IDENTIFICATION AND MANAGEMENT OF DISPERSE MINE SPOILS

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EXECUTIVE SUMMARY

This report details a project that has focussed heavily on soil properties and the impacts of infiltrating water on both soil properties and soil behaviour. Included with the report is a review of literature covering aspects of soil chemistry, structure, clay dispersion, and tunnel erosion. Readers not familiar with those aspects of soil science may find it helpful to read the literature review (Appendix 1) prior to working through the main body of the report.

Mine sites that have been involved in, and have supported the project, are:

- Coppabella Coal Mine (Australian Premium Coals Pty Ltd) – 10 km east of Coppabella and 39 km west of Nebo, Central Queensland.
- Higginsville Gold Mine (Resolute Mining Ltd) – 70 km north of Norseman and 110 km south-south east of Kalgoorlie, Western Australia.
- St Ives Gold Mine (Gold Fields) – 80 km south of Kalgoorlie and 20 km south of Kambalda, Western Australia.
- Telfer Gold Mine (Newcrest Mining Ltd) – approximately 450 km East of Port Headland, Western Australia.
- Jundee Gold Mine (Newmont Australia) – approximately 193 km north of the township of Leinster, Western Australia.

This project has highlighted a number of important issues.

Firstly, it has shown the importance of soluble salt content in some spoils, and the need to manage salt content to maintain stability.

Secondly, the project has shown the existence of effectively two mechanisms for tunnel erosion (movement of dispersed clay and also movement of non-cohesive fine particles), where previously tunnel erosion was attributed solely to clay dispersion. This finding has been supported by considerable field observation, and means that the range of materials at risk from tunnel erosion is greater than initially believed.

Irrespective of the method by which tunnels form, the project has indicated strong interactions between the design of constructed landforms and the development of tunnel erosion. Where water is ponded over saline sodic spoil, leaching of salt by the ponded water results in reduced soluble salt, increased dispersion, and development of tunnel erosion. For non-cohesive materials, long durations of ponding are also a major factor in developing tunnel erosion. Although retention of rainfall and runoff water on constructed landforms is widely considered to be highly desirable, in practice there is a range of situations where ponding of water is a recipe for disaster.

Because of the range of mechanisms by which tunnel erosion develops, there is no single test that will provide optimal information across the entire range of materials considered. Rather, it appears that initial assessment of soil chemical and physical data is required, followed by specific tests to assess the specific tunnel erosion mechanism indicated by material properties. Initial soil/spoil parameters that provide information on tunnel erosion potential are:

i) EC (to assess potential salinity impacts on dispersion);
ii) Cations, with particular emphasis on exchangeable sodium percentage (ESP) to assess dispersion potential;
iii) Particle size distribution (to provide an indication of soil cohesion and liquefaction contributions to tunnel formation/failure), and
iv) Clay mineralogy (for swelling influence).

Based on the data obtained, a judgment can be made on which subsequent tests are most appropriate.

The Emerson dispersion test will provide a quick assessment of the presence of spontaneously dispersive material, and is most appropriate for samples of high ESP and low EC. The influence of EC must be taken into account for material that does not test as spontaneously dispersive, especially saline materials.

Pinhole tests provide a very good indication of tunnelling following the development of preferential flow paths. The test provides data on a material’s resistance to tunnel development. The pinhole test is suitable for dispersive materials of high and low salt content, and also for samples that tunnel by liquefaction, though those latter materials will create some difficulties during analysis.

Leaching column tests provide a good indication of the hydraulic conductivity of a material and of its potential for sealing or blockage of pores to form on the soil surface or at depth. High hydraulic conductivity can be associated with tunnel formation or liquefaction failure of the fine sand and silt size fraction. Leaching column tests are useful on materials with a high hydraulic conductivity as the sediment load within the leachate can be measured to assess the level of fine particle movement through the soil. The occurrence of a seal or blockages is an important element to be aware of for a potentially tunnelling material as these restrictions to flow can increase the water ponding on a material, increasing the volume of flow concentration at points that a tunnel forms.

Leaching of extremely saline materials may be necessary prior to Emerson and pinhole testing to assess the influence of a material’s salt content on dispersion and tunnelling potential.

Erodibility measurements provide an indication of the potential for continued development of tunnels (and tunnel gullies). Erodibility measurements did not appear to assist in predicting initiation of tunnelling for any material, although some limited tunnelling was observed on some tests and a low resistance to rill initiation was shown for many of the samples. The combined low critical shear and high rill erodibility of unstable spoils was due to a combination of the dispersive nature of the materials (particularly Coppabella and Higginsville samples), poor structural strength (particularly Coppabella, Jundee and Telfer samples) and low levels of coarse material (rocks) required to provide an armour on the eroding surface (particularly Higginsville samples). Characteristics contributing to high erodibility are also factors in the initiation (dispersive and poor structural strength nature) and potential progression and severity of tunnelling when it has occurred.

Materials susceptible to tunnelling fall into three groups:
- saline sodic
- non-saline sodic
- fine, non-sodic materials of low cohesive strength

Saline sodic materials may – at least initially – be stable. Therefore, it may be acceptable to place these materials relatively close to the surface of a waste dump, provided leaching (over the long term) is limited. Leaching of salts and conversion of these materials to a non-saline sodic and dispersive condition is highly undesirable.

This means that:

(a) prolonged ponding of water at any point on the landscape should be completely avoided as it will accelerate salt leaching and tunnel formation; and
(b) deep drainage below the topsoil layer should be minimised so that salt leaching is not significant.

Non-saline sodic materials will be susceptible to tunnel erosion as soon as they are placed on or near a waste dump surface. Options for constructing stable landforms of this type of material are limited. Where a stable topsoil can be placed over the spoil, there is still potential for water draining below the topsoil to cause tunnel development. Options to avoid or minimise the potential for tunnel development in this type of material include:

(a) avoiding placing the material closer than 1 m to the surface (if possible);
(b) placing at least 0.5 m of stable (non-cracking) topsoil over the spoil;
(c) keeping waste dump outer batter gradients very low (as low as 5% if possible), so that gravitational forces aiding tunnel formation are drastically reduced;
(d) avoiding ponding of water; and
(e) ensuring that cracks and other pathways for water to enter the spoil are minimised.

There is also potential to use gypsum to stabilise these materials.

For non-saline, non-sodic materials of low cohesion, the major priority is to avoid prolonged ponding. Deep drainage into the spoil from an overlying topsoil layer is not of concern, provided the water moves as unsaturated flow.

Therefore, the top of the dump needs to have a stable surface layer (covering the spoil) that has high water infiltration and storage capacity, so that all rain falling on the top of the dump can move into the surface layer and be held under tension in soil/spoil pores. Minimisation of runoff is desirable, and it is essential that any low-lying areas do not receive runoff from large surrounding areas. Volumes of runoff ponded at any point should be kept as small as possible.

For batter slopes, level berms to trap and pond runoff are highly undesirable. Instead, if berms are used, they should be designed to drain rapidly to stable rock drains so that the duration of ponding at any point in the system is kept to a minimum.
It is acknowledged that construction of stable rock drains overlying material susceptible to tunnelling is extremely difficult.

For existing dumps subject to tunnel erosion, remediation and repair appears to be difficult in some cases and often impossible.

Work on dump tops is generally possible, provided access to the top of the dump is present and suitable equipment is available.

However, for outer batter slopes, difficulty of access to berms means that although it may be necessary – for example – to spread and incorporate gypsum, compact a loose and unstable material, or to remove unstable material and replace it with a more stable spoil, it will be virtually impossible to get suitable equipment to the location of the problem.

The problem with existing unstable dumps is not only that erosion rates can, in some instances, be high. Unlike rocky materials, finer spoils susceptible to tunnel erosion are most unlikely to armour, or to have any mechanism by which erosion would be reduced over time. Therefore, those relatively high rates of erosion can be expected to continue indefinitely.

Therefore, the importance of early diagnosis of potential tunnelling problems and adoption of strategies to prevent such long-term instability is essential for successful mine closure.

In general, the management options available to mine sites that excavate materials susceptible to tunnelling are to either:

(a) avoid the problem by ensuring that tunnelling materials are not exposed to runoff and shallow drainage: or
(b) remediate the problem by applying some form of amendment.

**Avoidance** of the problem is undoubtedly the easier and most cost-effective option, but relies on mine site management being able to accurately identify materials that will be susceptible to tunnelling, and to provide for selective handling.

**Remediation** of materials susceptible to tunnelling is typically seen as relying on application of gypsum to remove exchangeable sodium and to increase the stability of the material of concern.

**Design options** to control or avoid tunnel erosion problems on waste dumps generally rely on minimising or eliminating the water pathways that would otherwise favour the tunnel erosion process.
1. INTRODUCTION

This report details a project that has focussed heavily on soil properties and the impacts of infiltrating water on both soil properties and soil behaviour.

Included with the report is a review of literature covering aspects of soil chemistry, structure, clay dispersion, and tunnel erosion. Readers not familiar with those aspects of soil science may find it helpful to read the literature review (Appendix 1) prior to working through the main body of the report.

1.1 Dispersive Materials and Tunnelling

Waste dumps are a common result of open pit mining activities. Stabilisation of such constructed landforms is a major component of mine site rehabilitation works. The presence of materials susceptible to tunnelling or piping has large impacts on landform stability and rehabilitation, as tunnel erosion tends to specifically impact on important structural elements of dumps such as berms and drains (Figure 1). Damage can then result either directly from the failure of those structural elements and the discharge of concentrated flows onto slopes below, or from the expansion of tunnels and their eventual collapse to form large gullies (Figures 2 and 3).

![Figure 1: Tunnel developed from a berm on a dump constructed of sodic spoil.](image1)

![Figure 2: Tunnel through a berm discharging concentrated flow onto the batter slope below.](image2)

![Figure 3: Large tunnel collapsed to form a gully.](image3)
In general, the development of tunnel erosion has been attributed to the presence of dispersive materials. These materials are typically sodic (containing relatively high quantities of exchangeable sodium) causing them to break down when wet and release clay particles into solution – the process of dispersion.

Tunnel erosion associated with sodic, dispersive subsoils has been reported in all Australian states (Boucher 1990). As Australia is recognised as containing the world’s largest area of sodic soils, with approximately 33% of the continent being affected (Surapaneni 2001), it is not surprising that mining activities involving the excavation of material from depth should encounter similar problems.

Dispersive spoils are widely encountered in Australian mining activities. Where mining deals with sedimentary materials such as coal, saline sodic spoils are common. Both the Hunter Valley and Bowen Basin coalfields are well-known examples of this.

Dispersive spoils also occur in a wide range of other mines. Often, the occurrence may be relatively small in extent, with management of the problem depending on its early recognition and the options available for treatment. Where tunnelling is not a problem, gypsum has been used to reduce surface hardsetting and poor infiltration. However, benefits from gypsum application are typically short-lived.

Highly dispersive smectite clays are excavated by gold and nickel mining in the Yilgarn region of Western Australia and pose considerable problems for rehabilitation. As well, a range of West Australian gold mines experience problems with dispersive tailings, particularly where tailings dam walls are constructed of tailings. Through the drier parts of Australia, high soluble salt and accumulation of sodium in oxidised waste rock are common. There can be little doubt that tunnel erosion causes landform instability on a number of mines where spoils are not considered dispersive.

For mine site waste dumps, the presence of materials susceptible to tunnelling does not necessarily seem to cause erosion rates dramatically higher than would be the case if other materials were used. However, tunnel erosion does result in gully erosion being the dominant erosion mechanism, leading to the failure of engineered structures aimed at controlling erosion. In general, the presence of tunnel erosion also typically means that site remediation and stabilisation are extremely difficult, and that erosion problems are likely to be particularly persistent, showing little tendency for armouring and natural stabilisation.

