A settlement hazard risk management framework for the development of backfilled open-cut quarries

M. Neves[1], PhD CEng MICE and G. Brink[2], PhD MEngNZ

[1]Tonkin & Taylor Pty, Engineering Group, Kings Technology Park, Level 3, 99 Coventry Street, Southbank, Vic 3006, Australia; PH +61 3 9863 8686; email: mneves@tonkintaylor.com.au
[2]Tonkin & Taylor Ltd, Geotechnical Group, Tonkin + Taylor House, 105 Carlton Gore Road, Newmarket, Auckland 1023, New Zealand; PH +64 9 355 6000; email: gbrink@tonkintaylor.co.nz

ABSTRACT

Surface mining operations typically lead to the disturbance of large areas of land over the life cycle of mines. With growing pressures on land use, particularly in urban areas, brownfield sites such as closed open-cut mines are being considered more and more for redevelopment opportunities. Naturally, these areas require reinstatement to some workable final surface level which is then suitable for the future development. Nevertheless, the business case that supports the decision to develop these complex areas should aim at balancing and optimising the investment required in the rehabilitation of the original site itself, as well as the cost of subsequent infra- and superstructure development. Controlled backfilling of these disused operations is often complex, including considerations of variability and engineering characteristics of the available backfill materials and the influence of groundwater recovery. Variations in the properties of the backfill material may not have any significant impact on some after-use activities (e.g. when the area is intended for conservation or agricultural land use after rehabilitation), but subsequent surface infrastructure development could be severely affected by settlement of backfilled land. The strategic planning and closure process for open-cut mines typically involves a number of different stages and a detailed consideration of the potential behaviour of the backfill is crucial in ensuring successful development. The purpose of this paper is to present a Risk Management Framework (RMF) focused on addressing excessive post-construction settlement. This RMF needs to form part of a more comprehensive geotechnical, and ultimately overall risk management and mine closure plan.

Keywords: settlement hazard, open-cut quarry, risk management framework

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, land currently and/or in the past subject to surface mining activities is increasingly being considered for future redevelopment opportunities post mine closure.

To enable such future development, any mined-out void needs to be reinstated to some workable final surface level through backfilling. The long-term settlement characteristics of such fills, which are typically of substantial thickness, becomes an important consideration for the future proposed development, especially as surface infrastructure can be severely affected by settlement of backfilled land. Therefore, controlled backfilling of mined-out voids is often a complex process and may result in settlement that continues for years after fill placement.

The purpose of this paper is to present a Risk Management Framework (RMF) to address excessive post-construction ground settlement in backfilled open-cut quarries, which should ultimately be incorporated in the mine closure plan. The benefits of developing and implementing such a RMF are the identification and management of any excessive post-construction settlement, as early as possible, within the area to develop. However, external factors such as dynamic economic market conditions, change in operational or land ownership and government incentives to redevelop brownfield sites can all affect the initially identified post-closure land use. The approach within the RMF will differ depending on the timing of implementation, but the ultimate aim will always be to successfully reintegrate the mining area into the developed community after mining operations cease.

2 BACKFILLING

2.1 Closure Process

The closure process for open-cast mines involves a series of different stages, outlined in the Strategic Planning for Mine Closure (ANZAC/MCA, 2000):

1. Stakeholder involvement;
2. Planning;
3. Financial provision;
4. Implementation;
5. Standards; and
6. Relinquishment.

The closure plan may even identify different potential future land-uses (e.g. groundwater collection and treatment system, agricultural use, conservation areas etc.). However, it is the authors' experience that, unless a clear post-closure development plan has been agreed on, backfill material is often indiscriminately sourced and placed with insufficient engineering controls. This may 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.).

