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Applications of impact rolling in mine closure

Robin Power [a,*], **Derek Avalle** [b], **Simon Dix** [c]

[a] *Insitutek, Australia*

[b] *Conplant, Australia*

[c] *Landpac, Australia*

Abstract

Mine closure presents complex geotechnical challenges associated with rehabilitating large, disturbed landforms, including waste rock dumps, tailings storage facilities (TSFs) and backfilled pits. These landforms often comprise heterogeneous, loosely placed or variably compacted materials with uncertain density, stiffness and long-term settlement behaviour. Closure objectives extend beyond stability to include prevention of spontaneous combustion and protection of groundwater from acid and metalliferous drainage. Achieving stable, low-permeability, trafficable surfaces is therefore essential to meet regulatory criteria, ensure public safety and enable sustainable post-mining land use. Impact rolling has emerged as an efficient, cost-effective and quantifiable ground improvement technique well suited to these conditions.

Impact rolling or rolling dynamic compaction applies high energy impact compaction (HEIC) using a tractor-drawn, non-circular drum that delivers concentrated impact loads to the ground surface. Unlike conventional cylindrical drum rollers, it induces deep-seated densification, increasing stiffness, reducing void ratio and lowering permeability across a broad range of mining wastes and overburden materials. This highly productive method enables large areas of uncontrolled or end-dumped fill to be treated rapidly and economically, reducing differential settlement risk and improving overall landform performance.

In landform reconstruction, impact rolling is used at pit bases to reduce permeability and limit contaminant migration. During backfilling, thicker lifts can be placed and compacted with confidence, maximising densification and increasing the effective volume of material placed within the void. At final levels, the technique assists in compacting capping layers designed to shed water and control infiltration. For existing landforms, applications include densification of waste rock dumps prior to or during capping, improvement of tailings beaches to support cover systems, and stabilisation of coal discard and overburden fills.

Integrated intelligent compaction measurement provides traceability of roller passes, ground response and settlement. When combined with verification tools such as plate load testing, geophysics (MASW, SASW, CSW etc.), cone penetration testing or variable energy dynamic probing and dynamic probing super heavy, impact rolling supports a performance-based closure strategy, delivering durable rehabilitation and reduced long-term risk.

Keywords: *impact rolling, settlement, permeability, compaction, mine closure, mine reclamation, mine tailings, coal ash ponds*

1 Introduction

Impact rolling – often referred to as high energy impact compaction (HEIC) and rolling dynamic compaction (RDC) – is a crucial, cost-effective technology used in mine rehabilitation to stabilise sites for closure. It is used to ensure stable post-mining land use by compacting waste rock dumps, tailings embankments and

* Corresponding author. Email address: robin.power@insitutek.com

backfilled pits to prevent long-term settlement and erosion. Impact rolling forms part of a performance-based closure strategy, delivering durable rehabilitation and reduced long-term risk.

2 Principle of impact rolling (high energy impact compaction)

Impact rolling is a ground improvement technique that utilises a heavy, non-circular 3-, 4- or 5-sided steel roller to compact soil by repeatedly impacting the ground at high speed, as shown in Figure 1**Error! Reference source not found.**. Impact rollers are typically towed behind a heavy tractor at speeds of 10 –15 km/h. The geometry of the roller induces a series of high energy, vertical impacts as it rotates, transmitting dynamic loads deep into the ground.

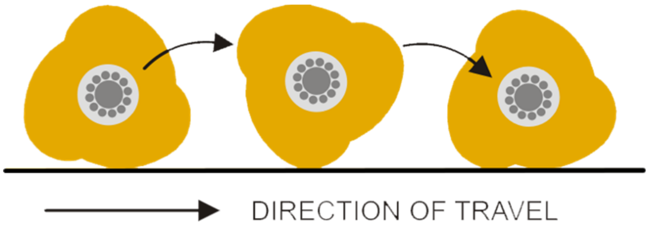

Figure 1 Schematic of the impact rolling concept

Over several passes, the process significantly densifies the soil to depths from 1.5 to 4 m, depending on the material and moisture condition and whether the material is pre-existing fill or freshly placed fill. There is potential to reduce the imported fill material quality requirements, again lowering cost. Impact rolling also lends itself to compacting heterogeneous material, which could include uncontrolled fill and material with significant changes in grain size.

A project-specific method specification is typically developed based on:

- impact roller configuration (module geometry, weight, width etc.)
- depth of compaction required to achieve the requirements
- number of passes required.

Trials are generally undertaken to optimise the number of passes and develop method specifications, while verification of the results is often prudent to validate the method specification for the materials being worked with on any specific site.

3 Verifying impact rolling performance

By integrating real-time intelligent compaction measurement (ICM) on the impact rollers and in situ validation tools with strength profile, bearing capacity and compaction control capability, site improvement is achieved and verified with quantifiable data.

3.1 What is intelligent compaction measurement

Using ICM, roller pass counts (Figure 2), settlement (Figure 3) and ground response (Figure 4) are measured, giving full visibility and traceability of the in situ conditions across the site and over each layer of placed material.

