Mine Closure 2024 – AB Fourie, M Tibbett & G Boggs (eds)

doi:10.36487/ACG_repo/2415_35

A conceptual risk management framework for post-closure settlement of fill

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Abstract

Surface mining operations in the Pilbara typically lead to the disturbance of large areas of land over the life cycle of mines. Due to this disturbance, final landforms typically include large voids and waste rock landforms that commonly remain within the disturbance footprint in perpetuity. In Western Australia, the Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) is responsible for regulating mining activities, including rehabilitation and closure. DEMIRS typically require at a minimum that all disturbed areas are rehabilitated and closed in a manner to make them physically safe to humans and animals, geotechnically stable, geochemically non-polluting/non-contaminating, and capable of sustaining an agreed post-mining land use without unacceptable liability to the state. To assist in achieving the desired outcomes (including increasingly stringent closure completion criteria set by stakeholders), waste material that would commonly sit within waste landforms is increasingly being utilised as backfill material to mined-out voids, and in some cases these landforms are constructed within the pit itself (in-pit dumps).

The controlled placement† of waste material is generally not considered feasible at open pit mines in the Pilbara. This is largely due to the scale of the operations (and therefore associated financial implications), variability in waste material properties, as well as the fact that most post-mining land uses in the Pilbara are not considered sensitive to ground settlement. The magnitude of settlement of unconsolidated waste materials in backfill and ex-pit waste landforms, which are often of substantial thicknesses, could however be pronounced. In addition, significant uncertainty surrounds the rate and duration over which settlement takes place; depending on the prevailing settlement component, material characteristics and other environmental factors (e.g. rise in groundwater levels). Such levels of change in the final surface level, if unaccounted for, are likely to have a significant impact on the as-built pit backfill and waste material landforms through the development of surface cracks, changes in the landform slope angle, development of preferential surface water flow paths and ponding.

The long-term settlement characteristics of the waste material captured in these landforms therefore becomes an important consideration in ensuring the closure objectives are achieved and, most importantly, maintained post-closure. Very little information surrounding settlement behaviour of waste material in the Pilbara exists in the public domain and published literature.

This paper is not intended as a detailed discourse on the mechanism of backfill settlement or the geotechnical assessment of the factors which govern it. The intent of this paper is rather to present a risk management framework (RMF) aimed at addressing the potential risk of post-closure settlement by considering the current paucity of technical, Pilbara-specific data on the topic of fill settlement. This RMF is intended to ultimately form part of a more comprehensive geotechnical and overall site rehab and closure risk management plan.

Keywords: *waste material, settlement, closure, risk management framework*

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†Controlled placement refers to fill placed using a performance specification, a method specification or a thick layer specification

1 Introduction

All surface mining methods involve the extraction or stripping of near-surface materials (both waste and ore), inherently leading to the disturbance of large surface areas of land over the life cycle of mining operations. With a greater focus on sustainable development, future uses of land impacted by surface mining activities are increasingly being scrutinised by regulators and other relevant stakeholders.

The extraction of Iron Ore in the Pilbara region of Western Australia (WA) is no different to other surface mining operations with regards to surface disturbance, but the inherent remoteness of the region dictates a different focus on post-mining land uses and associated closure objectives. Increasingly stringent requirements by regulators and stakeholders, together with limited ex-pit capacity for waste material storage means waste material being redirected as backfill material to mined-out voids, or in the form of in-pit waste rock landforms (WRL's). Due to the scale of operations and inherent variability in 'historically placed' waste material, the controlled placement and/or the engineered construction of fill and WRL's are generally not feasible, with material at most subject to localised traffic compaction.

Ground movement associated with settlement of these waste materials could be pronounced and in the order of hundreds, if not thousands, of millimetres. The factors controlling the rate and magnitude of settlement are, however, often highly variable and poorly defined. Significant uncertainty surrounds the timeframe over which settlement takes place and when settlement could therefore reliably be considered as having reached its full extent.

Effective forward planning for rehabilitation and closure can improve the efficiency of rehabilitation and assist in achieving full relinquishment, while minimising residual risk. Emphasis is placed in this paper on presenting a conceptual risk management framework (RMF), aimed at identifying and managing the phenomenon of settlement in thick fills post-closure. The RMF is intended to be site-specific and aimed at ensuring relevant closure objectives are achieved over the agreed closure and relinquishment timeframe. The framework should be integrated into the site's mine planning and operational risk management strategies, closure studies, as well as the mine closure plan (MCP).

This paper is not intended as a detailed discourse on the mechanism of backfill settlement or the geotechnical assessment of the factors that govern it. The effects of settlement on other mine waste landforms, civil infrastructure and/or management facilities (e.g. tailings, heap- and leach pads, hazardous material waste dumps, etc.) are also beyond the scope of this paper.

2 Settlement of fill

2.1 Mechanism

In its simplest form settlement of unconsolidated fill material (e.g. mine waste used in backfilling of pits and stored in WRL's in the Pilbara) Day & Wardle (1996) and Hills (1994) recognised that the total settlement occurring during and after placement of fill material could be subdivided into four components, as indicated in Figure 1. Total settlement (S_{total}) represents the sum of all four components once all potential for collapse settlement has been realised and creep settlement has stabilised (Equation 1).

$$S_{total} = S_i + S_c + S_{cl} + S_{cr} \tag{1}$$

where:

S_i = immediate settlement (commencing immediately after placement at t_0)

S_c = consolidation settlement

S_{cl} = collapse settlement (upon saturation of the fill at t_{sat})

S_{cr} = creep settlement.