2.2 Components of Backfill Settlement

Day and Wardle (1996) and Hills (1994) recognised that the total settlement occurring during and after placement of backfill material could be subdivided into four components, as indicated in Figure 1 below:

1. Immediate settlement;
2. Consolidation settlement;
3. Creep settlement; and
4. Collapse settlement.

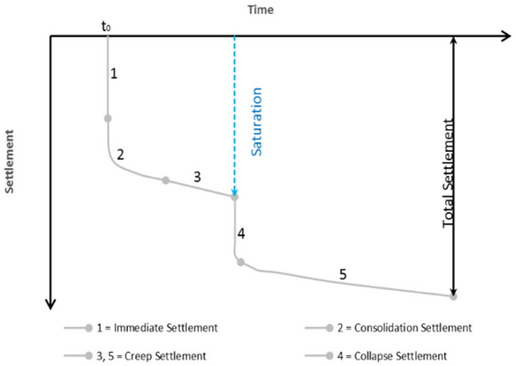

Figure 1. Components of backfill settlement (adapted from Day, 2013)

2.2.1 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 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 (Day, 2013). Where cohesive material (i.e. material with a high fines content) 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 and Watts, 2001).

Immediate and consolidation settlements are generally not expected to have a significant impact on future developments above backfilled mining voids, as the backfilling operations typically takes many months to years to complete. Therefore, immediate and the majority of consolidation settlements are effectively “built out” (Day, 2013) during earthfilling operations and prior to redevelopment.

2.2.2 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 of creep settlement under self-weight and the time elapsed since fill placement which still remains the most widely used, and accepted, method for predicting creep settlement of open-cast backfill (Hills, 1994). Long-term settlement monitoring has been carried out at numerous restored open-cast 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.

2.2.3 Collapse Settlement

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 in fill does not automatically reduce with time. This is highly dependent on the fill material properties, particularly the density and moisture content at time of placement. Charles and Watts (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 predominates 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 and leaky drains / soakaways, or by a rising groundwater table following cessation of mine void dewatering operations (Day 2013; Hills 1994). This often represents a serious hazard for buildings on fill.

The magnitude of the settlement potential is typically expressed as a percentage of the thickness of fill material subjected to saturation. However, heterogeneity in the backfill material properties makes collapse settlement predictions difficult. Additionally, and unlike other settlement mechanisms, collapse potential does not automatically reduce with time. 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 potential risk of collapse settlement in the fill during or subsequent to building on the site should be assumed.

2.2.4 Differential Settlement

Rather than a separate component of the backfill settlement process, differential settlement manifests as a result of lateral variability in the magnitude and/or rate at which any of the aforementioned settlement components occur. This can take place due to a variety of factors, including variability in backfilling process (including differential stockpile surcharging), backfill material properties, underlying pit profile, pit boundaries and rate at which groundwater levels re-establish across the site. The resulting changes in surface settlement profile may lead to excessive angular distortion of surface structures.

3 SETTLEMENT RISK MANAGEMENT FRAMEWORK

By definition, a 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.

The proposed RMF discussed here focuses exclusively on the risk of excessive post-construction settlement for future infrastructure development on backfilled open-cast mining operations (Figure 2).

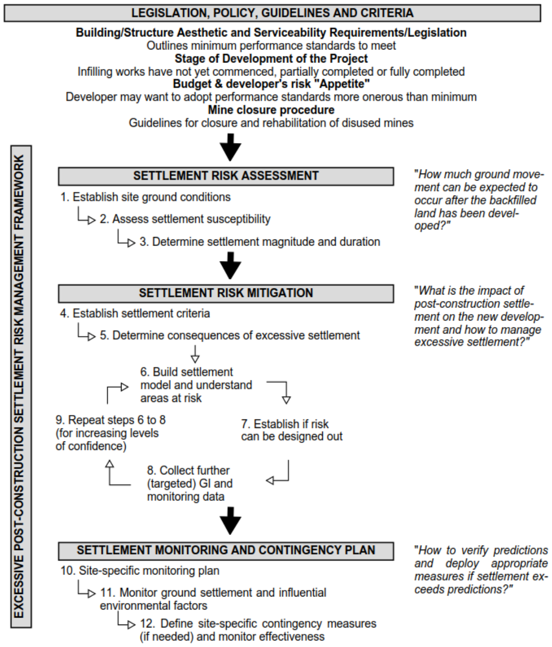

Figure 2. RMF stages of implementation

Note that, and as described earlier in Section 2.2.1, post-construction settlement is mostly influenced by the risk of creep and collapse settlement. As such, the RMF can be broadly divided into three separate stages of implementation:

1) Settlement risk assessment;
2) Settlement risk mitigation; and
3) Settlement monitoring and contingency plan.