ICM produces real-time data that is immediately available to the operator, empowering them. Pass count monitoring (Figure 2) enables the operator to see how many passes have been done across the site and any gaps between rolling paths. If more than one operator is impact rolling on the same site, ICM data is synchronised between the in-cab displays every 15 seconds, giving all operators a unified, live view of compaction progress – enabling a complete, synchronised picture of the site's status directly on each operator's display.

ICM data can also be viewed in real time by an engineer on site or remotely via a smart phone or computer, enabling better informed and more timely decisions to be made.

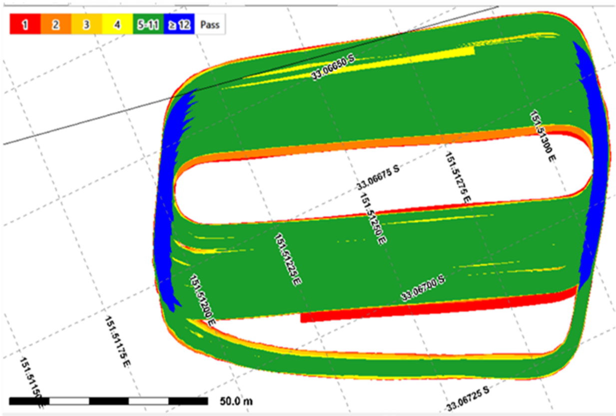

Figure 2 Impact rolling pass count measurement

ICM tracks surface levels so that surface settlements can be measured (Figure 3), providing a direct relation to densification. Once the finite energy of impact rolling has expelled as much air as possible under the specific circumstances, i.e. once the rate of surface settlement has reduced sufficiently or has reached 'effective refusal', impact rolling can cease as it is delivering little additional benefit at that time.

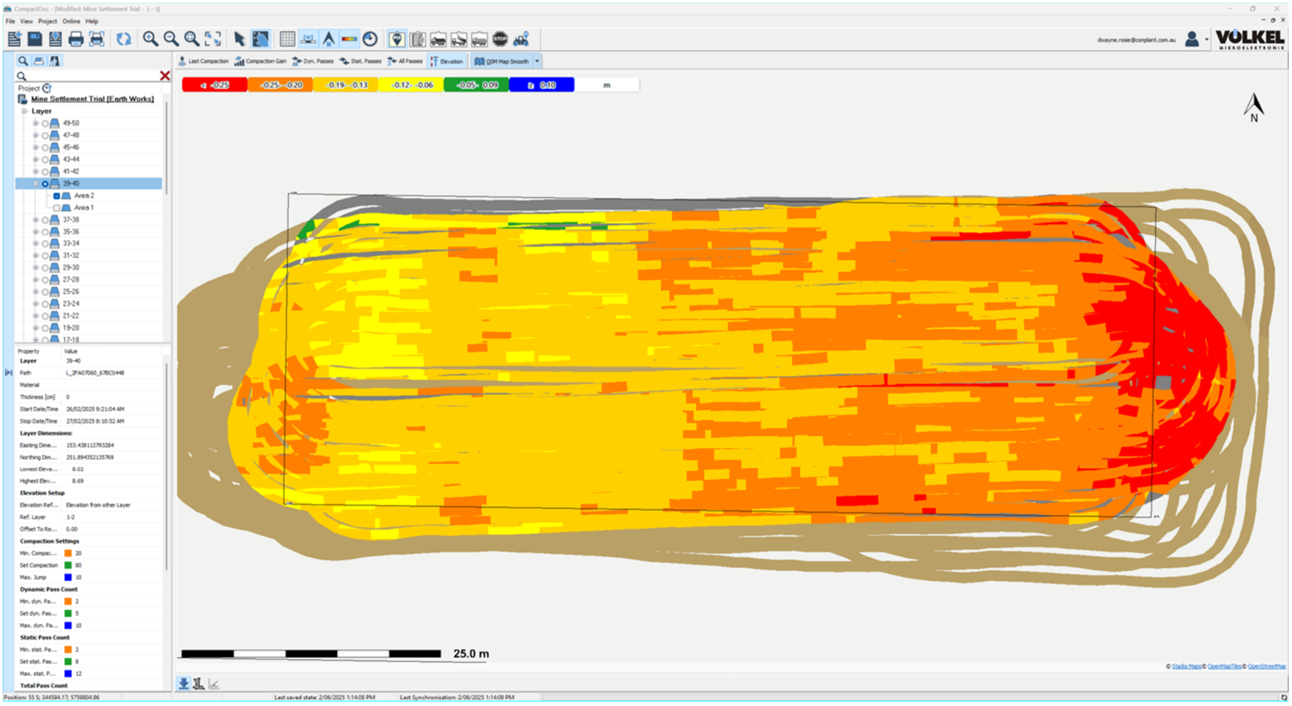

Figure 3 Impact rolling settlement measurement

Ground response (Figure 4) is impact roller drum deceleration. At a high level, ground response is essentially how the ground reacts when subjected to high energy impacts. The system measures the response to the dynamic loading of the impact roller drum on the ground performance. From this, soil parameters can be inferred. Those inferred parameters may include relative stiffness, likely deformation behaviour under load, improvement trends with additional passes, areas requiring further treatment or investigation, and potential alignment with the target modulus or bearing capacity criteria.