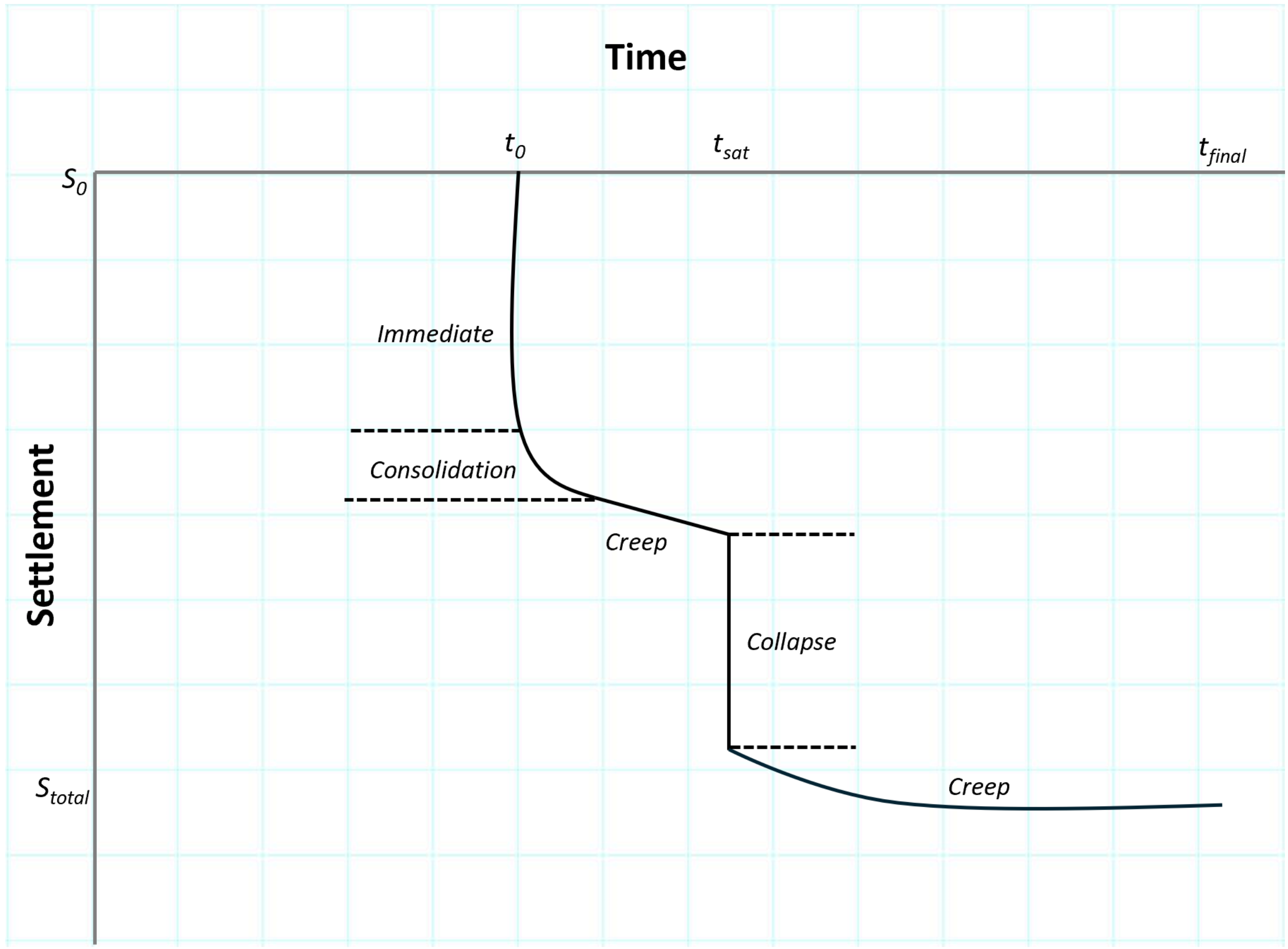

Figure 1 Components of backfill settlement (adapted from Day 2013)

2.1.1 Immediate and consolidation settlement

Immediate settlement can be defined as 'settlement under constant volume due to shear strains in the material as a result of the application of load'. This takes place instantly upon loading of the material (Day 2013) and through the strains experienced due to self-weight as the fill is being placed.

Consolidation settlement, also referred to as primary consolidation, can be seen as the (largely) plastic deformation of the backfill material due to the dissipation of excess pore pressures under self-weight. In the case of partially saturated granular material being used as a source of backfill, the development of excess pore pressure is limited and/or likely to rapidly dissipate (Day 2013). Where cohesive material (i.e. material with a high percentage fines) and high moisture content are used during backfilling, consolidation will be time-dependent and a function of the slow (relative to free-draining granular materials) dissipation of water from the soil pores (Charles & Watts 2001).

2.1.2 Creep settlement

Hills (1994) states that the mechanism for creep settlement, also known as secondary consolidation, is one of gradual rearrangement of the material particles, resulting in a reduction in void ratio and increase in the density of the material. This behaviour occurs over long-term time periods under constant stress and environmental conditions, the rate of which diminishes with time (Charles 2008).

Sowers et al. (1965), based on the analysis of several rockfill dams in the US, established a relationship between the amount creep settlement under self-weight and the time elapsed since fill placement which still remain the most widely used, and accepted, method for predicting creep settlement of backfill in open pit mines (Hills 1994). Long-term settlement monitoring has been carried out at numerous restored open pit mining sites in the past (Charles 2008; Day 2013), to investigate the validity of the creep model, the engineering behaviour of the backfills and, ultimately, the suitability for building development. In all of these, the backfill properties are reported as heterogeneous and, due to the variability in environmental conditions at all study sites, the data gathered cannot be generalised and should only be regarded as indicative.