1.2 Options for Management – Current Situation

In general, the management options available to mine sites that excavate materials susceptible to tunnelling are to either:

(c) avoid the problem by ensuring that tunnelling materials are not exposed to runoff and shallow drainage; or
(d) remediate the problem by applying some form of amendment.
Avoidance of the problem is undoubtedly the easier and most cost-effective option, but relies on mine site management being able to accurately identify materials that will be susceptible to tunnelling.

Laboratory tests for identification of dispersive materials have been developed and tested, but there has been little research on relationships between test results and the development of tunnel erosion (relative to issues of hardsetting and infiltration, for example). Adding to the uncertainty of testing for dispersion and tunnelling, the mechanisms of erosion of dispersive materials have not been researched. There is currently little information on the relative importance of various erosion processes, and limited information on the particular conditions under which dispersive materials are most vulnerable. The limited research that has been carried out on erodibility of dispersive materials has shown a strong bias towards interrill erosion, which is probably the least important erosion process affecting those materials.

In dealing with mine spoils, it must be emphasised that literature on characterisation procedures, and associated prediction/modelling of erosion processes, suffers from the central assumption that ‘as mined’ materials have properties that do not change after placement in dumps. This is a severe weakness for many Australian mine spoils that are saprolitic (rather than pedological) in nature and are commonly saline, sodic, at extremes of pH and devoid of biological materials/activity. In order to predict the mid to longer term performance of dumps, it is essential that the inevitable microstructural, chemical and mineralogical evolution of wastes can be predicted and the impact of these changes on erosion hazard determined.

Remediation of materials susceptible to tunnelling is typically seen as relying on application of gypsum to remove exchangeable sodium and to increase the stability of the material of concern.

Design options to control or avoid tunnel erosion problems on waste dumps have generally not been considered. From the outset of this project, it was considered quite likely that some designs that are currently widely used may create surface and sub-surface water pathways that actually increase the potential for tunnel erosion to develop. Equally, it should be possible to design landforms in such a way that potential for tunnel erosion is minimised.

1.3 Project Aims

This project aimed to develop:

(a) procedures for identification of dispersive spoils – which can preferably be applied to drill core samples to give early warning of the presence of problem materials;

(b) methods for prediction of potential erosion risks for various degrees of dispersion;

(c) recommendations for placement of dispersive materials so that waste dump stability is not compromised; and
recommendations for management of existing dumps of dispersive material.

1.3.1 Approach
The major components of this research program are:

- evaluation of erosion mechanisms on dispersive materials to obtain a realistic measure of the tunnel erosion potential of a range of materials and to develop methods for assessing tunnel erosion risk;
- evaluation of methods for measuring susceptibility to tunnel erosion and the identification and/or development of a method that correlates strongly with both field and laboratory-measured erosion properties;
- assessment of methods for measuring dispersion; and
- investigation of methods for dealing with dispersive materials, including design/construction of new waste rock dumps, and stabilisation of existing dumps.

1.3.2 Planned outcomes and benefits

The project aimed to produce guidelines for the identification and management of spoils that are dispersive and/or susceptible to tunnel erosion, for use on mine sites throughout Australia. These guidelines will specify procedures for the measurement of dispersion and assessment of potential tunnel erosion hazards, and will outline options for the management of dispersive materials. It is expected that the development and adoption of these guidelines will greatly reduce the cost of:

- waste dump rehabilitation for some sites;
- on-going maintenance costs for some waste rock dumps; and
- off-site impacts from unstable waste rock dumps.

1.4 Contributing Mines

Mine sites that have been involved in, and have supported the project, are:

- Coppabella Coal Mine
- Higginsville Gold Mine
- St Ives Gold Mine
- Telfer Gold Mine
- Jundee Gold Mine

1.4.1 Coppabella

Operated by Australian Premium Coals Pty Ltd, the Coppabella coal mine is located approximately 10 km east of Coppabella and 39 km west of Nebo in Central Queensland. The area is in the Bowen Basin, an established grazing, farming and
coal mining region. Site clearing began on 7 July 1998, and construction and final commissioning of the mine and washplant was completed in January 1999.

Extensive deposits of Tertiary alluvium cover the lease areas, generally to a depth of 20 to 50 m. They comprise poorly consolidated clays, sands, silts and mixtures of these, with lesser gravel and unconsolidated sand towards the base. All are very soft and heavily weathered, and throughout the Bowen Basin, Tertiary spoils are recognised as posing problems with both revegetation and erosional stability.

1.4.2 Higginsville

Operated by Resolute Mining Ltd, the Higginsville gold mine is located approximately 70 km north of Norseman and 110 km south-south east of Kalgoorlie. It is now undergoing rehabilitation following completion of mining. Closure plans for the palaeochannels have been completed and submitted to the Department of Mineral and Petroleum Resources (MPR) for approval.

Following remnant cyclone activity in 1999 it was determined that the Higginsville Palaeochannel waste dumps were unstable and susceptible to erosion. Studies undertaken indicated that erosion and instability were likely to continue due to construction practices and the dispersive nature of some waste dump materials. It was determined that long term management options were needed for mine closure along with a better understanding of the mechanisms driving dump instability.

1.4.3 St Ives Gold Mine

St Ives is located 80 km south of Kalgoorlie and 20 km south of Kambalda, near Lake Lefroy in the Eastern Goldfields region of Western Australia. In December 2001, Gold Fields acquired the St Ives and Agnew gold mining operations in Western Australia from WMC Resources Limited.

At St Ives, excavation of a palaeochannel area is occurring in one of the pits, leading to concerns that, although waste dumps are sheeted with rock and then topsoiled, there may be potential for tunnelling to develop below the rock, leading to instability over the longer term.

1.4.4 Telfer Gold Mine

The Telfer mine is located approximately 450 km East of Port Headland in northern Western Australia. Operated by Newcrest Mining Ltd, it has produced in excess of five million ounces of gold since 1977 and has a current quoted resource of 18 million in situ ounces of gold and 667,000 tonnes copper.

Following a feasibility study, work has commenced on an expansion project. The Telfer expansion is expected to cost approximately $1.0B. Construction commenced in October 2002 and should be completed within 2 years. Annualised production is expected to be 800,000 oz gold and 30,000 t copper for over 20 years with higher production expected in the early years.
Although much of the siltstone material excavated to date appears to be relatively stable, there are indications that the materials that will be predominantly excavated during expansion of the pit will be less stable.

1.4.5 Jundee Operation

Newmont Australia’s Jundee operation is located in the Yandal Goldfield of Western Australia, 590 km northeast of Perth, and approximately 193 km north from the township of Leinster. Jundee, the largest of the Yandal operations, began production in 1995. It comprises a complex of open pits that are approaching depletion and an underground mine accessed through a decline with its portal in the Main Pit. A number of small satellite pits are planned in the future. (Information from the Newmont web site.)

The Jundee operation has a number of waste dumps that are visibly affected by gullying. In at least some instances, gullying has been triggered by tunnel erosion of berms, with the failed berm directing concentrated flows onto lower batter slopes. The situation is exacerbated by the potential for such failures to cascade downslope when 40 m high slopes are constructed as a series of lifts and berms.
2. METHODS

2.1 Site Inspection

An initial inspection of the original 4 mines was carried out in August-September 2002, after commencement of the project. The inspection assessed tunnel erosion occurrence on the mines, and identified materials suitable for sampling and study.

2.1.1 Coppabella

Waste rock dumps at this site showed not only considerable tunnelling, but also a very distinctive pattern. On waste rock dump slopes, tunnels and intake holes were numerous, with the presence of numerous transverse cracks on the slopes providing intake points for tunnelling to develop (Figure 4).

Tunnels were relatively small (generally <0.5 m diameter). In some cases, rills were almost certainly the result of collapse of small tunnels. Of greatest concern was the observation of cracking in the base of those rills, with indications of a new generation of tunnels being formed below the first.

Figure 4: Transverse cracking (left), and numerous tunnel outlets on a waste dump slope (right) at Coppabella (300 mm steel rule shown to demonstrate the relatively small tunnels formed)

2.1.2 Higginsville

Erosion observed at Higginsville is distinctive for:

- large gullies formed by collapse of tunnels (Figure 5)
- tunnels being less numerous, but much larger than at Coppabella
- intake points for flow to enter and/or initiate tunnels being largely restricted to dump tops and berms (Figure 5). The latter is particularly interesting as the berms at Coppabella actually showed very few intake points.
2.1.3 St Ives Gold Mine

Inspection of the site identified a number of recently excavated materials that exhibit tunnelling potential, with small intake holes and tunnels being evident (Figure 7). However, in general, the materials inspected had not been placed in large enough quantities and had not been exposed to rainfall and runoff for long enough to enable comprehensive assessment of their susceptibility to tunnelling.

**Figure 5:** Large size of a gully formed by collapse of a tunnel, and intake points along a berm at Higginsville

**Figure 7:** Indications of tunnel erosion potential in spoils at St Ives, with intake hole(s) in brown spoil (left) and a small tunnel with collapse points in a white spoil (right).
2.1.4 Telfer Gold Mine

For Telfer, the issue seems to be distinctly one of “sink-hole” development on any flat, water trapping surfaces (Figure 8), probably indicating that there has not yet been time for tunnels to develop.

![Figure 8: A sink-hole on a waste dump top at Telfer, including a crack around the intake hole due to subsidence](image)

2.1.5 Jundee

Inspection of Gourdis waste rock dumps from the Newmont Jundee Operation (July 2003) identified gullies formed from tunnelling, typically associated with berm structures on the dumps (Figure 6).

![Figure 6: Gully formed by collapse of a tunnel from berms on Gourdis waste rock dump, Newmont Jundee Operations](image)
2.2 Sampling and sample selection

At each mine, up to 10 samples were taken of a range of materials to cover the full range of spoils present.

Those initial samples were analysed, and 5 samples per site were then selected for detailed study on the basis of both field observations of erosion and material properties. The aim of sample selection was to ensure that:

(a) the samples studied were of significance to the mine site from which they were taken (representing a significant proportion of total spoil excavated); and

(b) the samples selected gave the widest possible coverage of material chemical and physical properties.

Sample nomenclature was as follows:

Coppabella     CPS
Higginsville    HVS
Jundee    JDS
St Ives Gold Mine   SIS
Telfer     TFS

2.3 Material Characterisation

Measurements were conducted on all samples collected from the original 4 mines to identify a smaller number of samples for further testing. Soil Electrical Conductivity (EC), pH, exchangeable cations, Exchangeable Sodium Percentage (ESP) and particle size distribution (categorised as clay, silt, fine sand and coarse sand) were measured for each material. Clay mineralogy characterisations have been conducted on the spoil materials from the original 4 mines by basic X-ray diffraction (XRD) for clay minerals using orientated aggregates and Mg/glycerol solvation.

Detailed information on material properties is given in Appendix 2.

2.4 Assessment of Rates of Erosion

First employed by Williams et al (2002), digital photogrammetry was used to assess volumes of erosion gullies formed from tunnels on the Higginsville and Jundee mines. The system is best suited for slopes with little vegetation cover that causes obscurement regions of the slope. It is preferable to have photographs taken as close to perpendicular to the slope to remove problems associated with extreme changes in aspect within the image.

From the length of time for which the dumps were constructed and the volumes of the gullies, erosion rates were estimated and parameters for the SIBERIA landform evolution model can be calculated. The estimated erosion rates can also be compared to other erodibility measurements for validation purposes using models such as the Water Erosion Prediction Program (WEPP) and SIBERIA.
2.4.1 Acquisition of images

Gullies on four of the existing waste dumps at the Resolute Higginsville Operation were photographed in July 2003. The gullies selected were all considered to have been initiated by tunnel erosion with remnant or collapsed tunnel sections visible on most sites.