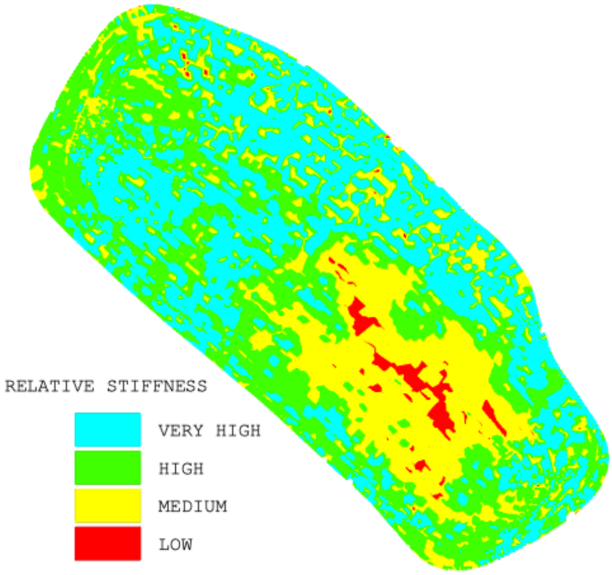

Figure 4 Impact rolling ground response measurement

ICM can also be used to identify weak or variable zones through onboard settlement monitoring, providing a method of large-area proof rolling and supporting targeted remediation.

3.2 Calibration of intelligent compaction measurement data

While drum deceleration and settlement show how the ground responds across the treatment area, it does not replace geotechnical testing. Without calibration, the ground response data is valuable as a diagnostic and quality control tool. It can show consistency, variability and changing behaviour during treatment. But if the goal is to link the response to design-facing parameters such as modulus, bearing capacity or expected performance, then a site-specific correlation process is required. This is not a limitation of ICM. It is simply sound engineering practice. The objective is not to eliminate in situ testing but to make it more meaningful by placing it within a broader ground response framework.

Depending on the objectives of the impact rolling process, suitable in situ testing methods would be chosen based on:

- strength versus depth profile and density. Penetration tests using a lightweight variable energy dynamic penetrometer (Figure 6) or heavier duty dynamic probing super heavy (DPSH) (Figure 5) instrumented penetrometers – with compaction interpretation software included, and VEDP and DPSH resistance plots – enable a continuous standard or modified compaction profile over the depth of testing. Checks of VEDP or DPSH cone resistance with co-located nuclear densometer tests allows calibration with software compaction interpretation. Cone penetration testing (CPT) can also be used but refusal in stiffer material due to it being a static push (as opposed to a dynamic penetration) can be an issue
- bearing capacity. Plate load testing (Figure 7) is a widely used method to determine allowable bearing capacity. Plate Load Testing is considered a particularly good method because it measures actual ground performance under load, in place and at full scale, eliminating uncertainty from sampling and empirical correlations. That is why it is often used as a benchmark or validation tool, even when other tests are used for broader site coverage.

In instances with particularly large grain size, visual observation can be used.

Figure 5 Dynamic probing super heavy – GRIZZLY rig

Figure 6 Variable energy dynamic penetrometer – PANDA

Figure 7 Plate load test with 762 mm plate

The in situ tests provide a high level of confidence at discrete locations but very often, in mine closure projects, the material is heterogeneous, which is where the complementary nature of ICM demonstrates its full value, providing visibility across the whole site (Figure 8).