2.1.3 Collapse settlement

Perhaps the most widely accepted interpretation of collapse settlement in partially saturated soils is based on the work of Rogers (1995), who defines soils as being collapsible where:

> *'…the constituent parts are at a meta-stable state and have an open packing, which can collapse to form a closer packed, more stable structure of significantly reduced volume'.*

The interparticle forces leading to the development of the initial meta-stable state (Figure 2) may comprise any of a combination of inter-particle locking, matric suction forces, cementation, flocculated clay particles and/or silt and clay bridges between particles (Brink 2020).

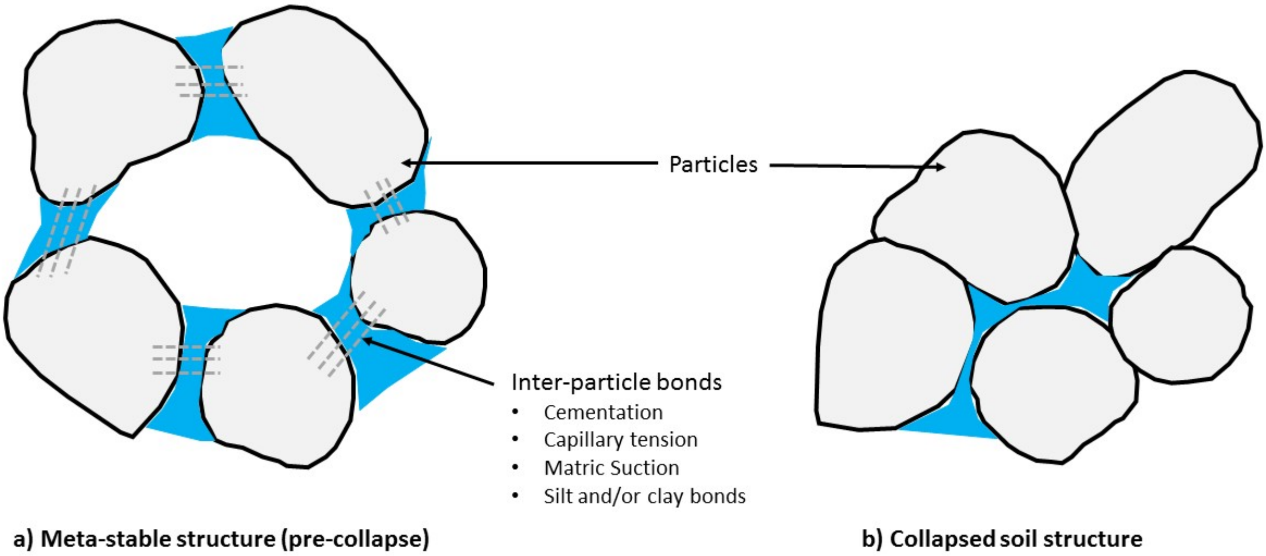

Figure 2 Schematic of collapse settlement mechanism (Brink 2020)

In its simplest form, the potential for collapse phenomenon may be identified though the existence of a collapsible soil fabric, recognisable through the presence of certain conditions in the subsoil structures:

- an open soil structure
- a high void ratio
- a low dry density
- a high porosity
- a geologically young or recently altered deposit
- of high sensitivity
- low interparticle bond strength.

Collapse settlement in open cast backfill can be seen as additional settlement under constant total stress resulting from an increase in the water content of the backfill. Unlike other settlement mechanisms (e.g. consolidation or creep), collapse potential infill does not automatically reduce with time. This is highly dependent on the fill material properties, particularly the density at which the material has been placed and the moisture content at time of placement and when collapse first occurs. Charles & Skinner (2001) state that for fill placed dry of optimum moisture content (OMC), collapse potential is predominantly a function of the ratio of dry density to maximum dry density (i.e. degree of relative compaction), whereas in materials placed wet of OMC the percentage air voids predominate collapse potential. Perhaps the most critical point is the fact that collapse settlement is possible in fill material compacted either wet or dry of OMC.

Field observation and research has shown that inundation of the fill with water is a major trigger of fill collapse settlement in opencast backfills. An increase in moisture content of the fill may occur as either the result of downward water infiltration from surface, through the old mine highwall, utility trenches, stone column ground improvement works, or by a rising groundwater table following cessation of mine void dewatering operations (Day 2013; Hills 1994).

It is the authors' experience that, unless a clear post-closure development plan has been agreed on, backfill material is often indiscriminately sourced and often placed with insufficient controls with regards to sequencing or proper scheduling of placement during the backfill process. Such an approach could lead to significant heterogeneity of the backfilled material due to variation in material properties (e.g. different mineralogical or chemical compositions, particle sizes, grading, etc.), as well as the degree of engineering or modification achieved during placement (e.g. compaction, saturation, etc.).

Such non-uniformity in material properties complicates the recognition of collapse potential for any particular site. It is therefore proposed that, unless it can be conclusively established that the fill does not have significant collapse potential, groundwater levels have returned to natural (pre-mining) levels or considerable collapse has already occurred; a risk of collapse settlement in the fill during or after building on the site should be assumed.

2.1.4 Differential settlement

Rather than a separate component of the settlement process, differential settlement manifests because of lateral variability in the magnitude and/or rate at which any of the settlement components occur. This takes place due to a variety of factors, including variability in material properties (natural and introduced through construction), underlying pit profile and boundaries, groundwater levels and rate of rise of water levels.

Variability in the properties that govern settlement of fill ultimately leads to variability in the severity of settlement observed across backfill sites and WRLs.

The differential, or relative, settlement between different areas is however likely to be of much greater significance to the overall integrity of the backfill or WRL, and therefore whether closure objectives are achieved and maintained.