Close range terrestrial photogrammetry was used. Images were obtained using a Kodak Pro 14n camera fitted with a Nikkon 60 mm lens. This lens/camera combination can provide accuracy of up to 1 mm, when images are taken from a distance of 10 m or less. Stereo digital pairs of photographs were taken with known camera locations at close range (<100 m) from the surface of interest. At least one control point was positioned to appear within each image. Camera and control point position locations were obtained using a theodolite.

Tilt was minimised via the use of a spirit level positioned on top of the camera. Convergence angles were maintained at approximately 8 to 10 degrees, where possible, to enhance the accuracy of data obtained from the images.

Three digital stereo pairs of images were obtained from each site, employing slightly different views and different aperture settings and shutter speeds. This was done to ensure suitable images were obtained for processing.

Large gullies, which could not be captured in an image set, were divided into sections. The largest gully had a total of four sets of images taken in an attempt to achieve complete coverage of the gully.

Data acquisition was efficient with a total of 7 gullies photographed within 2 days in the field.

2.4.2 Data processing and analysis

The resulting stereo digital pairs of images were processed using the SIRO3D (Mapper3D) software developed by CSIRO’s Division of Mining and Exploration. SIRO3D produces a three-dimensional model of the mine site dump wall.

The software requires the position of both camera locations and a control point in the photo. Combined with image data, the software then uses triangulation to determine a mass of 3D points (CSIRO, 2000). This model is presented in SIRO3D as a point ‘cloud’ of X, Y and Z values. To create this ‘cloud’, pixel by pixel matching between the two images needs to be performed. The greater the matching the more accurate the final 3D data will be.

During data processing, a number of difficulties were encountered in achieving high level matching between the stereo pairs of images. Complex gully morphology excluded large areas of gullies hidden behind gully walls. Low slope gradients within an image and extreme changes in perspective between images led to matching failure.
A number of processing techniques were used to minimise the effects of these factors, including:

- Images were sectioned into segments in which high levels of matching could be achieved (uniform planes present in both images) using the SIRO3D software’s irregular area feature and then ‘mosaicked’ back together. ‘Mosaicking’ was by far the most common processing technique employed;
- String matching, where individual points are matched manually, was used on areas of images where automated matching failed;
- Data were processed to remove outliers.

Although these practices were effective in improving the quality of the data obtained, they also significantly increased processing time.

Once data of a sufficiently high quality were obtained for each of the sites, analysis was undertaken to determine volumes of spoil lost due to erosion. Data analysis capabilities in SIRO3D are limited and data were therefore exported as XYZ files into ArcView GIS for analysis.

ArcView created 3D representations of the data ‘cloud’, interpolating areas without data through a Triangulated Irregular Network (TIN).

Volumes for each of the sections of gullies were determined using the cut and fill feature contained in the ArcView Spatial Analyst extension.

The volume calculations – together with estimates of gully frequency – were used to determine approximate erosion rates experienced for three of the waste dumps at Higginsville.

2.5 Testing for Dispersion (Emerson test) (AS 1289.3.8.1 – 1997)

The Emerson test (Emerson 1967) initially measures both slaking and spontaneous dispersion of an air-dry soil aggregate immersed in excess water. If spontaneous dispersion is “slight to nil”, the soil is remoulded at near maximum field water content, and dispersion is again observed. Finally, if soil does not disperse after remoulding, the soil is shaken in water.

This test does not allow for high salinity materials, encountered in measurements on some mine spoils, particularly those of marine origin. If the salt content of a material is very high, then spontaneous dispersion may not occur, even when immersed in excess water. Higginsville samples appeared to be affected by this phenomenon, and to refine the selection of the freshly extracted pit samples supplied by Higginsville mine, their Emerson test results were reassessed (Figures 9 and 10) following leaching of the material (using short leaching columns, see section 2.5). Following application of 500mL (equivalent to 60mm depth) of deionised water, samples were dried and the leached samples put through Emerson tests.
2.6 Testing Tunnel Erosion Potential – Leaching Columns

Short leaching columns (Figure 11) were used to assess sample hydraulic conductivity and the extent to which leaching of soluble salts reduces the stability of the surface layer of each material. The short leaching columns used a soil layer 10mm deep with 40mm depth of water ponded above it. Leachate depth, leachate sediment loads and soil and leachate EC were measured at 50 to 100 mL leachate output intervals (intervals based on infiltration rates) to assess changes in infiltration rate through time and in response to amounts of leaching of soluble salts from the sample.
Long leaching columns (Figure 12) were used to assess both sample hydraulic conductivity and potential for tunnel generation. The long leaching columns used a soil layer of 100mm depth, with 300mm depth of water ponded above it. Infiltration rates, leachate EC and total sediment in leachate were measured at 50 to 100 mL leachate output intervals.

Soil layers for these columns typically formed a seal that reduced water movement through the soil layer. The impact of shrinkage cracks on the tunnel erosion potential of samples that formed a strong surface seal was then assessed by drying samples and then ponding water on them again.
2.7 **Testing Tunnel Erosion Potential – Pinhole Tests** *(AS 1289.3.8.3 – 1997)*

The Pinhole Test (AS 1289.3.8.3) applies mechanical energy to the sample via water flow through a pinhole of 1.07mm diameter (Schafer 1978) placed in a compacted soil specimen. Distilled water is passed through the pinhole, with an initial mean velocity 0.4 to 0.8 m/s, and measurements are taken of the water turbidity and flow rates exiting the pinhole. Visual inspection (Figure 13) of the pinhole is carried out after testing is complete (Schafer 1978). Dispersive clay soils produce turbid water with a rapidly eroding hole, whereas non-dispersive clay soils result in clear water at the outlet and little change in pinhole size (Sherard *et al.* 1976).
2.8 Testing Erodibility (Rill Parameters)

Rill erosion measurements were conducted on 750mm long plots on initial slopes of 17% and 34%. Plot surfaces were compacted and then pre-wetted (light spray to wet surface and initiate runoff) 2 hours prior to rill flow applications. Flows (using deionised water, EC = 0) were concentrated on the centre of the plots to initiate a rill line and measure sediment loads and rill flow characteristics (width and depth of flow, Figure 14). These data were then used to generate rill erosion parameters ($K_R$ = rill erodibility, $\tau_c$ = critical shear) for each of the materials.
2.9 Testing Management Options (Gypsum, Compaction)

Gypsum applications were tested on 2 materials from Coppabella (CPS1 and CPS5). These samples were selected for testing as CPS1 varied greatly in behaviour to the other four samples during testing and CPS5 provided the highest sediment loads in leachate during earlier testing.

Application rates equivalent to 5, 10 and 20 t/ha of gypsum were thoroughly mixed into 100 mm deep samples of spoil. Treated samples and a control sample were then assessed using the long leaching column tests measuring infiltration rates, leachate Electrical Conductivity (EC) and sediment concentrations in the leachate. Bulk densities were kept constant during this test.

To test long-term persistence of gypsum effects, a total of approximately 1900 mm depth of deionised water was leached through samples with 5 t/ha gypsum before the reduction in soil EC caused by the leaching resulted in some dispersion, indicated by the leachate becoming cloudy due to the presence of dispersed material. (In agriculture, gypsum applications commonly need to be repeated a number of times before soil Exchangeable Sodium Percentage (ESP) is reduced to a level such that the soil remains stable).

Compaction trials were conducted using long leaching columns for all materials supplied by Telfer. Two levels of compaction were applied to each material, consisting of:

1. loosely placing the material to a depth of 100 mm, and
2. heavily compacting material to a depth of 100 mm.

Bulk density of the variously compacted materials was measured, and then an initial leaching trial was run over 24 hours to assess infiltration rates and leachate sediment levels.
3. RESULTS

3.1 Material Properties

Detailed information on material chemical, physical, and mineralogical parameters is shown in Appendix 2.

Broadly, the materials susceptible to tunnel erosion, that were selected for study, fall into three main groups:

- (a) non-saline sodic
- (b) saline sodic
- (c) non-saline, non-sodic, silty

These groups have distinctly different patterns of tunnel erosion under field conditions and thus will have quite different management requirements.

The Coppabella materials are largely non-saline and sodic. They are relatively sandy, and consist primarily of quartz and a small proportion of kaolinite minerals. Of the samples from Coppabella, CPS3, CPS5, CPS6 and CPS7 behaved similarly throughout testing, with measured dispersion controlled by their sodicity. CPS5 and CPS7 were spoil samples with differing EC levels. Samples CPS3 and CPS6 were both topsoil samples, though CPS3 has a lower clay content and lower ESP level than CPS6. The clay mineralogy of all Coppabella materials was very similar, with illite present only as a trace in the spoils, and not present at all in topsoils.

CPS1 differed from the other Coppabella materials as it tunnelled via a combination of dispersion (due to sodic clay) and liquefaction (movement of fine sand and silt sized particles through the soil mass forming tunnel pathways). This may be due to the presence of a trace of smectite (swelling clay) that the other Coppabella materials did not contain.

The Higginsville and St Ives samples are largely saline and sodic. This is to be expected for paleochannel materials in an environment where high salt levels are common in subsoils.

The predominantly clay materials from Higginsville contain various levels of quartz, kaolinite and smectite minerals. The smectite component in some of these materials caused high levels of swelling during testing (especially HVS16 and HVS17) followed by shrinkage upon drying. This swelling and shrinking cycle forms cracks, which appear to be a major pathway for water to move through these materials and initiate tunnels. (Dispersive clays, when wet, can be highly impermeable, and without water movement, tunnel formation is impossible.)

All St Ives materials are highly sodic and saline, with salinity levels varying considerably. Initial Emerson tests indicated that SIS4 was dispersive and had the highest level of smectite in its mineralogy. This material was observed in the field to have a strong crust with minimal erosion over the surface but also weak cohesion beneath the crust with voids (tunnels) present adjacent to rocks in the waste dump.
SIS8 was markedly different from the other materials, being primarily a sandy material (higher quartz mineralogy).

The Telfer samples are non-saline and have relatively low sodicity. Initial particle instability was only observed in samples with the highest ESP (only 7%). The mineralogy of these materials consisted primarily of quartz, kaolinite and illite, with no trace of swelling smectites. The tunnelling characteristics associated with this material are driven by liquefaction within the soil structure.

### 3.2 Tunnel Erosion Rates, Higginsville

The following tables (Table 1 and Table 2) summarise the results obtained for the sites at Higginsville. A total of three gullies produced representations accurate enough for volumes to be calculated. As these gullies were representative of the range of gully sizes present at Higginsville, it was possible to estimate total erosion experienced on the dumps.

If a soil dry bulk density of 1.3 g/cc is assumed, then gully volumes shown in Table 2 equate to erosion rates (on batter slopes, NOT relative to total dump area), of:

- Challenge East (rehabilitated 1996-7) 97.5 t/ha/y
- Challenge West (rehabilitated 1996-7) 86 t/ha/y
- Mitchell (rehabilitated 1999) 53 t/ha/y

The actual erosion rates estimated are based on gully data only, with rilling and unexposed tunnels not taken into account, so actual total erosion rates may well be 20-30 t/ha/y higher than the estimate based on gullies alone. The lower erosion rate estimated for the most recent dump may indicate that that dump is of lower erodibility. It may also be due to erosion by tunnelling taking time (potentially up to several years) to develop into exposed (visible) tunnel-gullies. It is also possible that rainfall during the life of the dumps may have been higher in the 1996-1999 period. As well, allowing for one or two non-eroding years after each dump was formed reduces the difference in observed erosion rates between the dumps.