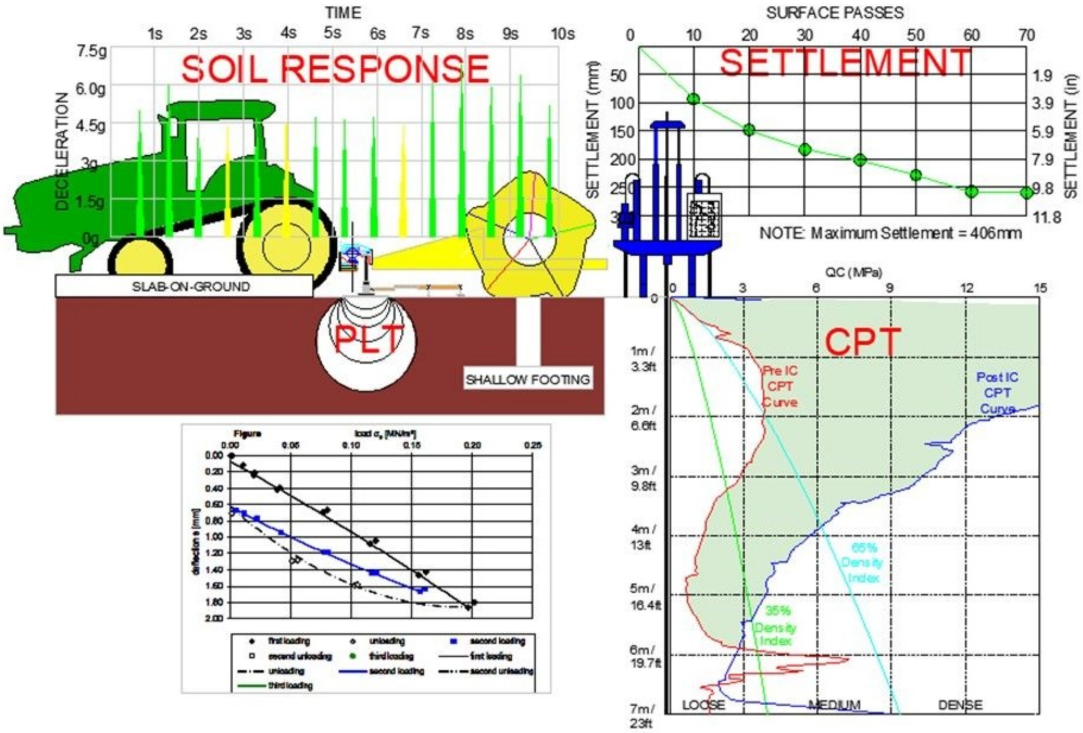

Figure 8 **In situ tests results at discrete locations complemented by intelligent compaction measurements**

ICM materially changes the quality control process. By recording ground response continuously across the treated area, variability becomes visible rather than assumed. Stronger and weaker zones can be identified, in situ test locations can be selected more intelligently, and confidence between isolated test points improves. In situ test methods are wide-ranging (Avalle 2004a).

ICM aids the responsible engineer with a higher level of confidence in what is being achieved between the in situ verification test points, enabling better decision-making and improved long-term performance (Figure 9).

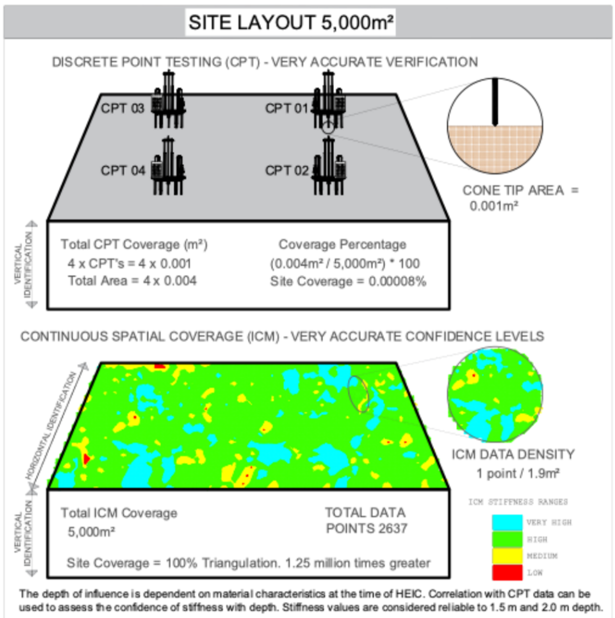

Figure 9 **Illustration of intelligent compaction measurement (ICM) ground response data paired with Cone penetration testing (CPT) data**

3.3 Impact rolling process flow

A typical impact rolling process flow is shown in Figure 10.

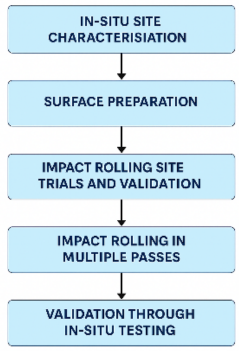

Figure 10 Typical impact rolling process flow

Site characterisation is a critical first step in assessing suitability for impact rolling. Often, review of existing geotechnical data is sufficient. However, in some cases intrusive testing (test pits, boreholes, DCP or instrumented penetrometers such as portable VEDP or crawler-mounted DPSH rigs) and laboratory testing are valuable in characterising materials and in situ density and moisture conditions. Field moisture content in relation to optimum moisture content (OMC) is an important consideration as a guide to roller effectiveness. The higher impact energy means that the maximum dry density is higher than for the modified Proctor compaction test, with a lower OMC. There can be limitations to the effectiveness of impact rolling and long-term fill performance if in situ moisture content is significantly outside the accepted range for controlled fill. This particularly applies to cohesive fill with higher moisture contents. On the dry side of OMC, the impact roller can generally be very effective due to the high energy delivered by the impact module.

Trials and their validation are often prudent and can include review of impact roller pass counts to confirm execution of the process as specified, induced settlement and ground response heat maps. Figure 11 is an example of trial results for ground response, varying the number of passes. It shows that, after 20 passes, there is very little change in deceleration of the drum, indicating the maximum level improvement has been realised. Based on the average CPT (q_c) and deceleration (G) value correlation, at 0–1.5 m depth, average CPT values are as follows: PASS 1 – 11.31 MPa, PASS 20 – 17.17 MPa, PASS 25 – 17.20 MPa.

Figure 11 tracks the progress of soil compaction over 25 passes. As the passes increase, the deceleration value rises, indicating a denser, stiffer material; Pass 25 = practical refusal.