2.2 Predicting collapse and creep settlement

As the name suggests, immediate settlement takes place immediately on application of a load to the fill material. As such, it is not observed during the construction of fills where any settlement which occurs during the construction period is 'built out' (Day 2013). In predominantly granular, unsaturated fill materials the development of prolonged excess pore pressures required for consolidation settlement is also unlikely to contribute significantly to settlement post-closure.

Equation 1 can therefore be simplified to present post-closure settlement of mine waste materials (Equation 2):

$$S_{total} = S_{cl} + S_{cr} \tag{2}$$

The current most widely accepted methods for predicting creep and collapse settlement of WRL's tend to rely on published relationships established from a handful of international case studies, as briefly summarised below.

2.2.1 Creep settlement

Creep settlement is probably the most challenging component of total settlement to predict accurately. There are two reasons for this difficulty. The first is the selection of the creep compression factor (α). This is the slope of the settlement / log-time graph as proposed by Sowers et al. (1965). The second is the prediction of the time (t_0) marking the commencement of creep settlement for a particular layer of backfill. Sowers et al. (1965) took this time as halfway through the construction period of the fill. This, however, assumes a continuous backfilling process. In opencast mines, particularly where truck-and-shovel mining takes place, the backfill may be placed in several stages (Day 2017).

Sowers et al. (1965) proposed creep settlement as comprising a linear relationship with log time (Equation 3) based on work carried out on fill for a number of rockfill dams.

$$S = \alpha(log_{10}t_2 - log_{10}t_1) \tag{3}$$

S represents the creep settlement expressed as a percentage of the fill height (creep strain) that occurred between times t_1 and t_2 from the beginning of the period of creep settlement, and α is the creep compression rate parameter. Difficulty arises in determining the time at which creep settlement began, with material placed first clearly beginning to settle before the placement of later materials. Sowers et al. (1965) took this time to be the date when half the fill was completed.

Hills (1994) proposed values of α depending on the method of placement of the fill. The value of the creep rate parameter (α) depends predominantly on the material placement method. Hills (1994) proposes typical α values based on documented observations for backfills in opencast coal mines in the UK, and consisting of shale, mudstone and sandstone (Table 1). Fills were placed using a combination of placement methods, with α values increasing as engineering effort decreases.

Table 1 Mean values and standard deviation of α values (after Hills 1994)

Placement method	Alpha *α* (%)	
	Mean	Standard deviation
Controlled (performance)	0.15	0.03
Controlled (method)	0.25	0.05
Controlled (thick layer)	0.50	0.15
Uncontrolled	0.80	0.28

2.2.2 Collapse settlement

There has been no shortage of attempts in the existing literature to correlate and predict collapse as a function of material characteristics or index properties such as density, clay content, moisture content, etc. It is the author's experience, however, that such empirical relationships are usually very site-specific and only tend to be valid for the environment in which these were developed.

Collapse is typically evaluated in terms of total stress (Figure 3), where an unsaturated soil sample is placed in an oedometer at natural moisture content (A), loaded in stages to the desired vertical total stress (B), before the sample is inundated with water and the vertical strain is recorded (B to C). Such a collapse test with the sample inundated at 200 kPa is widely referred to as a collapse potential test, and the vertical strain (B to C) during inundation is taken as the collapse potential. The sample is then loaded to point D and unloaded to point E under saturated or near-saturated conditions.