One other possibility is that erosion rates may actually increase through time, with large, open gullies producing higher erosion rates than tunnels at a relatively early stage of development.

The data for Higginsville is reasonably consistent with data from other sites. For example, one waste dump/tailings dam in the northern WA goldfields region (a site that also had tunnelling present) was estimated to have rates of erosion varying from 33-250 t/ha/y on its batter slopes, depending on berm failures, etc. (There was evidence of some tunnelling at that site.) Rates of erosion of 20-100 t/ha/y appear (in Landloch’s experience) to be reasonably common on unstable waste dump outer slopes in the WA Goldfields, even for situations where tunnel erosion is not present.

However, although the measured erosion rates are not unduly high relative to other sites in the area, there remains the issue that gullies in dispersive material will not armour or stabilise over the long term, whereas in other materials, a significant reduction in erosion through time could be expected.
<table>
<thead>
<tr>
<th>Waste Dump</th>
<th>Face</th>
<th>Site</th>
<th>Description</th>
<th>Representation</th>
<th>Volume (m³)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pluto East</td>
<td>East</td>
<td>HG1</td>
<td>Small Gully</td>
<td>Good</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Neptune East</td>
<td>East</td>
<td>HG2a</td>
<td>Large Gully - Right Arm</td>
<td>Good</td>
<td>428</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HG2b</td>
<td>Large Gully - Left Arm</td>
<td>Fair</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HG2c</td>
<td>Large Gully – Central Section</td>
<td>Fair</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neptune East</td>
<td>East</td>
<td>HG3</td>
<td>Rilled slope</td>
<td>Good</td>
<td>N/A</td>
<td>Not used in analysis</td>
</tr>
<tr>
<td>Mitchell</td>
<td>East</td>
<td>HG4</td>
<td>Medium Gully</td>
<td>Good</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>HG5</td>
<td>Rilled Slope</td>
<td>Not available</td>
<td>N/A</td>
<td>Matching not achieved</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>HG6a</td>
<td>Medium gully – lower section</td>
<td>Not Available</td>
<td>N/A</td>
<td>Matching not achieved</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>HG6b</td>
<td>Medium gully – top section</td>
<td>Not Available</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturn West</td>
<td>North-East Corner</td>
<td>HG7a</td>
<td>Large Gully – Right side</td>
<td>Not Available</td>
<td>N/A</td>
<td>Incomplete Processing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HG7b</td>
<td>Large Gully – Left Side</td>
<td>Not Available</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HG7c</td>
<td>Large Gully – Top Section</td>
<td>Not Available</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Summary of gully/slope representations obtained through photogrammetry.
**Table 2:** Gully frequencies and estimated erosion rates

<table>
<thead>
<tr>
<th>DUMP</th>
<th>GULLY SIZE</th>
<th>NUMBER</th>
<th>TOTAL NUMBER</th>
<th>APPROXIMATE TOTAL VOLUME SPOIL LOST (m³)</th>
<th>DUMP BASE (km)</th>
<th>DUMP AREA (ha)</th>
<th>NOTES FROM TRACEY SIMPSON (RESOLUTE MINING)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Challenge East</strong></td>
<td>Large</td>
<td>1</td>
<td>1</td>
<td>3944</td>
<td>7</td>
<td>88</td>
<td>Waste dump rehabilitated from 1994 (limited) to 1999 from N to S. The majority during 1996 and 1997.</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>8</td>
<td>16</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>small</td>
<td>251</td>
<td>279</td>
<td>609</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Challenge West</strong></td>
<td>large</td>
<td>2</td>
<td>2</td>
<td>2624</td>
<td>4.5</td>
<td>66</td>
<td>Waste dump rehabilitated from 1996 to 1997 from N to S.</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>2</td>
<td>12</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>small</td>
<td>114</td>
<td>149</td>
<td>482</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mitchell</strong></td>
<td>large</td>
<td>0</td>
<td>0</td>
<td>246</td>
<td>2.45</td>
<td>15</td>
<td>Waste dump rehabilitated 1999</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>small</td>
<td>10</td>
<td>24</td>
<td>243</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gullies defined as:
- **large**: cross-section >5 sq. metres
- **medium**: cross-section 2-5 sq. metres
- **small**: cross-section <2 sq. metres

Small rills were not included in estimates of gully volume
3.3 Dispersion Measurements (Emerson Test data (AS 1289.3.8.1 – 1997))

Emerson results are included in the material data shown in Appendix 2.

The majority of materials selected for study were shown to be dispersive by the Emerson Test, with the exception of the Telfer samples.

However, the sample selection process demonstrated a weakness of the Emerson Test. Initial samples from Higginsville were taken from the waste dumps and Emerson Test data showed the materials to be highly dispersive. Subsequent bulk samples were sourced from the pit. The pit samples had generally higher salinity than samples of the same material taken from the waste dumps, and Emerson testing of the pit samples showed them to be non-dispersive. This contrast between the results is due to the high salinity of the pit samples preventing dispersion in the relatively small volume of water used in the Emerson Test. Following a small amount of leaching of these materials, their salinity was reduced, and the majority of materials changed from stable (slaking but no dispersion) to unstable (spontaneous dispersion) after leaching (Appendix 2, Table 3).

3.4 Tunnelling Measurements Using Columns

3.4.1 Short leaching columns

Short columns were used to assess the leaching and infiltration rates exhibited by the surface layer of materials collected. Considerable difference was observed between the behaviour of the non-saline and saline materials (Appendix 3, Tables 1 and 2 respectively).

Infiltration rates of the non-saline, sodic materials from Coppabella were high throughout testing for 4 of the 5 samples (CPS3, CPS5, CPS6 and CPS7), whereas CPS1 rapidly formed a seal that allowed very little leachate to pass through. The leachate of all of these materials was highly turbid and dominated by dispersed clay, although leachate sediment loads were not high (mass of dispersed clay is low).

There was little variation in infiltration rates between the non-saline, non-sodic Telfer samples during short column tests (all rates considered “moderate”). The leachate of these materials contained both clay and silt that had been leached out of the soil.

There was a distinct difference between one of the Jundee samples compared to the behaviour of the others. Sample JDS4, a red material used as topsoil in the Gourdis waste rock dump areas, was characterised by a moderate steady infiltration rate (20 to 30 mm/h) and relatively low levels of sediment in the leachate (0.4 to 0.9 g/L). The other materials were characterised by sealing, severely reducing the flow through material and moderate to high sediment concentration in the leachate passed through the materials.

Infiltration through the saline, sodic materials from Higginsville and St Ives varied greatly across the samples, although the typical pattern was initially high levels of infiltration and leaching leading to dispersion in the materials once EC had
decreased. This caused the materials to seal. Leachate sediment load was
-dominated by leached salt (leachate EC ranged from 10 mS/cm to 90 mS/cm to
produce apparent sediment loads of 7 to 86 g/L). Little to no sediment was visible in
the majority of leachate from Higginsville and St Ives samples during the short
column leaching tests. The high levels of calcium in sample SIS1 may have enabled
this material to maintain a consistently high infiltration rate during testing.

3.4.2 Long leaching columns

Long leaching columns were used to assess infiltration rates and tunnel development
potential in a greater depth of material than the short leaching columns. Similar to
the short column tests, there were differences between samples in measured
infiltration rates. Infiltration rates through the non-saline, sodic materials
(Coppabella) were consistent across the 4 repetitions for each material (except
CPS1). Half of the tests conducted on CPS1 had the tendency to seal, allowing very
little leachate to pass through the sample or to form a small tunnel (allowing some
material through before clogging and sealing occurred). The other Coppabella
materials produced initially high infiltration rates with lower constant infiltration rate
attained further into the trial (example CPS6 and CPS7 – Figure 14).

![Figure 14: Infiltration rates through time for Coppabella samples CPS6 and CPS7.](image-url)
Sediment produced from the long leaching columns on the Coppabella materials ranged from 0.6 g/L from CPS3 (high movement of water through material) to 20 g/L from CPS5, which caused the material to seal/clog during the test.

Infiltration rates through the non-saline, non-sodic materials from Telfer were consistent across the 4 repetitions of each sample. Samples TFS2 and TFS6 demonstrated the lowest levels of sediment loss during testing, with lower rates of infiltration than the other samples (Table 3). These materials initially tested as more stable (Emerson result of 8 and 6 respectively) than TFS4 or TFS7 (Emerson rating of 2). Sample TFS5 was also more stable than TFS4 and TFS7 according to initial dispersion tests, but produced greater sediment losses. The considerably higher infiltration rate (and associated higher velocities of water movement through the sample) displayed by this material may have contributed to its increased sediment loss.

Table 3: Infiltration rate and sediment loss for the initial 150mm depth of leachate on uncompacted Telfer samples.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Infiltration rate (mm/h)</th>
<th>Sediment Loss (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFS2</td>
<td>10.01</td>
<td>2.80</td>
</tr>
<tr>
<td>TFS4</td>
<td>15.70</td>
<td>14.02</td>
</tr>
<tr>
<td>TFS5</td>
<td>25.84</td>
<td>10.48</td>
</tr>
<tr>
<td>TFS6</td>
<td>7.82</td>
<td>3.24</td>
</tr>
<tr>
<td>TFS7</td>
<td>15.96</td>
<td>9.40</td>
</tr>
</tbody>
</table>

Infiltration rates through the non-saline, sodic materials from Jundee had a large degree of variation. The only sample that provided consistent results was JDS4 that maintained a moderate infiltration rate (steady infiltration rate ~8 mm/h) throughout the test. The variation for the other Jundee materials was similar to that experienced in the short leaching column trials with a seal or blockage of flow forming in most of the tests and any resultant leachate producing similar sediment loads to that of the short leaching columns.

Infiltration rate through the saline, sodic materials from Higginsville and St Ives mines was restricted in many of the long column tests by the formation of a seal within the sample. Leaching and subsequent dispersion of the surface layer results in the pores being blocked and flow through the soil being prevented. Swelling clays identified as a component of many of these materials contributed to the blockage of pores.

A further assessment was conducted on all of the materials that experienced reduced infiltration rates due to sealing/swelling. These materials display shrink/swell characteristics (shrinking on drying) leading to cracking (Figure 16). Repeated drying cycles were conducted on all Higginsville samples and samples SIS1, SIS2, SIS4 and SIS5 from St Ives to generate cracking through the depth of the material tested.
Three drying cycles were applied to these materials to generate an observed flow path, resulting in tunnel failure in up to 50% of the replicates from each material.

Figure 16: Cracking of the surface layer following drying of a swelling clay sample (SIS5) in long leaching columns.

3.5 Pinhole Tests (AS 1289.3.8.3 – 1997)

Pinhole tests were conducted on each material (3 replicates) to assess the resistance to tunnel formation following the generation of a potential flow path (pinhole) in the material. Results of the pinhole testing (Appendix 4) demonstrate the instability of most of the materials collected for this project. A rating of D1 and D2 indicates a dispersive material (D1 – highly dispersive), while ratings of PD1 and PD2 indicate potentially dispersive and ND1 and ND2 indicate stable (non dispersive) materials (ND1 – very stable).

The highly saline clay-rich materials from Higginsville and St Ives mines provided the greatest variations in pinhole test results. The localised leaching around the pinhole during testing reduces the influence of salinity on the dispersion/failure of the samples during testing. This lessens the salinity impacts noted for the Emerson Test. The reduced influence of salinity was observed in many of the materials tested. Sample HVS16 provided the most stable test result (D2 or ND2) of the Higginsville materials and was also the least dispersive following Emerson and leaching tests (refer to section 3.3). Samples SIS2 and SIS5 from St Ives consisted of very cohesive clay aggregates that required a large force to break down. These materials produced stable results through pinhole testing (ND2). The major tunnelling feature observed for these materials, in the field and during testing, was associated with water movement between large stable aggregates. The remaining Higginsville and St Ives samples demonstrated reasonably high instability during testing.
The pinhole test was originally designed to assess the dispersion failure of clay-rich materials. The main mode of failure was expected to be clay dispersion, allowing soil around the pinhole to be removed by flow through it.

