are among the most productive and cost-effective methods for extracting large, low-grade orebodies at depth. However, a defining characteristic of all cave mining methods is that ore extraction induces deformation that propagates upwards and eventually reaches the ground surface. The resulting subsidence evolves gradually: initial elastic deformation gives way to the development of tension cracks, followed by formation of a subsidence crater that expands both vertically and laterally as mining continues, and eventually stabilises after cessation of mining. Schematic evolution of the subsidence is illustrated in Figure 1.

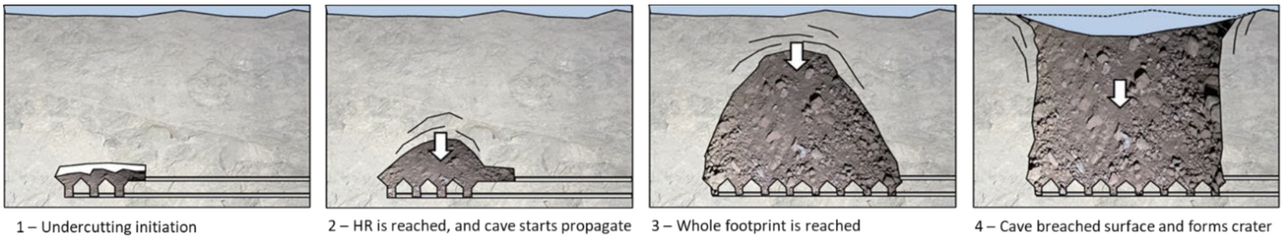

Figure 1 Schematic evolution of the cave subsidence. After hydraulic radius (HR) of the rock mass is reached, with continuous mining the cave propagates upwards and eventually breaches the surface and forms a subsidence crater

The impacts of unmanaged subsidence can be severe. They include permanent restriction of land uses within the subsidence-affected area, negative visual, ecological and social impacts on the surrounding landscape, exposure of reactive or acid-generating materials to oxygen and water, surface water ingress leading to long-term water management costs, and risk of early dilution when surface soils are mobilised into the muckpile by water ingress. Examples of surface subsidence are illustrated in Figure 2.

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(a) (b)

Figure 2 (a) Example of a surface subsidence crater intersecting an open pit at San Manuel; (b) Evolution of surface subsidence at Northparkes E48 (Google image)

Despite the significance of these impacts, there is limited precedent for active management of caving subsidence through backfilling. Only a handful of operations have attempted it (Jakubec et al. 2026). Examples include the Padcal block cave mine in the Philippines, see Figure 3 (Monis 2026), where waste rock from the former open pit has been continuously placed into the active subsidence zone to provide a surface for water management. At San Manuel in Arizona, development waste was deposited into the active subsidence crater near the steep escarpment forming the crater boundary. At Telfer in Australia, development waste was deposited onto the predicted cave breakthrough area to limit initial lateral crater growth. At Kiruna in Sweden, waste rock was deposited into active subsidence, although this practice was subsequently discontinued due to noise and dust impacts on the adjacent town. More recently, New Afton mine in Canada has deposited thickened, cement-amended tailings into an inactive subsidence crater while an adjacent ore block is being mined. In all these cases, backfilling was implemented as a reactive or opportunistic measure, often using whatever waste material was available. For further details on these case studies, refer to the authors' other *Caving 2026* paper, Jakubec et al. (2026).