Once future land-uses have been confirmed, a timeline to implement the separate stages of the RMF must be developed. Each project will have its own unique timeline, depending on the point in the operational life-cycle where planning for post-closure land development takes place, as well as planning legislation / administrative procedures.

3.1 Settlement Risk Assessment

The objective of the settlement risk assessment stage in the RMF is to answer the following question:

How much ground movement can be expected to occur after the backfilled land has been developed?

This requires an evaluation of the potential for excessive post-construction settlement to take place, its magnitude and duration. A thorough assessment of this risk requires an understanding of the potential severity and likelihood of each of the contributing settlement components (refer Section 2.2).

To arrive at a meaningful answer, several phases of geotechnical desk study and field investigations may be required, as the prediction tools are revisited with newer information.

3.1.1 Sampling and testing

When scheduling ground investigation works (GI) and associated laboratory testing, distinct approaches should be used, depending on the stage of development of the site:

1) Infilling works have not yet commenced;
2) Infilling works have been partially completed; or
3) Infilling of open pit has been completed.

The three scenarios listed above offer different degrees of certainty with regards to the characterisation of the backfill and assessment of its engineering characteristics, which require distinct sampling and testing regimes to inform the design.

In scenarios 2) and 3), ahead of scheduling GI, it is important to gather all available project data to date, which may include truck dockets, site notes, earthworks testing results and occasionally historical GI records, if applicable. However, this information is usually sparse and will likely need to be complemented with new data, which should specifically target settlement predictions. Depending on timeframes, a phased approach may be adopted, in order to balance the geotechnical model's accuracy with cost and time implications.

When scoping GI, an understanding of the key components of the proposed development is crucial, i.e. which assets are due to be completed first and/or are more susceptible to excessive settlement, to enable a targeted GI and not a widespread approach.

Furthermore, GI sampling techniques should be selected based on the likely testing regime. The latter should be preliminarily defined ahead of procuring GI to ensure the scheduled testing is not compromised by the available quality/type of samples.

3.1.2 Settlement susceptibility

A preliminary settlement susceptibility assessment can occasionally be made based on a desktop study. However, the available historical data and/or literature may not be (fully) applicable to the backfill materials in analysis and may require validation. Nonetheless, this high-level review can be useful when scoping GI, following which a first site-specific settlement susceptibility assessment can be completed.

This exercise should highlight the different types of settlement that the fill materials are susceptible to, their likelihood of occurrence and, just as importantly, a spatial indication of where these are likely to manifest. However, limited local data/published case histories may be available for some of the identified components of settlement (e.g. collapse settlement). In these instances, reliance on a statistical analysis of the GI results often provides a more accurate insight on the probability of occurrence, as opposed to literature-based correlations.

As a result, it is recommended that GI sampling and associated laboratory testing schedule strive to achieve a representative understanding of the fill properties at depth and across the site.

3.1.3 Settlement magnitude and duration

For the backfill materials identified as susceptible to settlement, the subsequent step is to predict its magnitude (usually providing a range of credible upper and lower bound estimations) and to forecast its occurrence over time. Note that some settlement components may not be time-dependent, but rather related to external factors. If any settlement components are estimated via empirical relationships from published literature (in the absence of GI results), careful consideration should be given to the uncertainty of extrapolating case history data to local fill characteristics.