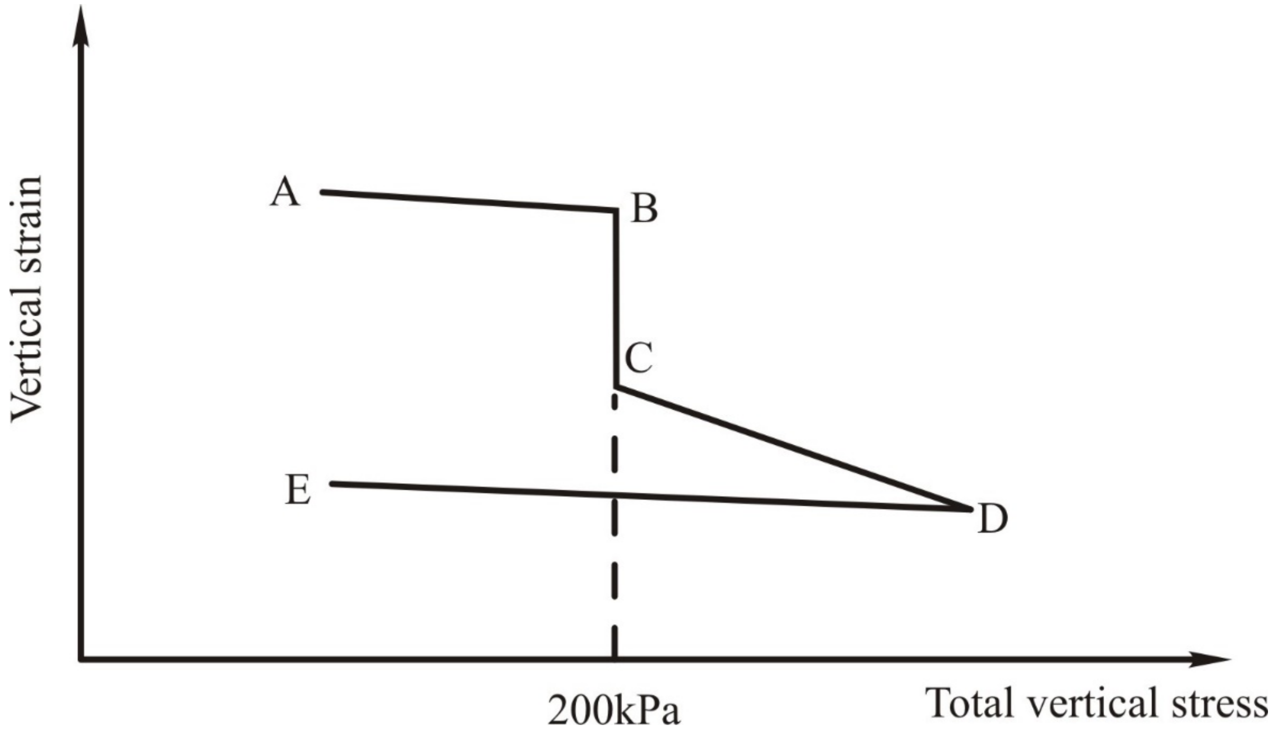

Figure 3 Collapse potential test (Brink & Heymann 2014)

Considering the potential differences in properties between fill and natural soil deposits, caution should be applied in commenting on the potential severity of collapse across the backfilled void through conventional small-scale laboratory tests alone. Such test regimes typically rely on samples collected at discrete point locations from a material of highly variable properties.

Further consideration should be given to the thickness of the collapsible horizon in the case of fill materials (typically equal to the thickness of material likely to be saturated). Table 2 (after Hills 1994) summarises the following typical values for collapse, expressed as a percentage of the thickness of the saturated material.

Table 2 Mean values and standard deviation of collapse settlement (after Hills 1994)

Placement method	Collapse settlement (%)	
	Mean	**Standard deviation**
Controlled (performance)	0.25	0.04
Controlled (method)	0.40	0.08
Controlled (thick layer)	0.90	0.28
Uncontrolled	1.20	0.41

2.3 Potential effects of settlement post-closure

At this point the reader may well be excused asking the question 'so what'? Proposed post-mining land uses in the Pilbara will very rarely include activities considered as being sensitive to ground settlement, as is typically the case in brownfield post-mining developments considered for (say) infrastructure redevelopment.

To consider the risk of settlement to successful closure execution (and ultimately relinquishment) of an open pit mining operation in the Pilbara, the potential implications to all requirements for final closure landforms needs to be considered. The risk of post-closure settlement can therefore be expressed as the risk of significant uncontrolled ground movement on the integrity of the final closure landform. In this instance uncontrolled directly relates to the uncertainty surrounding both the magnitude of fill settlement and the timeframe over which settlement will fully manifest (i.e. S_{total}). Similarly, integrity of the final closure landform (WRL, backfill, etc.) should be considered in terms of whether the landform continues to satisfy the agreed closure objectives post-closure following settlement, and not only in terms of the absolute design integrity.

The following example aims at demonstrating the potential magnitude of settlement of a 'typical' landform comprised out of granular, unsaturated fill and using the creep and collapse settlement relationships described in Section 2.2.

Example:

Material used during backfilling can be assumed as uncontrolled and uncompacted mine waste, 100 m thick and tipped in 20 m lifts using conventional mining equipment. Groundwater levels in Pit A are assumed to return to +50 m above the floor of the pit where it will stabilise within three years of backfill being completed. Variability in the rate of groundwater rise across the pit footprint is not expected. Consistent with the assumption stated in Section 2, neither immediate nor consolidation settlements are considered to contribute to the total settlement post-closure.

For the purposes of this assessment it is assumed that all requirements for closure have been satisfied at the point in time that backfill of Pit A is completed, and that any settlement will therefore occurr post-closure of the mine site.

- Predicted S_{cr} = 1 m, occurring over a timeframe of approximately 10 years.
- Predicted S_{cl} = 0.5 m, occurring over the period of groundwater rise in the backfill.
- S_{total} = 1.5 m, occurring over a time span of 10 years. Periods of accelerated settlement will occur as groundwater levels rise.

In the case of the example the theoretical area of maximum settlement would correlate with the area of the pit where backfill is the thickest, decreasing in those areas where the underlying pit profile leads to a corresponding reduction in overall fill thickness (Figure 4).

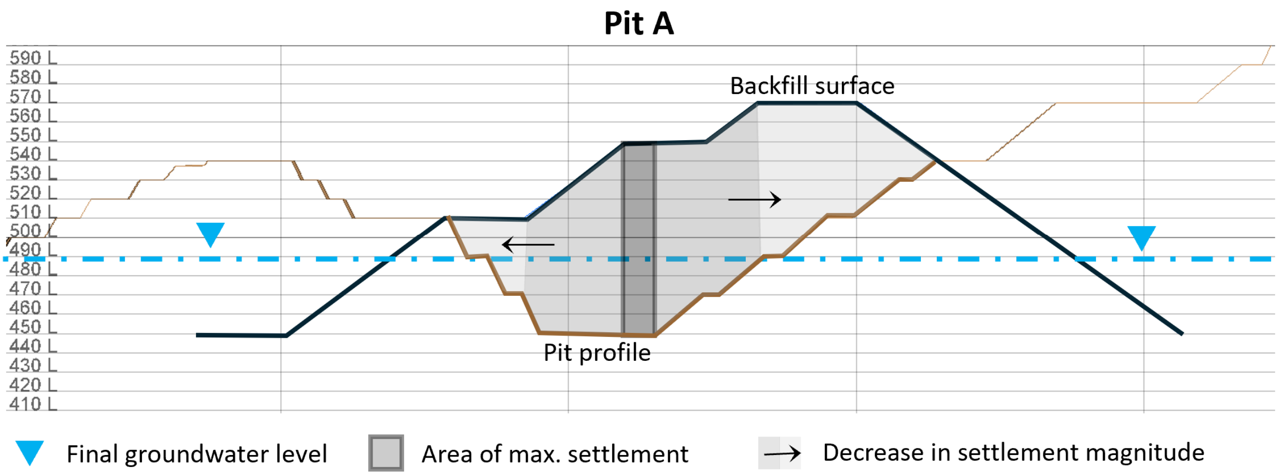

Figure 4 Hypothetical simplified pit fill scenario and settlement distribution

It should be emphasised that although the expected severity of settlement in this simplified example will correspond to the areas of maximum fill thickness (all other factors being assumed equal), variability in material properties, groundwater level rate of rise, traffic compaction, etc. may significantly impact on the distribtion and timing of maximum settlement actually observed onsite.