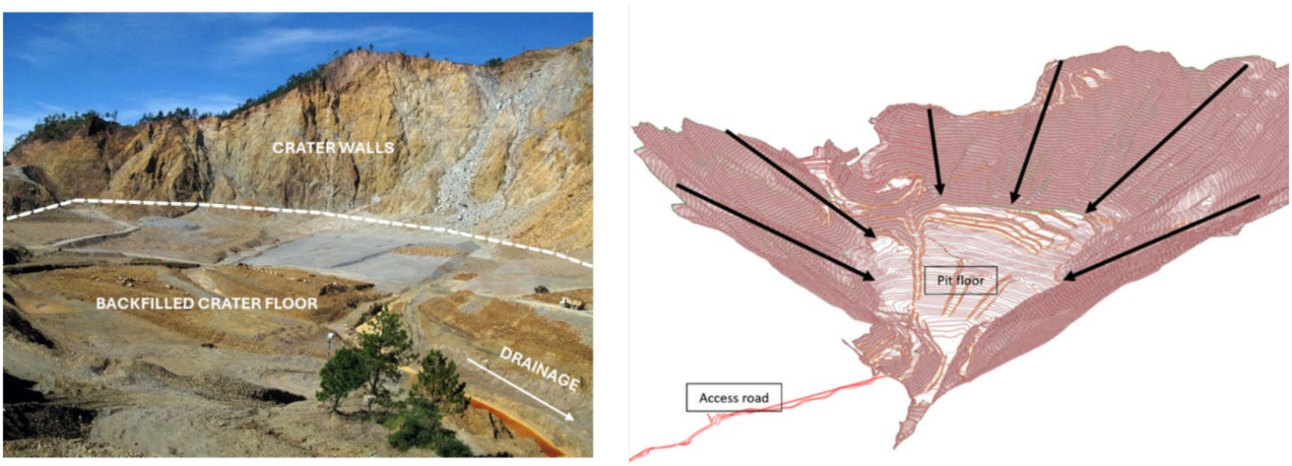

Figure 3 Example of successful backfilling of subsidence crater at Padcal mine (after Monis 2026)

No comprehensive methodology exists in the published literature for evaluating the technical feasibility, costs, risks and benefits of subsidence filling as a planned operational and closure strategy. This paper proposes such a methodology, drawing on SRK's experience in evaluating subsidence management options for cave mining projects.

2 Subsidence filling strategies

Strategies for subsidence filling can be distinguished by when filling begins relative to mining operations.

One strategy, column filling during mining, is illustrated schematically in Figure 4. It requires fill to be deposited before or very soon after the initial breakthrough of the cave to surface and maintained continuously throughout the mine life to keep pace with the rate of subsidence. The objective is to constrain any inward movement or toppling of the native material surrounding the ore and waste column, thereby restricting subsidence to the initial breakthrough footprint. This strategy requires the largest volume of fill – roughly equal to the volume of ore extracted, less the volume of swell of waste remaining in the column. The opposite strategy, crater filling after mining, is illustrated in Figure 5. It involves filling the subsidence crater only as a closure measure after mining ceases. There is no constraint on lateral expansion of the subsidence-impacted zone during operations, meaning the final disturbed area will be at its maximum. This option requires the smallest fill volume, equal to the post-mining crater volume, but does not address water management or sulphide oxidation concerns during the operating period. Between these 2 end members, a number of other strategies are conceivable wherein the subsidence crater is allowed to develop but is then filled progressively as mining continues. The degree to which these strategies limit lateral expansion of the subsidence zone depends on timing and several variables, including rock properties, fill scheduling, and the geometry of the cave.

Two broad categories of fill material can also be considered: material sourced from purpose-built borrow pits, and tailings in filtered, thickened, cemented or otherwise amended form. Each category has different implications for availability, transport logistics, geotechnical properties, environmental characteristics, and cost. The choice of fill material interacts with the filling strategy – for example, the large fill volumes required for column filling may only be achievable with tailings, whereas the smaller volumes for post-mining crater filling might be locally available.