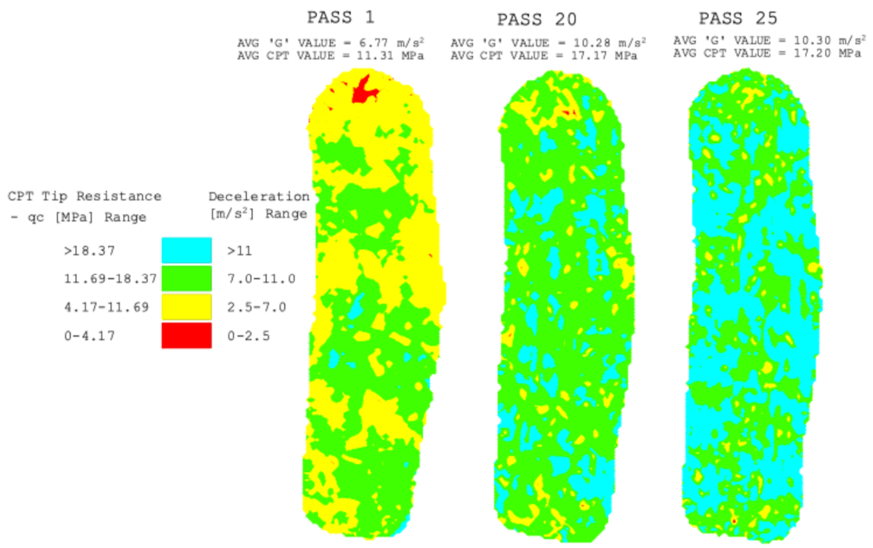

Figure 11 Average deceleration (G) values versus cone penetration testing (CPT) tip resistance (q_c)

Final validation testing after impact rolling can be achieved using the same methodology used for trials, but on a grid assessed to provide appropriate statistical coverage.

4 How impact rolling assists with mine closure

Mine closure presents complex geotechnical challenges associated with rehabilitating large, disturbed landforms, including waste rock dumps, tailings storage facilities (TSFs) and backfilled pits. These landforms often comprise heterogeneous, loosely placed or variably compacted materials with uncertain density, stiffness and long-term settlement behaviour (Avalle 2007; Scott & Jaksa 2012; Brink & Heymann 2024).

Closure objectives extend beyond stability to include prevention of spontaneous combustion and protection of groundwater from acid and metalliferous drainage. Achieving stable, low-permeability, trafficable surfaces is therefore essential to meet regulatory criteria, ensure public safety and enable sustainable post-mining land use. Impact rolling has emerged as an efficient, cost-effective and quantifiable ground improvement technique well suited to these conditions (Jaksa et al. 2019).

Impact rolling is used to:

- increase stability, due to increased stiffness, and reduce settlement risk for waste rock dumps, TSFs and backfilled pits (Jaksa et al. 2019)
- lower permeability and reduce seepage, protecting groundwater from acid and metalliferous drainage and reducing the risk of spontaneous combustion.

5 Increasing stability and reducing settlement

Impact rolling can accelerate rehabilitation and compaction efforts for mine closure. On mining sites where large earthmoving equipment are capable of moving and placing significant volumes quickly, having the ability to compact large volumes in a timely and efficient manner is an obvious advantage of impact rolling because of its ability to compact ground efficiently by means of a faster operating speed (10–15 km/h) and compaction of thicker layers than conventional circular drum rollers that rely on either static weight, kneading or vibratory action. Impact rollers can compact soil and spoil materials in thick lifts (up to 2 m for placed material and 3–4 m for in situ material, depending on soil type), which is far more efficient than traditional, thinner-layer, slower vibratory rolling methods. Impact rolling provides far superior mechanical interlock due to the high levels of energy being transferred into the soil that facilitate deep-seated particle rearrangement (Avalle 2007).

Impact rolling improves the density and stability of TSF embankments, reducing the risk of settlement and increasing long-term, post-closure performance. It is also an application used for the improvement of tailings beaches to support cover systems, as well as for the base of TSFs to provide a very low-permeability foundation (Scott & Jaksa 2012). During backfilling of voids, thicker lifts can be placed and compacted with confidence, maximising densification and increasing the effective volume of material placed within the void.

5.1 Thick layer compaction of coal spoil

It is common practice for spoil from mining operations to be backfilled into a previously mined void. This was the case on this 550 ha site. The ground conditions comprised glacial clays and coal measures deposits of sandstones, mudstones, shale and siltstone. Coal seams were up to 40 m thick.

The total volume of mine spoil to be placed was 12 Mm^3. The weekly volume of placed spoil was more than 250,000 m^3 (Figure 12).

Figure 12 Daily impact rolling of 250,000 m^3 of coal spoil (Landpac)

The sheer volume of overburden material being generated each week required a rethink on the method of placement and compaction.

After trials to demonstrate impact rolling performance, a method specification was developed stipulating that fill layers were to be end tipped and spread using dozers to 1.2 m loose lift thickness depths (Figure 13).

The key performance assessment criterion was 95% of the standard maximum dry density (SMDD); a compaction requirement to minimise settlement and reduce the likelihood of spontaneous combustion of the coal waste and overburden.