Differential settlement will lead to variability in final surface level and compromise the integrity of completed rehabilitation and cover material designs. Extensive cracking is likely to occur, leading to preferential flow path development on surface and through the fill. This in turn may lead to erosion/piping, ponding of water in depressions and ultimately potential design stability issues associated with a compromised design. Further effects may include environmental factors (sedimentation, leaching of water through waste dump and potential hazardous materials), as well as failure to meet/continue to meet stakeholder expectations (i.e. closure landforms become an ‘eye sore’ because of settlement).

Settlement may only manifest to its full potential long after closure, with significant uncertainty surrounding the timeframe required for this to happen. Furthermore, unless it can be conclusively established that the fill does not have significant collapse potential, groundwater levels have returned to expected levels or considerable collapse has already occurred, a potential risk of collapse settlement may remain in perpetuity.

Considering that most of the site infrastructure is likely to have been removed during mine closure execution, unforeseen settlement occurring at any subsequent point after may pose a logistical (and financial) challenge in regaining access and to carry out any required remedial works.

Lastly, the reputational stakes are also at an all-time high for mine operators who fail to meet regulator and community expectations in relation to rehabilitation outcomes and post-mining land uses.

3 Settlement risk management framework

The settlement RMF presented here is aimed at addressing the potential risk of post-closure settlement by considering the current paucity of Pilbara-specific data on the topic of fill settlement in the published literature. The RMF is not intended to act as a stand-alone risk management feature, but rather ultimately considered in conjunction with a comprehensive geotechnical and overall site rehab and closure risk management plan.

3.1 Overview of mine closure in WA

The 'social licence to operate' for mining in WA is increasingly linked to what land uses can be made available following cessation of mining activities, and the sufficiency of mine closure and rehabilitation practices is continuing to attract increasing scrutiny. Regulations surrounding mine closure and rehabilitation are also evolving continuously, and stakeholder expectations are becoming increasingly rigorous.

Australian State and Territory Governments are mostly responsible for the regulation and management of mine closure requirements for the mining industry (ANZMEC & MCA 2000). In WA the Department of Energy, Mines, Industry Regulation and Safety (DEMIRS) is the lead regulator and decision-making authority for mining projects under the Mining Act 1978 (Mining Act), including rehabilitation and closure. The DEMIRS objectives are that mines are rehabilitated and closed in a manner to make them physically safe to humans and animals, geo-technically stable, geochemically non-polluting/non-contaminating, and capable of sustaining an agreed post-mining land use without unacceptable liability to the state (DEMIRS 2020).

The intent is for these objectives to be integrated in the closure planning process, developing the closure knowledge base and degree of stakeholder engagement throughout the life cycle of the mining operation.

Legislative requirements governing the activities associated with mining operations in WA typically include:

- *Mining Act 1978* (Government of Western Australia 1978) – details the terms and conditions upon which exploration and mining for minerals can be undertaken within WA.
- *State Agreement(s)* – represents a legal contract between the Western Australian Government and a Proponent.
- *Environmental Protection Act 1986* (Government of Western Australia 1986) – details environmental management requirements for mining projects in WA.
- *Aboriginal Heritage Legislation* – the Aboriginal Heritage Act 1972 (Government of Western Australia 1972) protects all Aboriginal heritage sites in WA.
- *Native Title Act 1993* (Commonwealth of Australia 1993) – recognises the rights and interests of Aboriginal and Torres Strait Islander people in land and waters according to the traditional laws and customs of these groups.

In addition to the above several policies, guidelines, industry standards and procedures also pertain to mine closure planning, which is beyond the scope of this paper to reference.

The MCP for the site incorporates all requirements from the above, as well as any other relevant legal obligations, commitments and stakeholder requirements to effectively plan for closure of the site. These are reflected through the closure outcomes and objectives for the site, as well as the closure completion criteria proposed for each of these outcomes and proposed final land use following closure.

Good mine closure and progressive rehabilitation planning can improve the efficiency of rehabilitation and assist in achieving full relinquishment, while minimising residual risk (i.e. remaining post-closure). This can otherwise be considered as a closure outcome which requires little (if any) ongoing management costs and presents little or no ongoing risk of liability to the former operator.

3.2 Proposed framework to manage risk of fill settlement to closure in the Pilbara

While the end of mining operations and closure may be many years away, early planning for rehabilitation and mine closure throughout a mine's operational life can improve the efficiency of rehabilitation and assist in achieving full relinquishment, while minimising residual risk.

By definition, an RMF is a structured process used to identify potential risks and define strategies for eliminating or managing the impacts to within tolerable limits. Its application to the challenges of integrating disused mining operations in land development areas can be complex and requires a careful balance of technical, commercial and planning aspects.

Neves & Brink (2020) have previously proposed an RMF for settlement of fill in disused quarries in New Zealand, aimed at addressing the potential risk of settlement to brownfield infrastructure redevelopments. Although the overall structure of the RMF presented here is similar, less emphasis is placed on refining potential settlement magnitude and rather focusses on the impacts on mine closure outcomes. The closure settlement RMF represents a risk-based approach to address settlement in mine closure planning. The framework comprises a simple, targeted site-specific set of actions focused on mitigating any residual risk to closure due to fill settlement (Figure 5).