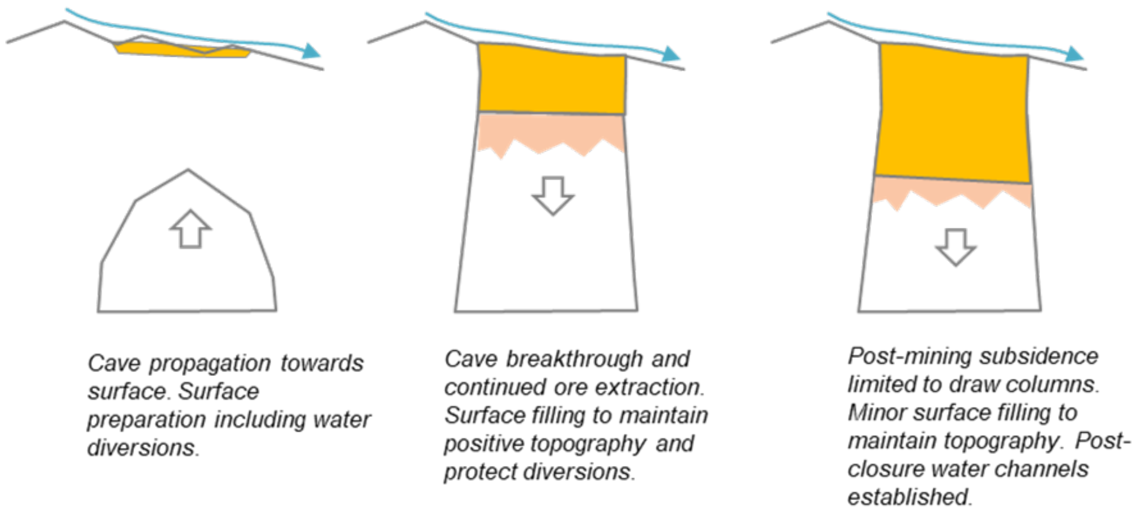

Figure 4 Column filling during mining

For the remainder of this paper, we assume column filling with filtered tailings as the selected option. Column filling offers the greatest potential to limit the extent of subsidence, control water ingress, and reduce long-term acid rock drainage risk. Making beneficial use of tailings that would otherwise need to be managed elsewhere, and avoiding the costs and environmental disturbance associated with a large-volume borrow source, are likely to favour tailings as the preferred fill option in many projects.

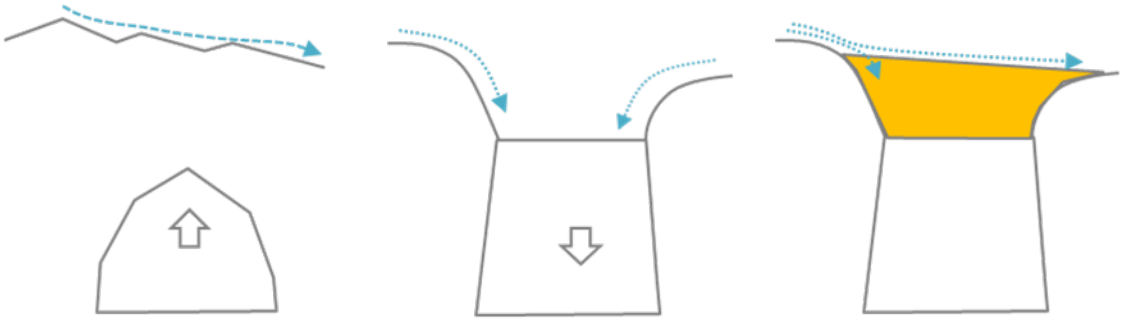

Figure 4 Crater filling after mining

3 Methodology for technical-economic assessment

The following subsections describe the key elements of a technical-economic assessment framework, organised thematically. The overall framework is based on a recent SRK project but is generalised to be usable in other situations. Each element may constitute one or more work packages in a typical study, and the level of detail will depend on the stage of study – from scoping through conceptual, pre-feasibility, and feasibility levels. For simplicity, the elements are listed in a rough sequence, for example, with results from geotechnical characterisation and initial subsidence modelling informing the design of surface preparation, but in reality, significant iteration is required.