Figure 13 Impact rolling of coal overburden in 1.2 m layer thicknesses

5.2 Settlement minimisation: copper mine – tailings dam wall raise

A 1.5 km-long dam wall is being raised 10 m with the placement and compaction of about 2.5 Mm^3 of material, made up roughly of equal parts of mine waste rock (overburden) and freshly blasted rock material (which has a larger grain size). Previously, 400 mm thick layers were used with conventional roller compaction. Impact rolling was used (Figures 14, 15 and 16) to:

- increase lift thickness from 400 to 800 mm
- improve the compaction process
- mitigate the lamination effect (clear delineation between layers) that conventional rollers deliver
- increase maximum grain size to 500 mm
- decrease the program duration
- minimise settlement
- minimise permeability.

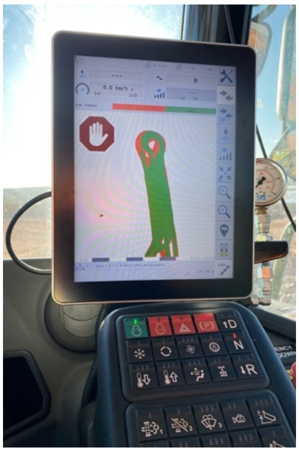

Figure 14 In-cab intelligent compaction measurement display for the operator

Figure 15 Mine spec impact roller (Broons BH-1950 MS)

Figure 16 Impact rolling trial for tailings dam construction

Because of the large grain size (> 20 % material retained on 37.5 mm sieve), the conventional compaction control method of nuclear density gauge (NDM) could not be used. To demonstrate the improvement of the compaction process and consistency of the rockfill, visual assessment is frequently used. The following aspects are the most common that are visually assessed (Figure 17):

- absence/presence of voids and loose particles assessed by hand disturbance of the fill
- homogeneity of the mixed material, absence/presence of clusters of large particles

- distribution of moisture content and stiffness through the layers, based on visual assessment of the wetting front and touching the material by hand
- excavation resistance (Figure 18).

Figure 17 Visual observation through the excavation

Figure 18 Excavation resistance test

These observations, combined with the ICM data showing pass count and settlement, were the basis of demonstrating the performance of the impact rolling approach.

To measure any saturation induced settlement, a trial pad was subject to a wetting-up stage where the layer was saturated and then loaded by heavy construction equipment. The time to saturate was based on the uptake of water into the pad, and multiple applications were required to achieve infiltration through the layer. The trial pad was saturated and left overnight to allow moisture to percolate through the trial pad. Loading of the trial pad and test slots was undertaken the following day to assess for settlement and the extent of the wetting front.

A poorly compacted material may result in 'collapse settlement' (hydro collapse) of the embankment; the sudden, large-scale downward movement of the ground when a partially saturated, loosely packed soil is wetted under load. This typically occurs if the material is not moisture conditioned appropriately during compaction, resulting in a less compacted layer.

6 Lowering permeability and seepage reduction

Unmanaged mine waste can pose significant environmental and safety risks, from pollution to land instability. Further, if you don't compact the voids in coal discard you provide conditions potentially conducive to spontaneous combustion in the coal.

Compaction reduces the voids present in soil, making it less permeable. At a particular density, for the same soil sample, permeability is higher for soils compacted to a drier OMC than those compacted to a wetter OMC. Soil compacted on the dry side of OMC generally possesses a more open structure with larger, interconnected pore spaces compared to the dispersed, closed structure of soil compacted on the wet side. Consequently, even at the same dry density, water moves more freely through the larger pores of dry side compaction (Scott et al. 2012).

Impact rolling delivers good compaction outcomes with wider moisture variations (Figure 19) and much larger particle sizes compared to traditional rolling (Avalle et al. 2020):

- typically +/-5 % OMC, dependent on material characteristics and depth
- particle sizes generally up to 1/3 of layer thickness.

For the treatment of dry materials, compacted granular soils will generally have higher dry densities (1.84–2.16 t/m^3) compared to clay-based or silty soils (1.36–1.84 t/m^3).

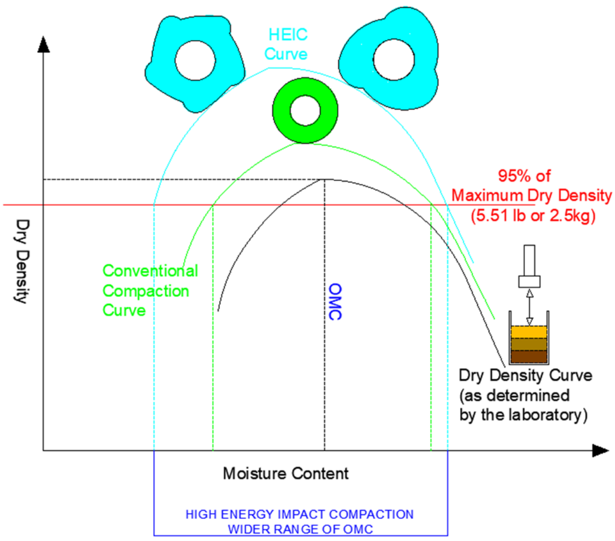

Figure 19 Wider moisture range for impact rolling

6.1 Permeability reduction: coal discard – coal washery, New South Wales

Much of the site was overlain by fill consisting of washery reject and tailings produced by the former coal washery. This material comprised sequences of very loose to loose deposits of sandy silt and sandy gravels covered in places by a thin, silty clay topsoil. The coal washery reject is generally contained by a perimeter earthfill embankment which was between 18 and 23 m in height.