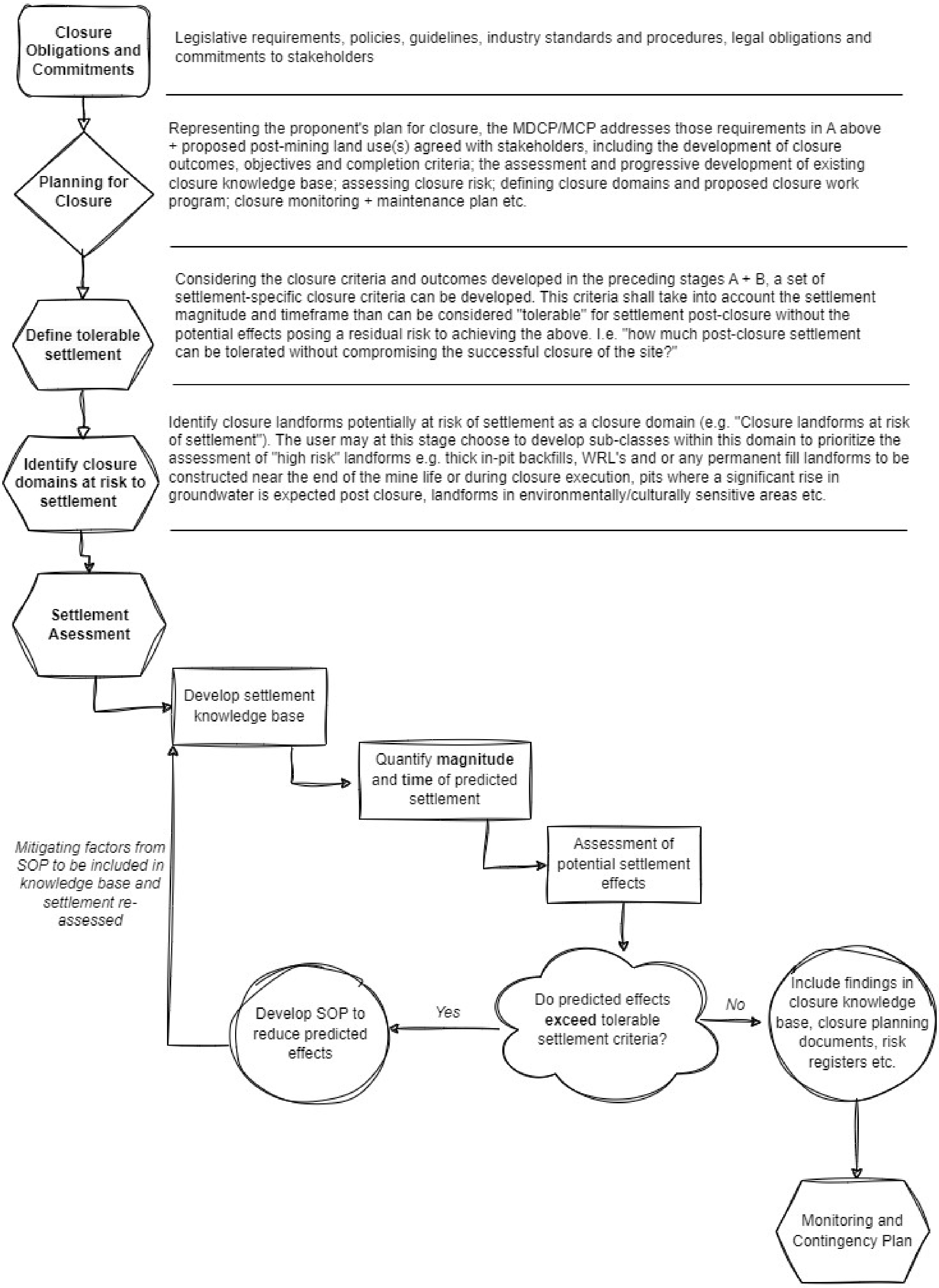

Figure 5 Proposed closure settlement risk management framework for opencast mines in the Pilbara

3.3 Settlement assessment

The main factors that influence creep and/or collapse settlement of opencast backfill are (after Hills 1994):

- fill material properties (grading, particle shape and composition)
- packing of the particles (structure and density)
- configuration of the fill
- potential for saturation of the backfill
- external loads exerted on the backfill.

The assessment of settlement and its potential effects on closure landforms will therefore require either:

1. Adopting settlement relationships established for international study sites as discussed earlier in this paper.
2. The implementation of a targeted testing and monitoring program, focused on assessing potential creep and collapse settlement for a particular site.

Although there are obvious advantages (particularly time and costs) in adopting the former approach, the creep factor α and collapse percentage value used in the assessment will be based on measurements from UK study sites as no data is available for Pilbara materials. Both assumptions have a considerable impact on the predicted magnitude and duration of settlement.

A proper understanding of the settlement behaviour of waste materials and effects on associated closure landforms in the Pilbara can only really therefore be further progressed through site-specific investigation and monitoring programs, targeted towards assessing each of the settlement components discussed in Section 2. The typical inputs to such an assessment are briefly discussed below (after Charles & Watts 2001) but will ultimately largely depend on:

a. the number of final landforms identified as being potentially sensitive to settlement
b. the level of detail and quality of existing site-specific data
c. complexity of the closure site
d. how stringent the agreed requirements for closure are.