3.1 Geotechnical characterisation

The assessment begins with characterisation of the rock mass and surficial materials in the subsidence zone. This includes evaluation of caveability, in situ and primary fragmentation of the upper strata, and properties of any weak or weathered overburden such as saprolite or residual soils. Surface topography and geomorphology must also be assessed to understand slope stability constraints, the thickness and distribution of surficial materials, and the presence of natural features such as watercourses that will influence the design. Geotechnical domaining of the subsidence area provides the basis for surface preparation design, slope stability assessment, and estimation of the behaviour of surrounding materials as they respond to the subsidence and the presence of fill. The key question at this stage is, "what are the properties of the material surrounding the subsidence zone, and how will it respond to filling?"

3.2 Subsidence prediction and fill behaviour modelling

Cave propagation models are required to predict the timing of breakthrough to surface, the shape and extent of the cave, and the rate of lateral expansion. Where existing models have been developed for the project, the assessment should review those models with a focus on the upper strata and parameters most relevant to filling. In addition, modelling of fill behaviour within the cave is needed to assess how the fill will perform as it descends into the subsidence zone. This includes evaluation of density changes and consolidation under increasing overburden, deformation of the fill under lateral confinement, and strains in the surrounding material. Methods that have proven useful include three-dimensional finite element modelling (e.g. PLAXIS), two-dimensional material point method modelling (e.g. Anura3D), and consolidation calculations (e.g. the Bauer method). These analyses feed directly into estimation of total fill tonnage requirements, which must account for uncertainty in cave volume, waste swell factors, and the density that fill will reach at depth.

3.3 Surface access and preparation

Column filling requires safe and efficient access to the subsidence area for heavy equipment throughout the mine life. Although this can be straightforward in flat areas, steeper topography adds significant complications. The surface may need to be reshaped prior to the initial breakthrough – cutting steep ridges and filling steep valleys to create workable grades. Conceptual design requirements include earthworks to achieve a balance of cuts and fills, haul roads to connect the fill source to the subsidence area, and slope stability assessment of both fill and surrounding surfaces. Where the surface preparation exposes reactive materials such as sulphide-bearing soils, the construction sequence must be designed to minimise the time that such materials remain exposed, for example by covering them with fill as soon as practicable. The sequencing of construction is an important design consideration in its own right, because water management infrastructure must typically be in place before any major disturbance of the subsidence area.

3.4 Fill conveyance, processing and placement

For a tailings-based column fill, the assessment must address the full chain from the process plant to the subsidence area. This typically includes design of a thickened tailings conveyance system, a filter plant and stockpile, and an equipment fleet for loading, hauling, spreading and compacting the filtered tailings on the subsidence area. Key operational parameters include daily deposition rates, drying cycles (which depend on local climate), and quality assurance and quality control requirements for moisture content and compaction density. The deposition plan must account for the fact that different areas of the subsidence surface may be subsiding at different rates, requiring adaptive management of where and when tailings are placed.

3.5 Water management

The filling strategy creates both an opportunity and an obligation for water management. The opportunity is that a well-maintained fill surface allows separation of non-contact water (natural stream flows diverted around the subsidence area) from contact water (water that has contacted fill materials or exposed reactive ground). The obligation is that this separation must be actively managed throughout the mine life and into closure. The assessment should develop conceptual designs for non-contact water diversion structures sized for design storm events, contact water collection and treatment systems including sediment control and routing of contaminated water to treatment facilities, and integration of the subsidence area water balance with the broader mine water balance. When geochemically reactive materials are present, the key question is whether the filling strategy enables effective separation of contact and non-contact water – if it does, the long-term water treatment burden can be substantially reduced.

3.6 Monitoring and instrumentation

Monitoring is central to the success of any subsidence filling program because key uncertainties – about cave shape, breakthrough location, and fill performance – can only be resolved through observation. The assessment should develop a conceptual monitoring program that addresses cave propagation (to detect deviations from predicted behaviour), surface deformation (to track subsidence extent and rate), muckpile behaviour (to monitor mixing and early dilution), and water quality (to confirm effectiveness of the water management system). The monitoring program serves 2 purposes: confirmation that the filling is performing as designed, and early warning to enable adaptive management when conditions deviate from predictions.