However, during pinhole testing, materials with low cohesive strength (sandy and silty materials) demonstrated the importance of liquefaction as a mechanism for tunnel formation in these materials. All materials with low clay contents and/or low cohesive strength (Coppabella, Jundee and Telfer samples and SIS8 from St Ives) gave rapid failures, producing predominantly D1 ratings.

### 3.6 Rill Erodibility

Rill erodibility was measured for all materials (Appendix 5).

As tunnels are initiated by what are effectively sub-surface rills, and later collapse to form gullies that are open to the surface, it was thought that rill erodibility information could be a useful indicator of the potential for tunnel formation on the various materials.

The rill parameters measured were critical shear for rilling to commence (usually referred to as $\tau_c$) and rill erodibility ($K_R$), which is a measure of the rate of detachment of sediment in a rill. High susceptibility to rilling is associated with low values of $\tau_c$ and high values of $K_R$.

Variability between materials was observed to closely correlate with clay mineralogy and material properties. The presence of a coarse rock component in many samples from Coppabella, Jundee and Telfer also produced some variation between similar materials.

#### 3.6.1 Coppabella samples

The sandy materials from Coppabella provided little resistance to erosion in most cases. This resulted in the rapid development of a deep, well defined rill and undercutting of the rill sidewalls over time for samples CPS3, CPS5, CPS6 and CPS7. Collapsing of sidewalls provided pulses of high sediment concentration in runoff. The higher measured critical shear of CPS3 and CPS7 was due to the presence of organic matter (including roots) in CPS3 (a topsoil material) and rock in CPS7.

#### 3.6.2 Higginsville samples

Rill testing on materials from Higginsville showed two differing patterns of erosion. Samples HVS13, and HVS18 rapidly formed well defined rills, with additional rill sidewall undercutting and scour points down the rills. Samples HVS15, HVS16 and HVS17 eroded primarily through scour points on the surface without forming a defined rill – indicative of a strong surface seal and a high critical shear value (often associated with dispersive materials) although sample HVS16 had a very low critical shear (0.2 Pa) possibly associated with a combination of rilling and scouring observed on this material. Samples HVS16 and HVS17 contained higher levels of
smectite and some swelling was observed following the pre-wetting phase and after
the testing was completed. The shrinkage cracks and surface seal generated on
these plots contributed to the pattern of rilling or scouring observed during rill
erodibility testing with overland flow and erosion directed down cracks on the plots.
Sample HVS13 produced the weakest surface crust with little swell-shrink of the
material (no smectite present) and rapidly produced a deep narrow rill (high rill
erodibility).

The measured values for the Higginsville materials were applied to the WEPP model
using a climate file for the Kalgoorlie area from 1995 to 1999 (inclusive). For each
material; the measured values for rill erodibility were used, an interrill erodibility of $2 \times 10^6$ kg.s/m$^4$ was based on WEPP values for clayey materials and the effective
hydraulic conductivity ($h_{eff}$) was based on the approximate infiltration rates from short
leaching column data. The infiltration rates were applied at approximately 25mm
infiltration depth, with HVS15 measuring very high, HVS moderate, HVS16 and
HVS18 low and HVS17 very low compared to each other. A 10 m rill spacing was
used in WEPP to simulate rilling/gullying at a reasonable spacing as WEPP lacks the
ability to simulate tunnelling. Average annual sediment yield produced from WEPP
modelling (Table 4) is similar to rates based on digital photogrammetry (refer to
section 3.2) with these results an average of all of the materials over each waste rock
dump:

<table>
<thead>
<tr>
<th>Location</th>
<th>Sediment Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Challenge East (rehabilitated 1996-7)</td>
<td>97.5 t/ha/y</td>
</tr>
<tr>
<td>Challenge West (rehabilitated 1996-7)</td>
<td>86 t/ha/y</td>
</tr>
<tr>
<td>Mitchell (rehabilitated 1999)</td>
<td>53 t/ha/y</td>
</tr>
</tbody>
</table>

**Table 4: WEPP simulation results from Higginsville sample data.**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$K_i$ (kg.s/m$^4$)</th>
<th>$K_r$ (s/m)</th>
<th>$\tau_{uc}$ (Pa)</th>
<th>$h_{eff}$ (mm/h)</th>
<th>Sediment Yield (t/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVS13</td>
<td>$2 \times 10^6$</td>
<td>0.0062</td>
<td>6.5</td>
<td>13.8</td>
<td>116.4</td>
</tr>
<tr>
<td>HVS15</td>
<td>$2 \times 10^6$</td>
<td>0.0035</td>
<td>5.2</td>
<td>90</td>
<td>40.0</td>
</tr>
<tr>
<td>HVS16</td>
<td>$2 \times 10^6$</td>
<td>0.00049</td>
<td>0.2</td>
<td>1.0</td>
<td>40.7</td>
</tr>
<tr>
<td>HVS17</td>
<td>$2 \times 10^6$</td>
<td>0.00084</td>
<td>7.6</td>
<td>0.1</td>
<td>110.6</td>
</tr>
<tr>
<td>HVS18</td>
<td>$2 \times 10^6$</td>
<td>0.0042</td>
<td>12.8</td>
<td>1.0</td>
<td>135.2</td>
</tr>
</tbody>
</table>

**3.6.3 St Ives samples**

Three of the St Ives materials (SIS3, SIS4 and SIS5) were highly resistant to the
formation of rills over their surface. The formation of a strong surface crust on
samples SIS3 and SIS4 resulted in shallow flows spread across the surface. Sample
SIS5 is composed of cohesive clay that formed a resistant surface seal that
completely resisted incision. Holes that allowed movement of water into the SIS5
material, and thus led to tunnel formation, were large voids close to clods that could
not be broken down by compaction when the plots were packed. (Similar holes and
tunnelling were observed in the field.).
Rills on sample SIS8 formed rapidly and cut a deep narrow path through the material. This material is non-dispersive, and its high rate of erosion is attributed to its particle size consisting predominantly of fine sand (little cohesion within the material).

### 3.6.4 Telfer samples

The Telfer samples all behaved similarly during rill measurements. As the silty material had little cohesive strength, the flow applied to the surface formed distinct rills quite rapidly, removing fines from around the coarser rock component. Rills formed during the testing tended to cut into the surface until sufficient rock had been exposed to provide armouring to the rill bed. This then led to spreading of the flow to forming wider, rock armoured rill lines with some undercutting of the rill side walls.

### 3.6.5 Jundee samples

All Jundee samples were characterised by formation of narrow rill lines with undercutting of sidewalls. Differences between samples JDS1, JDS2 and JDS3 were largely due to varying rock content. Rills formed on JDS4 were broader than rills formed on the other materials, due to higher contents of rock and organic matter, with the rock causing flow to spread more widely. JDS5 provided little resistance to rilling, as it was a powdery silty material with little cohesive strength.

### 3.7 Tests of Management Options

#### 3.7.1 Gypsum amendment

Gypsum is normally added to soils to reduce clay dispersion by increasing soil EC and reducing ESP. Therefore, the materials most likely to respond to gypsum addition are those with low salinity and high sodicity. From that, it can be inferred that the Coppabella materials are the samples most likely to show a useful response to gypsum.

Gypsum applications (application rates of 5, 10 and 20 t/ha) were tested on two materials from Coppabella: CPS1 and CPS5. CPS5 was selected for the gypsum trial as it provided the highest leachate sediment loads during earlier long column testing and was similar to CPS3, CPS6 and CPS7 in behaviour. Gypsum applications were very effective in reducing tunnel erosion experienced by Coppabella sample CPS5. Gypsum application increased the infiltration rate of sample CPS5 by up to five times that of an untreated sample and produced leachate containing no dispersed clay (Figure 17).

CPS1 was selected due to its unique behaviour amongst the Coppabella samples. Tunnelling exhibited by CPS1 is at least partly due to liquefaction failure rather than dispersion (CPS1 is predominantly a fine sand). Gypsum applications on CPS1 had no apparent effect on tunnel development. The long leaching column tests showed that 25% to 50% of all samples failed due to tunnelling regardless of the gypsum quantities applied. Surface sealing and tunnelling of this material is largely due to its low structural strength and the high mobility of the very fine sand component when wetted. Therefore, addition of gypsum and improvement in clay stability could be expected to have little effect on the overall stability of this material. It can also be
inferred that gypsum would likewise have minimal effect on other materials with similar characteristics (e.g. Telfer samples with low clay content and high fine sand/silt content).

![Figure 17: CPS5 gypsum trial – 5 t/ha application on left (column 12), no gypsum applied to samples on right (producing dirty leachate).](image)

To test long-term persistence of gypsum effects, water was leached through the samples of CPS5 that had received the equivalent of 5 t/ha gypsum until some dispersion occurred. This was indicated by the leachate becoming cloudy due to the presence of dispersed material. A total of approximately 1900 mm depth of water was required before the reduction in soil EC caused by the leaching resulted in dispersion.

3.6.2 Compaction

For materials that form tunnels due to liquefaction rather than to clay dispersion, the addition of gypsum (as noted above) is unlikely to offer any benefit. However, any treatment that reduced the rate of water penetration is likely to reduce or prevent tunnel formation. For that reason, compaction was tested on the non-saline, non-sodic materials from Telfer.

Compaction considerably reduced infiltration rates and soil loss (Table 5) for all Telfer samples except sample TFS2, which was the most stable material according to initial tests (Emerson rating of 8). Sample TFS2 showed a considerable decrease in its infiltration rate due to compaction, but little variation in total sediment lost in leachate.

The considerably higher “final” or 24 hour infiltration rates associated with many of the loosely packed materials were a result of some tunnel development in the leaching columns. The majority of these tunnels were blocked by sediment transported during the initial very high flow rates during tunnel development. Initial
leachate sediment loads for some loosely packed samples were up to 40g/L (initial sediment load was measured from the first 400mL of leachate produced during testing) (Figure 18). Coarser particles can move into and block small tunnels, occasionally forming a slumped area on the surface.

**Table 5: Effects of compaction on infiltration rate and sediment loss - Telfer materials.**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Treatment</th>
<th>Dry Bulk Density (t/m³)</th>
<th>Initial Infiltration rate (mm/h)</th>
<th>24 hour infiltration rate (mm/h)</th>
<th>Sediment Loss (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFS2</td>
<td>loose</td>
<td>1.34</td>
<td>16</td>
<td>14.5</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>compacted</td>
<td>1.71</td>
<td></td>
<td>0.9</td>
<td>1.3</td>
</tr>
<tr>
<td>TFS4</td>
<td>loose</td>
<td>1.38</td>
<td>138</td>
<td>24.3</td>
<td>13.8</td>
</tr>
<tr>
<td></td>
<td>compacted</td>
<td>1.68</td>
<td></td>
<td>2.2</td>
<td>0.2</td>
</tr>
<tr>
<td>TFS5</td>
<td>loose</td>
<td>1.33</td>
<td>555</td>
<td>56.7</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>compacted</td>
<td>1.66</td>
<td></td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>TFS6</td>
<td>loose</td>
<td>1.33</td>
<td>19</td>
<td>11.3</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>compacted</td>
<td>1.65</td>
<td></td>
<td>1.2</td>
<td>0.2</td>
</tr>
<tr>
<td>TFS7</td>
<td>loose</td>
<td>1.30</td>
<td>2377</td>
<td>21.8</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>compacted</td>
<td>1.56</td>
<td></td>
<td>1.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>

A Infiltration rates for compacted samples were only taken over a 24 hour period as initial rates were too low to measure.  
B Infiltration rate for 24 hour period for uncompacted material is measured up to a maximum of 500mm of leachate depth applied and sediment loss is calculated from this.