Having estimated the magnitude and occurrence of the predicted settlement, a three-dimensional model of the site can then be established to help assess the projected total and differential settlement at the surface. The 3D model will typically comprise of a series of discrete soil blocks, each with a given set of settlement characteristics. Naturally, the sum of the accumulated settlements within each soil column provides an estimate of the total settlement at surface, at that given location. This discretisation is especially important, because for the majority of developments the key settlement hazard is not the total amount of surface settlement, but rather the post-construction differential settlement experienced across site.

Therefore, for a successful development, it is crucial to develop a model that can not only compute the magnitude of settlement across the site, but also model its time dependency, so as to estimate a spatial distribution of the post-construction surface settlement at any given point in time. Naturally, the grid discretisation will be a function of the level of detail needed, as well as the amount of data gathered.

3.1.4 Large-scale field tests

Given the nature of GI, the information gathered from a finite number of data locations will be extrapolated to the wider fill materials. As such, and even if an expanded program of laboratory tests is completed (leading to a more complete and statistically significant set of results), there will always be a limit to the level of confidence of extrapolating data from relatively small selected samples to the entire fill. The latter will always present some inherent lateral and vertical variability in properties, when compared to naturally deposited soils.

A more representative behaviour of the infill materials can be obtained by undertaking large scale field trials, which can substantiate or disprove the predictions of actual post-construction settlement performance. This increased level of confidence in the settlement predictions does however require relatively larger levels of investment, as illustrated in Section 3.2.2.

3.2 Settlement Risk Mitigation

Once the risk of settlement has been assessed, measures can be developed and implemented to manage the risk of ground movement to the future infrastructure development. The settlement criteria, and subsequent preferred mitigation measures, tends to be a function of the proposed type of construction and its settlement tolerance. The latter is usually defined by the structure’s allowable differential settlement and acceptable damage levels. Often, a maximum differential settlement of 1:500 across a building footprint is used, which is governed by aesthetic and serviceability requirements (Skempton and MacDonald, 1956). Other factors, including the time at which the RMF is developed, budget, risk appetite of developers and legislation, may all influence the preferred mitigation measures.

The impact of settlement on the new development can be graded using the following categories:

- **Inconsequential**, which will not impact on the performance of the (infra)structure/services and therefore does not impact on the structure design;
- **Significant**, which may either require some form of settlement mitigation measures to be implemented or a more detailed study of the proposed foundations behaviour ahead of structure design; or
- **Very significant**, where fill settlement mitigation measures will need to be specified and monitored ahead of structure design.

Understanding the severity of the hazard is therefore fundamental to help the development stakeholders assess the viability of a project as early as possible, as well as to enable expert geotechnical advice to inform on the civil and structural design of the works. This is especially relevant as the geotechnical component of the design (or as a minimum some preliminary advice) precedes other disciplines.

The time available for assessing the geotechnical properties of the site and/or developing mitigation measures needs to take that into consideration. Furthermore, any strategies put into place will likely require hold/monitoring periods to assess their effectiveness and corroborate the design predictions.

On the other hand, having a fixed date of completion results in a limited period of time over which mitigation measures can be monitored. As the latter may be further constrained by planning and financial restrictions, a staged approach to assessing the risk (i.e. likelihood and consequences) of settlement linked with incremental levels of investment may be advantageous.

This RMF proposes to address the delicate balance between confidence in the settlement prediction model and the level of investment by relying on the following decision inputs:

1) Construction programme with indicative durations of the fill settlement mitigation measures and associated monitoring;
2) Confidence in the settlement prediction model versus cumulative level of investment curves; and
3) Lower and upper bound forecast of the post-construction settlements, for a given level of confidence.

3.2.1 Construction programme and developer's business case

The development of the construction programme is essential as it informs the developer and designers on the time available to undertake geotechnical works. Given the importance of this discipline in these projects, an early geotechnical input in the decision process in crucial. Depending on the size and planning of the scheme, different approaches can be employed for distinct areas of the site.

Areas which may need to be developed first, often related to the financial viability of the entire development, may not allow for a phased and progressive approach to the development of the geotechnical model. In such case, the risk of excessive post-construction settlement can be designed out by employing flexible foundation systems and structure types which are not as susceptible to differential settlement. A similar methodology can be employed for high importance level structures within the development.