3.3.1 Review of historical data

With natural soils the geological processes which created them have to be inferred from observations of the soils themselves, with man-made fills there may be direct evidence of the manner in which they were formed and the date of their origin. All available historical evidence should be collected in a preliminary desk study to determine the history of fill placement. InSAR satellite monitoring techniques may potentially be useful when considered in combination with the available information to develop a preliminary understanding of the settlement behaviour and effects of various materials or under different conditions, particularly when considering the availability of historical monitoring data.

3.3.2 Ground investigations

The historical review stage usually forms the basis for the design of the ground investigation including the location and number of boreholes, trial pits and any in situ tests. The aim of the ground investigation would be largely to assess and/or validate ground and hydrogeological conditions (both vertically and laterally), while simultaneously providing opportunities for sampling and installation of monitoring equipment.

3.3.3 Laboratory testing

Samples of fill obtained during the ground investigation can be subjected to laboratory testing. However, testing may only be possible on finer-grained fraction of the material, as large particle sizes may preclude conventional test methods. Furthermore, variability infill properties may require increased sampling frequency to ensure that the samples are representative. Disturbed samples obtained from trial pits or boreholes can be used to determine index and classification properties including density, moisture content, liquid and plastic limits, particle size distribution, and particle density.

Undisturbed samples may be tested to determine compressibility and strength parameters of the fill. In many fills it may be difficult to obtain an adequate quality of sample, and the fill may be so variable that such samples are not representative.

3.3.4 Field testing

Where impractical to obtain small undisturbed samples for laboratory testing, field tests may be of assistance in determining the strength and compressibility of the fill. This may include any number of in situ testing techniques, including:

- standard penetration test
- cone penetration test
- dynamic probing
- flat dilatometer
- pressuremeter.

Many of the in situ techniques above are hampered by the presence of larger clasts in the material through which the equipment is driven.

Large-scale load tests in the field offer, arguably, the best insight into the potential behaviour of the material under the site conditions. Examples of such tests that have been previously carried out with success include large-scale trial embankments to assess creep and flooding experiments to assess collapse potential, as outlined in a number of case studies by Day & Wardle (1996) and Day (2017). The advantage in the planning and execution of such tests during the operational life cycle means that operational resources could be used in developing the test site.

3.4 Settlement effects and monitoring and contingency plan

Depending on the outcome of the assessment, the magnitude (S_{total}) and/or duration of settlement may be considered as either being acceptable (i.e. potential effects are within the set criteria) or not. In the event of the former the results are to be captured in all relevant knowledge and risk databases and closure planning documents. It is recommended the assessment results are reviewed as part of the agreed closure planning documents review cycle and/or following any changes that may impact on the outcome of the assessment.

Where the potential effects due to the predicted settlement magnitude and/or duration is considered as beyond the set criteria, mitigation measures will be required to reduce ground movements. The benefit of identifying this early in the mine life is obvious, allowing sufficient time to redirect operational activities, waste material types, adapt groundwater management practices, etc. as part of a standard operation procedure (SOP).

Any changes made to reduce settlement (i.e. as part of a SOP) will trigger the re-assessment of settlement and its effects to confirm the adequacy of the proposed measures.

The final stage of the RMF is focused on a) verifying predictions and b) defining appropriate contingency measures in case predictions are exceeded.

Settlement monitoring forms a critical component in evaluating and managing any residual risk to closure. Ultimately, it aims to provide a) timely notification of where and when predicted ground movements are likely to be exceeded and b) insight to the potential reasons for the observed exceedances.

A detailed, site-specific monitoring regime ideally should include a variety of ground deformation monitoring methods and technologies, which are currently available to the geotechnical engineer. Regardless of the specific measurement methods selected, the monitoring regime should ultimately be developed on a best-for-site basis. It is important for any settlement monitoring program to not only focus on quantifying ground settlement, but also capture environmental factors that may have a direct influence on observed ground movements (e.g. groundwater levels and climate variations), as well as confirming that mitigation measures work as intended (e.g. any subsoil drainage systems are free flowing).

Contingency measures form the final line of defence in the RMF, providing the developer with options to protect their assets from settlement-induced damage. The successful implementation of such measures relies heavily on the site monitoring program to ensure any actions are fit-for-purpose and implemented in a timely manner. As is the case with the settlement monitoring program, contingency measures need to be developed on a site-specific basis and agreed with all stakeholders prior to inclusion in the RMF.

4 Conclusion

Settlement of waste material used in the construction of closure landforms may potentially be in the order of thousands of millimetres and continue to occur many years following closure of the site. The potential effects of unforeseen and uncontrolled post-closure settlement could severely impact closure landforms and whether these continue to satisfy the requirements for successful closure of the site.

The paper attempts to emphasise the extreme dearth of published information surrounding the potential settlement behaviour of waste material typically used in closure landforms in the Pilbara. Consequently, any assessment of potential settlement will have to either rely on relationships from international study sites (and accept the associated uncertainty in the assessment outcome), or initiate a targeted investigation and monitoring program focused on developing an understanding of the potential settlement implications for the site in question. In the event of the latter approach, significant benefit can be obtained by incorporating full-scale load tests as part of the site investigation process.

The closure settlement RMF represents a risk-based approach to address settlement in mine closure planning. The framework comprises a simple, targeted site-specific set of actions focused on mitigating any residual risk to closure due to fill settlement.

Lastly, the only way through which the assessment of settlement of Pilbara WRL's will be able to move away from detailed site-focused assessments (involving investigations, laboratory testing, field trials, etc.) is through sharing information. Publishing the results and outcomes from assessments will ultimately allow relationships to be established for waste materials in the Pilbara, in turn allowing for the simplified (but reliable) estimation of creep and collapse settlement components.

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