**Figure 18: TFS4 compaction trial – uncompacted sample on left (leachate sediment load in bottle 4.7g/L), heavily compacted sample on right (no leachate when picture taken).**
4. DISCUSSION

4.1 Assessment of the “Success” or Failure of Test Methods

The development of laboratory tests of soil chemical parameters has relied on correlation between some test result and measured soil responses or behaviour in the field. For example, tests of soil fertility are typically correlated with measured fertilizer responses. Fundamental to that approach is an expectation that a quantitative test result will have some mathematical relationship (neither necessarily linear nor precise) with a quantifiable field soil behaviour or response.

Experience in this project indicates that that approach is not appropriate in this case.

Firstly, tests of dispersion or of tunnelling potential do not provide a quantitative result. In general, the tests provide a rating, with the test developer providing an assessment of which ratings indicate a high risk of tunnelling or dispersion, and which ratings carry a low risk. (Generally there is an intermediate area of considerable uncertainty.)

Secondly, a quantitative measure of tunnel erosion potential would not, on its own, be completely useful. As this project has shown (see following section), there are two distinctly different mechanisms by which tunnel erosion develops, with each mechanism having quite different requirements for prevention of tunnelling. Equally, there are at least three quite different types of material that are at risk of tunnelling, and the management requirements of each material type will be quite different. For that reason, there is a need for information on both the magnitude of risk and the type of risk.

Thirdly, considerable difficulties in developing a quantitative ranking of tunnel erosion potential on the basis of field observations became obvious very early in the project. It was observed that:

- the degree of tunnel development was strongly influenced by waste dump design;
- differences in length of exposure to rainfall and runoff and in the quantities of spoil placed at given locations introduced enormous variations in observed response; and
- tunnel development is extremely difficult to assess in the short to medium term, as tunnels are not clearly visible until the roof of the tunnel collapses and the full magnitude of the underlying void becomes visible.

For these reasons, the more standard research approach resting heavily on statistics to “prove” test functionality is not possible in this case.

Rather, the following analysis has relied heavily on understanding of processes, and on logical application of knowledge with respect to fundamental processes of soil behaviour.
4.2  **Mechanisms of Tunnelling**

Water flow through a soil or spoil is an essential component of the tunnel erosion process. However, to remove significant quantities of soil and initiate a tunnel generally requires the high rates of water movement that are carried by a preferential flow path, especially if the material is dispersed and highly impermeable.

Therefore, the two essential components of tunnel initiation are:

(a) high rates of water movement, generally through a preferential flow path; and

(b) a material that is sufficiently unstable for the preferential flow paths to be able to detach and remove significant quantities of that material (usually particles fine enough to be transported through pores without blocking them).

Because pore blockage does occur, the particles able to be removed from the soil during tunnel initiation are typically quite small – clay or silt sized – unless the initial pores are very large.

4.2.1  Preferential flow paths

Water movement through materials containing dispersive clay will form preferential flow paths as the water transports the dispersive clay elsewhere. Provided the permeability of the material is sufficient to minimise pore blockages, the continued removal of dispersed clay will gradually increase the rate of flow through the preferential flow path and generate tunnel failures.

Soils containing clay that swells on wetting may undergo surface cracking as they shrink when drying. When rewetted, these surface cracks can provide preferential flow paths into the material if the swelling process is too slow. Water flow through these cracks can then move soil particles (especially if dispersive clays are present) and/or expose unstable underlying material.

Soil with rapid infiltration rates (high permeability) can allow the movement of fine soil particles within the soil mass. This allows the development of larger pore spaces and flow paths if left unblocked. Combined with blockage of alternate starting flow paths, preferential flow will develop in the unblocked paths. Fine sand and silt dominated materials with poor soil cohesion were observed to develop these preferential flow paths.

Contributing to the size and occurrence of preferential flow paths that lead to tunnel development are:

a) Water ponding (structures or depressions capturing surface runoff), thereby increasing the quantity of water that infiltrates at a point. This increases not only the rate of water movement through the pores but also the total volume of water that is moved. (Effectively, the volume of water infiltrating at a point may be increased by several orders of magnitude as a result of a water-collecting structure.) Infiltration of ponded water also dramatically increases potential
leaching of salts, thereby greatly increasing the potential for a stable saline-sodic material to become non-saline and dispersive. Waste dump design, by its impact on flow paths, concentration of flows, and residence times of runoff, can have a dramatic impact on this component of the tunnel erosion process.

b) The seasonality of the prevailing environment, which will influence wetting-drying and swelling-shrinking cycles, thereby affecting the exposure and degradation of unstable subsurface material to tunnel generating mechanisms. (Prolonged ponding of water, by increasing surface water contents, can also promote cracking on drying.)

c) The spatial variability of the material in a waste dump, which can cause zones of high infiltration surrounded by zones with lower infiltration, increasing the potential for the high infiltration zone to form a significant preferential flow area.

4.2.2 Susceptibility to detachment by flow

Following the development of a preferential flow path within a material, tunnels will only develop if the flow is able to detach and remove particles from the walls of the pore in which it flows.

Detachment of particles can occur as a consequence of wetting if there is dispersive clay present. Wetting to saturation will cause dispersed clay to be released into solution, where it will move with the flow. Because the clay particles are extremely fine, they can move readily through the spoil with (relatively) little potential to block pores.

Detachment of particles can also occur readily in non-dispersive materials in situations where the s(p)oil mass has extremely low cohesive strength. Low cohesive strength will be favoured under conditions of:

(a) saturation; and
(b) materials high in silt or sand.

Positive pore pressures drastically reduce cohesion in any soil or spoil, and tunnels have been observed in even quite coarse sands in situations where sub-surface flows create saturated conditions and significant rates of flow (Figure 19). Generally, however, tunnelling in non-cohesive materials is restricted to materials high in fine particles (silt or fine sand sized), simply because those finer particles are more easily moved and less likely to block pores. However, it should be borne in mind that tunnelling in non-cohesive materials is strongly favoured by saturation and positive pore pressures, and therefore, management of surface water flows and durations of ponding is extremely important; again indicating the importance of waste dump design.
Figure 19: Tunnel in coarse granitic sand underlying a bitumen road, resulting from positive pore pressures associated with accumulation of sub-surface flow at a low point.

Silt and sand–sized particles carry little net charge, and therefore do not have potential for the particles to bond together and be cohesive, whereas clay particles can carry considerable charge and can be quite cohesive as a result.

The important difference between the detachment mechanisms is that clay dispersion is quite sensitive to soil/spoil chemical properties, whereas liquefaction of a non-cohesive material is not.

4.3 Testing to Predict Tunnelling Potential of a Material

4.3.1 Emerson test (AS 1289.3.8.1 – 1997)

The Emerson test provides a rapid identification of soils that disperse spontaneously in water (Emerson rating of 1 or 2). Materials with these ratings are particularly susceptible to tunnelling.

However, this method only considers the stability of a material “as tested”. Materials with very high salt content (and high EC) (e.g., spoils from Higginsville and St Ives) may not spontaneously disperse even when immersed in excess water, as their high salt content will prevent dispersion (see Section 2, Figure 8). However, with time, leaching of the soil by rainfall and ponded water may sufficiently reduce the EC of the soil solution that spontaneous dispersion in water can occur. Therefore, the Emerson test does not identify materials with strong potential to develop tunnelling behaviour if they have associated high EC levels.
To account for effects of high EC, sample EC should be assessed as part of standard testing procedure. If EC is high, both dispersion and EC should be reassessed following leaching of the material.

The Emerson test is also unable to identify materials susceptible to tunnelling for which the dominant mechanism is liquefaction rather than dispersion. Results from Emerson testing must be compared against soil solution and structural data to determine a material's potential to tunnel.

There may also be a procedural problem with the Emerson test, in that it specifies selection of aggregates for testing, yet in some materials the aggregates present are relatively stable and it is the finer sized particles not held in aggregates that are dispersive. Effectively, the method – if followed accurately – can ignore the very part of the sample that is most important.

4.3.2 Leaching column tests

Leaching column tests provide a measure of the changes in hydraulic conductivity (permeability) and migration of salts and soil particles that are likely to occur in the surface of a soil or spoil exposed to rainfall and runoff.

The permeability (pore and particle size distribution) and cohesive nature (presence of clay) of materials will also influence the movement and removal of soil particles. As particles of soil are repositioned, the hydraulic conductivity is affected by the blocking, or creation, of preferential flow paths. Leaching columns provide an indication of the levels of particle movement likely to occur within the soil structure. A severe reduction in hydraulic conductivity provides a guide to particle movement within a material (either dispersed clay or silt/sand movement), as it indicates a large-scale blockage of pores within the soil. Soil particle removal is also measured during leaching column tests via leachate sediment loads. To predict the tunnelling potential of a material, leaching tests provide a good indication of soil migration and thus the potential for development of preferential flow paths.

Leaching columns also provide a rapid indication of the influence of management practices, such as gypsum applications or compaction, on potentially tunnelling material. The trials of gypsum application on Coppabella samples CPS1 and CPS5 and compaction tests on Telfer samples provided information on the changes to infiltration rates and leachate quality under these management practices. Long-term assessment can also be conducted via continued application of water (continued leaching testing), and the influence of drying and cracking on swelling-shrinking materials can be assessed.

The leaching column tests provided a very variable result for some materials. The uniformity of flow was a principal factor in this variability. Speed of water flow through a material determines the rate at which dispersed clay can exit the soil structure or the movement of fine particles (silt and fine sand) within the soil structure.
4.3.3 Pinhole test (AS 1289.3.8.3 – 1997)

In the pinhole test, mechanical energy is applied to the sample via water flow through a small hole (pinhole 1.07 mm diameter, Schafer 1978) placed in a compacted soil specimen. Deionised water is passed through the pinhole, with an initial head of 50 mm (equivalent mean velocity 0.4 to 0.8 m/s), and measurements are taken of the water turbidity and flow rates exiting the pinhole. A measurement of the final size of the pinhole is carried out after testing is complete and measured as a ratio against the initial pinhole size. The pinhole test is specifically designed to identify dispersive soils susceptible to tunnelling. Dispersive clay soils produce turbid water with a rapidly eroding hole, whereas non-dispersive clay soils result in clear water at the outlet and little change in pinhole size (Sherard et al. 1976).

On predominantly clay materials tested from both Higginsville (all samples) and St Ives (SIS1, SIS2, SIS4 and SIS5) mine sites, the pinhole test produced reliable results. The high salinity of these materials had limited impact during the test, as salt in the soil around the pinhole was rapidly leached out, allowing the final dispersive potential of the materials to be demonstrated during testing.

On the low clay materials from Coppabella, Telfer, Jundee and St Ives (SIS8), the pinhole test demonstrated that these materials had low cohesion. There was little differentiation between these materials, with initial water flows easily removing soil surrounding the pinhole, increasing its size. This resulted in accelerated flow rates and erosion producing turbid water at the outlet. Samples containing dispersive clays (primarily Coppabella samples) typically failed rapidly with all of the soil exposed to water flow removed easily. The pinhole test generally proved difficult to carry out with materials prone to liquefaction (primarily Telfer samples as well as CPS1 from Coppabella), as soil around the pinhole tended to collapse on wetting and sealed the hole. Once flow was generated through the liquefaction prone materials, their failure followed a similar pattern to that of samples high in dispersive clay.