When a phased approach fits within the timescale of the development, it often yields a better return on investment for the developer, as it progressively enables new information to be collected to update and enhance settlement predictions. This procedure allows for the improved accuracy of the settlement predictions to be weighed against the cumulative level of investment, which helps the developer gauge the financial impact of each stage of the works.

3.2.2 Confidence in settlement prediction model outcome versus level of investment

When a phased approach is employed, both the additional financial investment and the level of confidence in the settlement predictions can be revised at each stage of the assessment. Indicative model outcome certainty and cumulative investment curves are shown in Figure 3 to illustrate this staged progression. Naturally, each project will have its own set of curves and, depending on its business case and construction programme, the number of relevant steps/iterations may also vary.

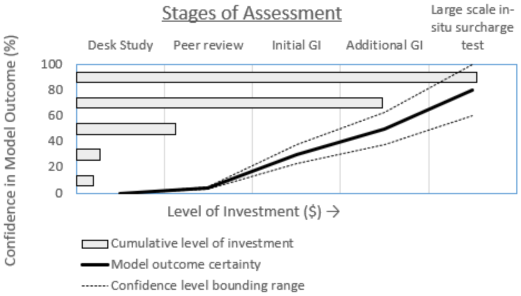

Figure 3. Example of confidence in model vs level of investment curves

Figure 3 depicts the effects of these incremental refinements (from the initial stage to proof of concept) in the overall level of confidence in the predictions.

Attention is also drawn to the peer review, at an early stage of the assessment, in order to corroborate the designer's views and provide confidence to the developer, whilst optimising the subsequent stages of design/assessment.

3.2.3 Settlement model outputs

To help inform decision makers on the likely risk of excessive post-construction settlement, a 2D visual output is proposed as the third decision input of the RMF (Figure 4).

Figure 4. Example of settlement risk areas for upper and lower bound estimates

Using this visual approach allows all relevant parties to understand the location of the development's risk areas, independently of their technical background. In turn, this information can help inform the most favourable building sequence, e.g. which components of the project should be prioritised or delayed, in order to allow for time dependent settlement to take place. Furthermore, this tool can also help delimitate the areas where remedial measures are needed and assist in targeting subsequent GI stages

For the best outcome, the settlement predictions must be revised as more information is gathered, narrowing down the range of settlement estimates and offering a higher degree of confidence in the modelling.

3.3 Settlement Monitoring and Contingency Plan

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

3.3.1 Monitoring

Settlement monitoring forms a critical component in evaluating and managing the residual risk to the future development and, due to the inherent uncertainty involved, predicting ground surface settlement "hot spots" in thick highly variable fill materials. Ultimately, it aims to provide the developer with 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-project basis which requires (amongst others) consideration of the proposed development and tolerance of structures to ground movement, site environment, access, budget, public perception and performance reliability.

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. subsoil drainage systems are free-flowing).

3.3.2 Contingency

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

The process to successfully rehabilitate disused open-cast mining operations as a feasible land option for future infrastructure development is a complex undertaking, and requires the input from a number of different specialist stakeholders to manage all associated risks. The RMF presented in this paper addresses a geotechnical risk often associated with such projects; the occurrence of excessive settlement of the backfill material post-construction. It is envisaged that this RMF will form part of a more comprehensive geotechnical, and ultimately overall risk management and mine closure plan.

The RMF provides a structured process to investigate and quantify potential risks due to backfill settlement, as well as identify potential strategies for eliminating or managing the impacts to within the limits tolerable to a particular project or developer. Each project will have its own unique timeline, depending on the point in the operational life-cycle where planning for post-closure land development takes place, as well as planning legislation / administrative procedures.

The approach of the RMF will differ depending on the type of post-closure development, where in the project life-cycle the RMF is implemented, the developer's risk appetite, as well as the market and environmental conditions. Nonetheless, the ultimate aim will always be to successfully reintegrate the mining area into the developed area after mining operations cease.

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