There was a history of erosion of the embankment slopes, with minor gully erosion evident on all batters. More prominent erosion gullies have also been noted up to 4 m deep in places. These deeper gullies had produced loose fan deposits of sediment at the toe of the batters.

Impact rolling was used to prepare a working platform on the coal washery reject for constructing the capping layer (Figure 20). It was used to target sensitive areas beneath structures and in areas where no engineering fill was to be placed. The geotechnical results indicated that significant density increases in the upper 1 m of the coal wash was achieved. The compaction process reduces the voids present in the coal discard and also causes stabilisation of the coal discard and overburden fills.

Figure 20 Impact rolling the coal washery reject to reduce voids and permeability

6.2 Compaction of capping layer over mine waste, Emerald, Queensland

For this project, close to 150 ha of worked-out open cut coal mine was to be reinstated to flood plain conditions.

Low-permeability capping layers are designed to shed water and control water infiltration, and, on coal waste, dumps:

- reduce convective transport of oxygen into a dump to very low levels and therefore reduce the risk of spontaneous combustion in coal waste and overburden
- reduce the infiltration of surface water through mine waste that can lead to environmental problems with acid mine drainage (AMD) and run-off.

On this site, impact rolling was used for the compaction of low-permeability capping layers on coal waste dumps (Figure 21).

Figure 21 Impact rolling capping layer

In the initial stages of the project, detailed results were obtained from trials to determine the most efficient method to meet strict environmental and engineering requirements for the ongoing placement and compaction of capping layers. Discussion of a trial program is presented in Scott & Jaksa (2012), which demonstrated that greater recycling of mine spoil materials can be undertaken with a reduced need to screen out large quantities of oversized materials (Figure 22) while still meeting densification objectives.

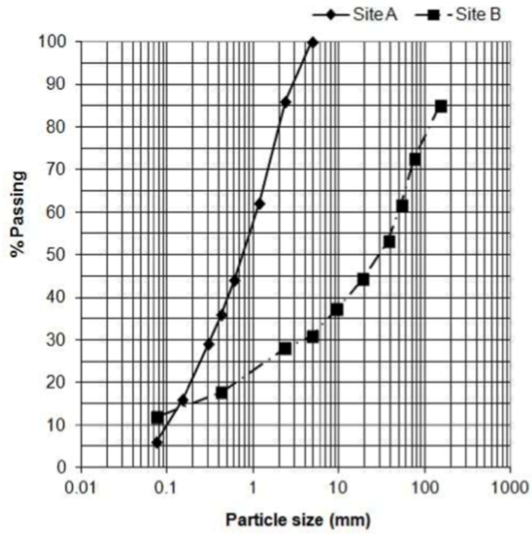

Figure 22 Typical particle size distributions for sites A and B

In this case study, with just 6 to 10 passes applied on the surface (Figure 23), improvement in density can occur to at least 1 m depth, while 30 passes can result in significant improvement down to at least 1.2 m (Figure 24). Depending on material composition and the number of impact roller passes, densification to 2 m and deeper can be achieved.

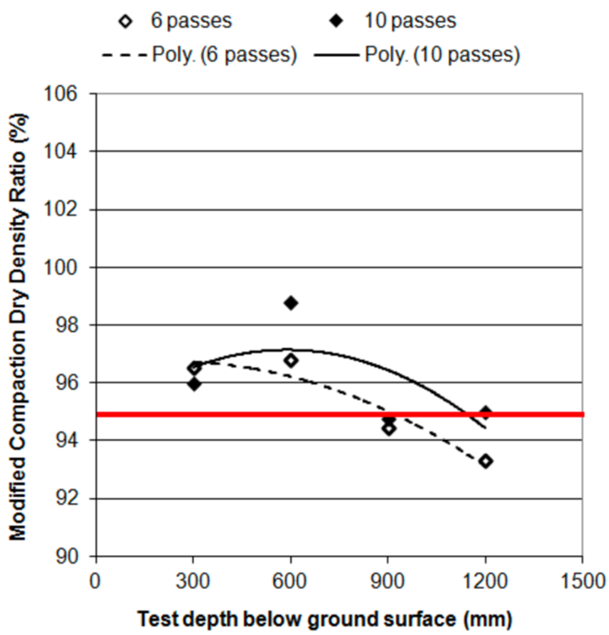

Figure 23 Dry density ration versus test depth for site A after 6 and 10 passes, respectively