3.7 Schedule integration

The subsidence filling program must be integrated with the overall mine development schedule. Critical path connections may exist between surface and underground construction – management of surface and underground water might be another cross-cutting linkage. A key scheduling requirement is that the fill conveyance and processing system be operational well before the predicted breakthrough of the cave to surface, providing a buffer against early breakthrough and allowing stockpiling of fill material for immediate deployment once subsidence begins.

3.8 Cost estimation

Capital and operating cost estimates should be developed on a basis that is directly comparable to any prior studies, so that the financial impact of adding subsidence management can be assessed alongside other project economics. Capital costs will typically include the tailings conveyance system, filter plant and ancillary facilities, surface preparation earthworks, water management infrastructure, monitoring systems, and access roads. Operating costs will include power, equipment maintenance, consumables, and labour for the surface fleet and water management systems. Where the filling program uses tailings that would otherwise be deposited in a conventional tailings storage facility, the incremental operating cost (the additional cost above what would have been spent on conventional tailings management) is the relevant metric.

4 Critical issues

In SRK's experience, the following issues require particular emphasis when evaluating subsidence filling options. They are organised from fundamental questions about whether the filling will achieve its intended purpose, through risks that the filling itself could create or amplify.

4.1 Will the fill control subsidence expansion?

The primary purpose of column filling is to support the surrounding soil and rock and thereby prevent lateral expansion of the subsidence zone. Geomechanical modelling can provide evidence that compacted fill will perform this function. Finite element and material point method analyses have been applied to assess how effectively crater growth can be constrained. The material point method is particularly useful because it can model much larger deformations than conventional soil mechanics approaches, confirming that fill retains its support function even as it moves deeper into the subsidence zone. However, residual uncertainties will remain at the conceptual design stage. For example, more detailed analyses of fill configurations and/or slopes around the crater should be completed as geotechnical data improves through later design stages.

4.2 Will the fill control long-term water quality?

In many subsidence environments, the overburden contains sulphide-bearing materials that will oxidise and release contaminants if exposed to air and water. Covering these materials with less reactive fill can eliminate or at least partially mitigate this problem. The potential for fill materials to be a source of contaminants also needs to be assessed. The surface water control enabled by a stable fill surface limits uncontrolled infiltration of water into the mine, and therefore may also limit mobilisation of contaminants generated within the muckpile and underground workings. Residual concerns that warrant attention include the extent to which contaminants left in the mine after closure will be mobilised by reflooding groundwater.

4.3 Slope stability

Surface preparation for column filling involves reshaping of natural terrain, and the resulting slopes must meet applicable factors of safety under both static and seismic loading conditions. As subsidence progresses, the surface shape will change in ways that are difficult to predict precisely. Assessments should consider extreme scenarios – for example, allowing the fill surface to subside until it is level with adjacent natural ground – to confirm that acceptable stability is maintained. A particular concern for filtered tailings fill is the risk of off-spec filtration. If the filter plant does not consistently meet moisture content specifications, inadequately compacted tailings can be susceptible to liquefaction under seismic loading. Contingency measures, such as an alternative disposal location for off-spec material, should be planned and included in cost estimates.

4.4 Uncertainty in subsidence breakthrough location

Stability assessments for the surface preparation are sensitive to the location of the initial subsidence breakthrough, particularly where the subsidence zone intersects steep or complex terrain. Even small horizontal differences in breakthrough location can correspond to large differences in breakthrough elevation on a steep slope, significantly affecting the stability analysis. Monitoring of cave propagation can provide weeks or months of advance warning of deviations from predicted breakthrough locations, allowing the surface preparation design to be modified. The risk is therefore primarily financial – the cost of late changes to the surface preparation – rather than a stability risk per se.