The pinhole test provides an assessment of a wider range of materials and failure mechanisms than do tests of dispersion, and appears to have considerable merit as a measure of tunnelling potential.

4.3.4 Erodibility test

The erodibility measurements were designed to provide an indication of the potential for continued development of tunnels (and tunnel gullies). Erodibility measurements did not appear to assist in predicting initiation of tunnelling for any material, although a low resistance to rill initiation was common in materials that tunnel. Low critical shear is due to a combination of dispersion (particularly Coppabella and Higginsville samples), poor structural strength (particularly Coppabella, Jundee and Telfer samples) and low levels of coarse material (rocks) required to provide an armour on the eroding surface (particularly Higginsville samples).

Low erosion resistance will lead to high rates of sediment removal once a tunnel has formed, thereby increasing the rate of tunnel development. Following the slumping/collapse of the surface above a tunnel, the low erosion resistance will allow rapid development of gullying in the slumped/collapsed region.

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4.4 Testing protocol

Because of the range of mechanisms by which tunnel erosion develops, there is no single test that will provide optimal information across the entire range of materials considered. Rather, it appears that initial assessment of soil chemical and physical data is required, followed by specific tests to assess the specific tunnel erosion mechanism indicated by material properties. Initial soil/spoil parameters that provide information on tunnel erosion potential are:

i) EC (to assess potential salinity impacts on dispersion);
ii) Cations, with particular emphasis on exchangeable sodium percentage (ESP) to assess dispersion potential;
iii) Particle size distribution (to provide an indication of soil cohesion and liquefaction contributions to tunnel formation/failure), and
iv) Clay mineralogy (for swelling influence).

4.4.1 Testing tunnelling risk

Based on the data obtained, a judgment can be made on which of the following tests is most appropriate. Figure 20 indicates the testing required to determine the presence of Potentially Tunnel Generating Material (PTGM) from a spoil sample. The occurrence of tunnel erosion on a site containing a PTGM will depend on preferential flow path development, with contributions from waste dump design, material particle size distribution and clay mineralogy and site seasonality.

The Emerson dispersion test will provide a quick assessment of the presence of spontaneously dispersive material, and is most appropriate for samples of high ESP and low EC. The influence of EC must be taken into account for material that does not test as spontaneously dispersive, especially saline materials. Leaching can be applied to materials that are not spontaneously dispersive to assess the impact of EC reduction within the material. This measurement is critical for any material that may have water ponded on it at some point in the landscape. Material that is spontaneously dispersive without leaching applied will be prone to tunnel formation. Material that is spontaneously dispersive after some leaching will need to have its EC managed to avoid the hazard of tunnelling associated with spontaneously dispersive materials.

Pinhole tests provide a very good indication of tunnelling following the development of preferential flow paths. The test provides data on a material’s resistance to tunnel development. As potentially tunnelling material tends to be heterogenous, a minimum of 3 repetitions of the test should be conducted on the material to determine the potential tunnelling risk associated with the material. The pinhole test is suitable for dispersive materials of high and low salt content, and also for samples that tunnel by liquefaction, though those latter materials will create some difficulties during analysis.

Leaching of extremely saline materials may be necessary for Emerson and pinhole testing to assess the influence of a material’s salt content on dispersion and tunnelling potential.
**Figure 20: Flow Chart to determine the presence of PTGM.**

- **LOW** (<1 mS/cm)
  - **EC**
  - **HIGH** (>1 mS/cm)
    - **No Dispersion**
      - **LEACH and EMERSON TEST\(^A\)**
      - **No Dispersion**
        - **ES**
          - **HIGH** (ESP > 5%)\(^B\)
            - **PTGM: SALINE, SODIC MATERIAL**
          - **LOW** (ESP < 5%)
            - **PTGM: saline, non-sodic material (additional testing required)\(^C\)**
    - **Spontaneous Dispersion**
      - **EC**
      - **LOW** (<1 mS/cm)
        - **ESP**
          - **HIGH** (ESP > 5%)
            - **PTGM: NON-SALINE, SODIC MATERIAL**
          - **LOW** (ESP < 5%)
            - **PTGM: non-saline, non-sodic material (additional testing required)\(^C\)**

**PINHOLE TEST**
- **STABLE** (ND1, ND2 ratings)
  - **Non-PTGM**
- **UNSTABLE** (D1, D2, PD1, PD2 ratings)
  - **PTGM: LIQUEFACTION MATERIAL\(^B\)**

\(^A\) Leach the soil sample (short column) to reduce soil EC, then reapply an Emerson test to the leached sample.

\(^B\) PTGM liquefaction materials may also include saline sodic materials that have indicated stability during other testing due to very high salinity.

\(^C\) These results are not typical. Additional tests are necessary to determine why dispersion is present in these low sodicity materials.
4.4.2 Estimating potential tunnelling severity of a given material

Tunnelling severity is heavily dependent on the development of flow paths and on the extent that flow concentration occurs within a potentially tunnel generating material. The assessment of the potential severity of tunnelling for a material needs to include;

- Waste rock dump design – water shedding (e.g. batter slopes) and water ponding (e.g. dump top and berm structures) components will provide different mechanisms for potential failures.
- Site seasonality – exposure to rainfall and runoff for a particular material influence the rate of tunnelling as well as drying cycles influence the susceptibility of a material to rapid tunnelling upon rewetting (especially for shrinking-swelling materials).
- Material erodibility – provides an indication of potentially tunnelling materials resistance to concentrated flows following tunnel and tunnel-gully development.

For the non-saline, sodic materials from Coppabella and Jundee, the long leaching columns were occasionally erratic with seal formation relatively common. Leachate generated by 4 of the Coppabella materials (CPS3, CPS5, CPS6 and CPS7) was typically only dispersed clay that creates turbid leachate with low sediment loads. Sample CPS1 was identified as different from the other Coppabella samples as it was inclined to fail through a combination of dispersion and liquefaction. During long column testing of this material it either failed catastrophically with a small tunnel forming (figure 21) or a sealed up. The initial watering caused 1 of the 4 replicates to fail with a second 1 failing after drying and a second wetting cycle. Erodibility testing of the Coppabella materials indicated very little erosion resistance (low critical shear, mostly 3-6 Pa, and high rill erodibility, >0.0012 s/m), which was evident from observations of surface rilling on the site. Low erosion resistance of these materials increases the potential for tunnelling to escalate to generate severe tunnel erosion and/or gullies.

![Figure 21: Tunnel formed in long column test of a replicate of CPS1.](image)
The Jundee materials were more erratic than the Coppabella samples with many sealing before leachate was produced. Sample JDS4 was distinctly different than the other 4 samples from Jundee as it was used as a topsoil material to cover the other spoils. This sample had a moderate infiltration rate (~7mm/h) with low sediment loads (0.5 g of soil lost by 150 mm leachate depth). The tunnel potential of this material is associated with its weak structure and it will erode rapidly if a preferential flow path develops through or on it (low erosion resistance from erodibility tests). The leachate that was produced by the few replicates of samples JDS1, JDS2, JDS3 and JDS5 that did not seal contained some sediment, but their reproducibility is suspect. Seasonality may have an important influence on many of these materials with the presence of swelling clays and poor erosion resistance contributing to tunnel formation and increasing tunnel development especially in areas of increased water ponding and flow concentration (e.g. berms).

The long leaching columns were effective in assessing the potential severity of tunnelling for the non-saline, non-sodic materials from Telfer (silty, liquefaction prone materials). These tests provided an indication of the potential for tunnelling, with variations observed between each material. Three of the samples (TFS4, TFS5 and TFS7) resulted in a very rapid flow rate through the column, resulting in higher sediment loads within the leachate. Silt percentage within these materials was the highest for any of the samples, and 2 of the 3 proved the least stable during Emerson testing of all Telfer samples (Emerson test result of 2). These materials would be highly susceptible to the formation of tunnels that would cause collapse and sink hole or gully development. The remaining 2 materials contained lower levels of silt and had higher stability under Emerson testing. The reduced rates of flow and soil loss through these samples would significantly reduce the potential for them to initiate the tunnelling process as well as reducing sinkhole development. Rill erodibility of the Telfer materials was strongly influenced by the presence of rocky material to provide some armouring and by the high silt content being highly mobile. This suggests that rock fragments may have some stabilising effect on the floor of a tunnel but may not reduce the development of sink-holes which are a major component of tunnelling failures associated with this material.

For certain materials, leaching columns are possibly too time consuming and somewhat erratic in their results to be routinely used to assess tunnel potential. Materials susceptible to crust formation and pore blockage were the most erratic, as infiltration and leachate measurements were very limited. In many of the saline, sodic materials from Higginsville and St Ives, seal formation occurred before any leachate was generated. It would be expected that shrinkage under field conditions would produce more significant cracking than that observed during leaching column tests to enable tunnel initiation. Tunnel failures were observed for some of the materials after multiple drying cycles were applied but their occurrence was typically in only 1 of 4 repetitions, limiting their reproducibility. Erodibility testing for these materials commonly resulted in patterns of scour within the rill line that are commonly associated with a dispersive, crust forming material. Scour points and undercutting of surface crusts for some of these material provides a good indication of the subsurface exposure that these materials may be subjected to during wet periods. The level of cracking and its influence on the surface of these materials provides another indication of the potential for subsurface exposure during drying and wetting cycles (seasonality). The potential for subsurface exposure combined with erodibility
measurements for these materials provides an indication of the potential severity of tunnelling.

4.5 Management of Materials Prone to Tunnelling

As noted previously, materials susceptible to tunnelling fall into three groups:

- saline sodic
- non-saline sodic
- fine, non-sodic materials of low cohesive strength

In some respects, the management requirements of each of these groups are not greatly dissimilar, but there are important differences.

4.5.1 Dump construction

**Saline sodic** materials are – at least initially – stable. Therefore, it should be acceptable to place these materials relatively close to the surface of a waste dump, provided leaching (over the long term) is limited. Leaching of salts and conversion of these materials to a non-saline sodic and dispersive condition is highly undesirable.

This means that:

(a) prolonged ponding of water at any point on the landscape should be completely avoided as it will accelerate salt leaching and tunnel formation; and

(b) deep drainage below the topsoil layer should be minimised so that salt leaching is not significant.

It is highly undesirable to have low points that will accept and store runoff from large catchment areas, and the top of the dump should be established either with a large number of relatively small cells to retain runoff relatively evenly on the surface, or with paddock dumping so that (again) any areas of ponding receive runoff from only relatively small areas. High water holding capacity in the surface layer will reduce potential deep drainage and leaching of salt. Establishment of vegetation to increase evapotranspiration and reduce deep drainage is highly desirable.

Runoff water from outer batter slopes should be moved off the landform as rapidly as possible. Level berms designed to pond water are a recipe for disaster, and large cross-slope rip lines designed to pond water are also likely to create problems.

**Non-saline sodic** materials will be susceptible to tunnel erosion as soon as they are placed on or near a waste dump surface. Options for constructing stable landforms of this type of material are limited. Where stable topsoil can be placed over the spoil, there is still potential for water draining below the topsoil to cause tunnel development. Options to avoid or minimise the potential for tunnel development in this type of material include:
(a) avoiding placing the material closer than 1 metre to the surface (if possible);
(b) placing at least 0.5 m of stable (non-cracking) topsoil over the spoil;
(c) keeping waste dump outer batter gradients very low (as low as 5% if possible), so that gravitational forces aiding tunnel formation are drastically reduced;
(d) avoiding ponding of water; and
(e) ensuring that cracks and other pathways for water to enter the spoil are minimised.