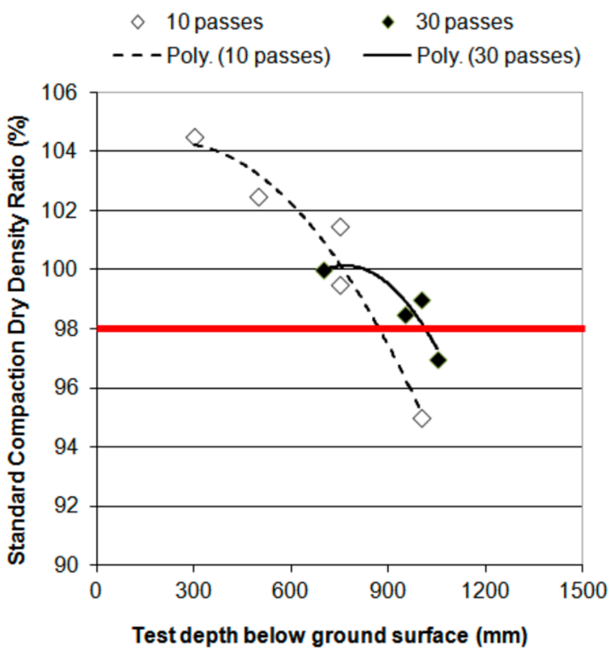

Figure 24 Dry density ratio versus test depth for site B after 10 passes and 30 passes, respectively

6.3 Coal mine/power station ash containment cell

In landform reconstruction, impact rolling is used at pit bases and on embankments to reduce the permeability of soil and limit contaminant migration. Impact rolling results in deep compaction, having the additional benefits of improving ground stability and reducing future and ongoing settlements (Du et al. 2024). Typical embankment slopes that can be impact rolled are up to a 1V:3H profile.

This project involved the compaction of the base for an ash containment cell and its side embankments (Figure 25), associated with the closure of a mine/power station. The materials were sourced from local stockpiles of mine overburden. An initial trial was undertaken in order to develop a method specification for the main works. In addition, the final capping layer over the buried materials was impact rolled to provide a denser and more uniform final surface designed to shed surface water.

Figure 25 Ash containment cell impact rolling

6.4 Acid mine drainage: Reefton, New Zealand

The objective of this project was to reduce AMD (Figure 26) – characterised by high acidity and elevated metal concentrations – from the pyritic mine overburden, which was a significant problem on this steeply sloping site. Contaminated run-off resulted in high levels of iron and sulphate, and low pH (acidity) in water systems, which may negatively impact aquatic ecosystems.

Figure 26 Permeability trails to reduce acid mine drainage

The convective transport of oxygen into poorly constructed waste rock dumps is generally the dominant mechanism supplying oxygen to oxidation sites within the waste rock. It has been demonstrated (Brown et al. 2014) that convection of oxygen accounts for 90% of the oxygen transport into a waste rock dump and diffusion accounts for 10%. The results in Figure 27 demonstrate an increase of approximately 15% in wet density because of impact rolling, reducing the convective transport of oxygen.

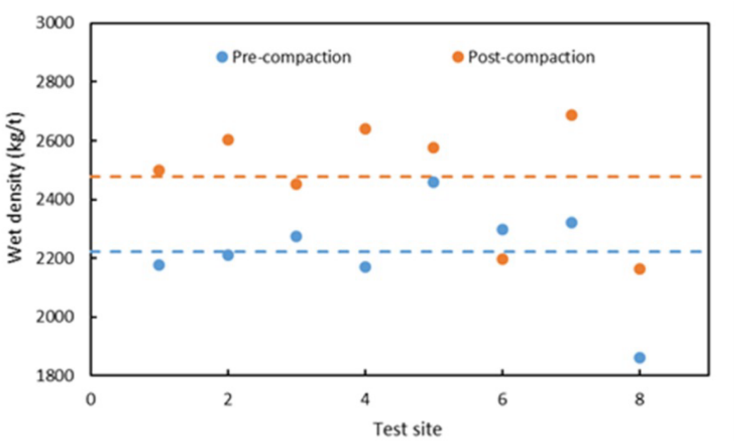

Figure 27 Densification of coal mine waste

Less water entering the reactive material means a lower volume of leachate is produced. Although permeability results are not available to the authors for this project, we can infer a permeability reduction based on work by Clyde Agriculture (Avalle 2004b), which conducted infiltration tests in conjunction with impact rolling at one of its cotton water storages near Bourke, New South Wales, Australia. The procedure adopted followed the principle of the double ring infiltration test, with 1 m diameter metal rings embedded within a 5 m square pond; the fall in water level being measured within the ring. The data reflects a significant improvement after 12 passes of the impact roller (Table 1).

Table 1 Infiltration rates, Clyde Agriculture

Number of passes of impact roller	0	6	12
Inferred infiltration rate (mm/day)	0.30	0.21	0.05

7 Key impacts of impact rolling in mine closure

Mines face pressure to deliver faster, safer and more sustainable projects cost effectively, including in the closure phase. Impact rolling addresses these challenges by:

- allowing thicker lift placement and faster schedules
- reducing costs tied to material import/export as a wider range of grain sizes and material variability can be accommodated
- being a cost-effective alternative to expensive excavation and replacement of material, allowing for better management of closure budgets
- delivering high-visibility, traceable, quantified quality control results using ICM
- providing improved safety and reduced environmental risk in creating more stable, less permeable surfaces with reduced erosion. Impact rolling helps meet stringent environmental, social and governance goals and regulatory requirements, fostering more a sustainable mining environment.

Impact rolling, validated by ICM and appropriate in situ tests, supports a performance-based closure strategy delivering durable rehabilitation and reduced long-term risk.

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