4.5 Uncertainty in cave shape

Two scenarios related to uncertainty in cave shape warrant particular attention. A stable overhang within the cave – where rock above the cave fails to propagate upward as expected – could present a threat to people and equipment working on the surface above. Mitigation through drilling and blasting or hydrofracturing is possible but costly and potentially disruptive to production. A narrow stable cylinder – where the cave propagates upward through a column narrower than the orebody – creates a different risk: the reduced volume of mobilised waste means the waste column falls faster as ore is removed, and waste arrives at the extraction levels more quickly, increasing the risk of dilution. Both scenarios are possible with or without column filling, but stable overhangs are a greater concern when a stable working surface is required above the cave, and stable cylinders may be more likely to develop when the cave walls are laterally supported by fill.

4.6 Fines migration and dilution

Migration of fines through the muckpile can create 2 types of risk: mudrush (uncontrolled ingress of water and fine solids into the working levels) and early dilution of ore at the drawpoints.

Mudrush risk exists with or without column filling, because fines will be generated by fragmentation of overburden materials regardless of fill type. Column filling with tailings increases the supply of fines but also allows much better control of surface water, which is a primary driver of a mudrush hazard. The net effect is expected to be a reduction in mudrush risk. The current state of practice in cave mining operations provides effective methods for monitoring and mitigating mudrush hazards, meaning that any increase in mudrush risk due to column filling will ultimately be a cost risk rather than a safety risk.

Dilution risk is less clear-cut. Empirical modelling of fines migrations show that overburden and/or waste rock between the ore zone and the fill has 2 contrasting effects. First, the overburden or waste separate the fill layer from the top of the ore column and thereby delays arrival of the fill at the extraction level. Second, the overburden or waste rock can itself be a source of dilution. The latter effect drives a need for good draw control practices with or without the column fill. It is more difficult to assess the extent to which a finer-grained fill material could migrate preferentially through the muckpile and create early dilution, even when good draw control practices are followed. Predicting the precise timing of fill arrival at the extraction level requires estimates of differential migration rates that are difficult to constrain in the absence of calibration data from operations using tailings fill. However, the economic significance of early-arriving dilution will be site-specific, and sensitivity analyses may allow the overall financial risk to be sufficiently constrained.

4.7 Non-technical risks

The scale of surface operations required for column filling – including haul roads, filter plants, stockpiles, and daily truck traffic – can amplify non-technical risks relative to conventional cave mining. Water demand, dust generation, noise from blasting and equipment, increased traffic on public roads, visual impact, and disturbance to nearby communities must all be assessed in the context of each project’s social and regulatory environmental requirements. Land access requirements may also be more extensive than for conventional operations. These risks are not unique to subsidence filling but their magnitude may be larger, and they should be assessed early in the evaluation process to identify potential fatal flaws or additional control requirements.

5 Conclusion

The methodology described in this paper provides a framework for assessing subsidence filling options with sufficient rigour to assess technical viability and develop cost estimates, enabling direct assessment of the financial implications of adding subsidence management to a project. Supporting technical analyses – particularly geomechanical modelling of fill performance and assessments of geochemistry, water balance and water quality – can provide reasonable confidence in the ability of the fill to control both subsidence expansion and long-term water management requirements.

Most risks identified through this methodology are manageable within estimated costs or represent quantifiable cost contingencies that are amenable to further assessment in later design stages. The more challenging risks arise from inherent uncertainty about cave behaviour – specifically the location of subsidence breakthrough, the three-dimensional shape of the cave, and the rate of fines migration within the muckpile. These uncertainties are unlikely to be fully resolved until cave and muckpile performance is observable in the field. However, mitigations exist for each: ground preconditioning can influence breakthrough location and cave shape, and rigorous draw control can reduce dilution risk. The costs and likely effectiveness of these mitigations can be evaluated in advance of any commitment to column filling.

For any project where subsidence filling is being considered, the authors recommend progressing from conceptual assessment through focused trade-off studies before committing to pre-feasibility or feasibility level design. The methodology presented here is intended to support that progression in a structured and auditable manner.

Acknowledgement

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