There is also potential to use gypsum to stabilise these materials. Where clay content of the spoil is low, the amounts of gypsum required per hectare may be relatively low. However, the costs of spreading and incorporating gypsum may outweigh the cost of the gypsum itself, though at (commonly) close to $100 per tonne (not including delivery costs), gypsum may be a significant cost. It is likely that at least 5t/ha of gypsum will be needed.

For non-saline, non-sodic materials of low cohesion, the major priority is to avoid prolonged ponding. Deep drainage into the spoil from an overlying topsoil layer is not of concern, provided the water moves as unsaturated flow.

Therefore, the top of the dump needs to have a stable surface layer (covering the spoil) that has high water infiltration and storage capacity, so that all rain falling on the top of the dump can move into the surface layer and be held under tension in s(p)oil pores. Minimisation of runoff is desirable, and it is essential that any low-lying areas do not receive runoff from large surrounding areas. For example, if runoff from an area of 5 ha is ponded on an area of 500 m$^2$, then the potential depth of water infiltrated in the ponded area will have been increased at that point by a factor of 100 relative to the rest of the waste dump surface. Volumes of runoff ponded at any point should be kept as small as possible.

For batter slopes, level berms to trap and pond runoff are highly undesirable. Instead, if berms are used, they should be designed to drain rapidly to stable rock drains so that the duration of ponding at any point in the system is kept to a minimum. (It should be noted that construction of stable rock drains on such materials is difficult.)

Compaction can be used to reduce water entry through these materials, but may simply result in perched water tables if used on level areas. However, there may be benefit from compacting spoil underlying topsoil in graded berms.

4.5.2 Remediation of existing dumps

Erosion data suggest that rates of erosion on dumps affected by tunnel erosion are probably similar to the higher rates recorded on eroding batter slopes of non-tunnelling material. However, the major difference between the two situations is that dispersive materials will not armour through time, so that erosion rates will remain high. In fact, data from the Higginsville site indicate that, if anything, erosion rates may increase with time. For that reason, it appears that dumps affected by tunnel erosion will require some form of remedial action if they are to be stabilised.
However, for existing dumps subject to tunnel erosion, remediation and repair appears to be difficult in some cases and often impossible.

Remediation works on dump tops are generally possible, provided the top of the dump can be accessed and suitable equipment is available. Necessary works may include filling in tunnels, compaction of re-worked areas, and addition of extra cover by topsoil.

However, for outer batter slopes, difficulty of access to berms means that, although it may be necessary – for example – to spread and incorporate gypsum, compact a loose and unstable material, or to remove unstable material and replace it with a more stable spoil, it will be virtually impossible to get suitable equipment to the location of the problem. If a mine is closed and much of its equipment decommissioned, the problems become even greater. Nor is that an unlikely scenario, as tunnel erosion may well take several years to become apparent.

This means that, for dumps drastically affected by tunnelling, the only available options appear to be either:

(a) placement of cover layer of stable material sufficiently deep to prevent further tunnel development; or
(b) long-term containment of the eroded materials.

4.6 Risk assessment

The risk of tunnels forming on a waste dump is a function of a large number of factors, including:

- susceptibility of the materials to tunnel formation
- water pathways and depth/duration of water ponding
- potential for deep drainage/ponding at depth
- batter gradients
- annual rain and seasonality of rainfall
- vegetation.

To attempt to integrate those factors, a risk assessment spreadsheet has been developed, using Fault/Event Tree methodology, with branches for each of the susceptible mine spoil types.

The initial risk assessment spreadsheet is effectively an expert system, giving weightings to different factors on the basis of scientific knowledge and experience.

An initial sensitivity analysis has carried out using the risk assessment model, and has identified some modifications that are necessary. However, for the risk assessment to be able to be applied with confidence, it needs to be validated for a wider range of sites, materials, and landforms than were available in the current project. A separate proposal detailing possible additional work to complete that validation is now being prepared.
5. CONCLUSIONS

This project has highlighted a number of important issues.

Firstly, it has shown the importance of soluble salt content in some spoils, and the need to manage salt content to maintain stability.

Secondly, the project has shown the existence of effectively two mechanisms for tunnel erosion (movement of dispersed clay and also movement of non-cohesive fine particles), where previously tunnel erosion was attributed solely to clay dispersion. This finding has been supported by considerable field observation, and means that the range of materials at risk from tunnel erosion is greater than initially believed.

Irrespective of the method by which tunnels form, the project has indicated strong interactions between the design of constructed landforms and the development of tunnel erosion. Where water is ponded over saline sodic spoil, with leaching of salt by the ponded water, results in reduced soluble salt, increased dispersion, and development of tunnel erosion. For non-cohesive materials, long durations of ponding are also a major factor in developing tunnel erosion. Although retention of rainfall and runoff water on constructed landforms is widely considered to be highly desirable, in practice there is a range of situations where ponding of water is a recipe for disaster.

Because of the range of mechanisms by which tunnel erosion develops, there is no single test that will provide optimal information across the entire range of materials considered. Rather, it appears that initial assessment of soil chemical and physical data is required, followed by specific tests to assess the specific tunnel erosion mechanism indicated by material properties. Initial soil/spoil parameters that provide information on tunnel erosion potential are:

- EC (to assess potential salinity impacts on dispersion);
- Cations, with particular emphasis on exchangeable sodium percentage (ESP) to assess dispersion potential;
- Particle size distribution (to provide an indication of soil cohesion and liquefaction contributions to tunnel formation/failure), and
- Clay mineralogy (for swelling influence).

Based on the data obtained, a judgment can be made on which tests are most appropriate.

The Emerson dispersion test will provide a quick assessment of the presence of spontaneously dispersive material, and is most appropriate for samples of high ESP and low EC. The influence of EC must be taken into account for material that does not test as spontaneously dispersive, especially saline materials.

Pinhole tests provide a very good indication of tunnelling following the development of preferential flow paths. The test provides data on a material’s resistance to tunnel development. The pinhole test is suitable for dispersive materials of high and low
salt content, and also for samples that tunnel by liquefaction, though those latter materials will create some difficulties during analysis.

Leaching column tests provide a good indication of the hydraulic conductivity for a material and potential for sealing or blockage formation on the soil surface or to depth. High hydraulic conductivity can be associated with tunnel formation or liquefaction failure of the fine sand and silt size fraction. Leaching column tests are useful on materials with a high hydraulic conductivity as the sediment load within the leachate can be measured to assess the level of fine particle movement through the soil. The occurrence of a seal or blockages is an important element to be aware of for a potentially tunnelling material as these restrictions to flow can increase the water ponding on a material, increasing the volume of flow concentration at points that a tunnel forms.

Leaching of extremely saline materials may be necessary prior to Emerson and pinhole testing to assess the influence of a material’s salt content on dispersion and tunnelling potential.

The erodibility measurements provide an indication of the potential for continued development of tunnels (and tunnel gullies). Erodibility measurements did not appear to assist in predicting initiation of tunnelling for any material, although some limited tunnelling was observed on some tests and a low resistance to rill initiation was shown for many of the samples. The combined low critical shear and rill erodibility was due to a combination of the dispersive nature of the materials (particularly Coppabella and Higginsville samples), poor structural strength (particularly Coppabella, Jundee and Telfer samples) and low levels of coarse material (rocks) required to provide an armour on the eroding surface (particularly Higginsville samples). These characteristics contributing to poor erodibilities are also factors in the initiation (dispersive and poor structural strength nature) and potential progression and severity of tunnelling when it has occurred.

Materials susceptible to tunnelling fall into three groups:

- saline sodic
- non-saline sodic
- fine, non-sodic materials of low cohesive strength

Saline sodic materials may – at least initially – be stable. Therefore, it may be acceptable to place these materials relatively close to the surface of a waste dump, provided leaching (over the long term) is limited. Leaching of salts and conversion of these materials to a non-saline sodic and dispersive condition is highly undesirable.

This means that:

(c) prolonged ponding of water at any point on the landscape should be completely avoided as it will accelerate salt leaching and tunnel formation; and

(d) deep drainage below the topsoil layer should be minimised so that salt leaching is not significant.
Non-saline sodic materials will be susceptible to tunnel erosion as soon as they are placed on or near a waste dump surface. Options for constructing stable landforms of this type of material are limited. Where a stable topsoil can be placed over the spoil, there is still potential for water draining below the topsoil to cause tunnel development. Options to avoid or minimise the potential for tunnel development in this type of material include:

(f) avoiding placing the material closer than 1 m to the surface (if possible);
(g) placing at least 0.5 m of stable (non-cracking) topsoil over the spoil;
(h) keeping waste dump outer batter gradients very low (as low as 5% if possible), so that gravitational forces aiding tunnel formation are drastically reduced;
(i) avoiding ponding of water; and
(j) ensuring that cracks and other pathways for water to enter the spoil are minimised.

There is also potential to use gypsum to stabilise these materials.

For non-saline, non-sodic materials of low cohesion, the major priority is to avoid prolonged ponding. Deep drainage into the spoil from an overlying topsoil layer is not of concern, provided the water moves as unsaturated flow.

Therefore, the top of the dump needs to have a stable surface layer (covering the spoil) that has high water infiltration and storage capacity, so that all rain falling on the top of the dump can move into the surface layer and be held under tension in soil/spoil pores. Minimisation of runoff is desirable, and it is essential that any low-lying areas do not receive runoff from large surrounding areas. Volumes of runoff ponded at any point should be kept as small as possible.

For batter slopes, level berms to trap and pond runoff are highly undesirable. Instead, if berms are used, they should be designed to drain rapidly to stable rock drains so that the duration of ponding at any point in the system is kept to a minimum.

For existing dumps subject to tunnel erosion, remediation and repair appears to be difficult in some cases and often impossible.

Work on dump tops is generally possible, provided access to the top of the dump is possible and suitable equipment is available.

However, for outer batter slopes, difficulty of access to berms means that although it may be necessary – for example – to spread and incorporate gypsum, compact a loose and unstable material, or to remove unstable material and replace it with a more stable spoil, it will be virtually impossible to get suitable equipment to the location of the problem.

The problem with existing unstable dumps is not only that erosion rates can, in some instances, be high. As well, unlike rocky materials, finer spoils susceptible to tunnel erosion are most unlikely to armour, or to have any mechanism by which erosion
would be reduced over time. Therefore, those relatively high rates of erosion can be expected to continue indefinitely.

Therefore, the importance of early diagnosis of potential tunnelling problems and adoption of strategies to prevent such long-term instability is essential for successful mine closure.
6. References


7. Acknowledgments

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APPENDIX 1: Literature Review
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1 BACKGROUND

Over the last 6 years, Landloch has been involved in numerous inspections of rehabilitated waste dumps across Queensland, Western Australia, and the Northern Territory. One factor in dump “failure” (where major erosion has occurred at points on the landform) that has consistently been observed is erosion associated with unstable, dispersive materials. The presence of such materials in waste dumps commonly results in the development of tunnel erosion, resulting in:

- failures of berms at points where tunnels develop, so that concentrated flows are discharged onto steep batter slopes below (Figure 1)
- instability of rock drains constructed over such materials
- creation of relatively unsafe landforms with, in some cases, widespread tunnels immediately below the soil surface
- development of large gullies once tunnels collapse (Figure 2)

In some areas of Australia, these unstable materials are consistently associated with erosional failures of waste dumps. Their poor physical characteristics can also lead to:

- high levels of suspended sediment in runoff that have particularly high potential to impact on regional aquatic ecosystems, and
- pronounced difficulties with the establishment of vegetation.

As well, such materials are typically low in rock, so that the gullies formed seldom armour or stabilise through time.

*Figure 1: Tunnels through berms on a waste dump, and resulting gullies on the batter slopes below*
In general, awareness of the occurrence and significance of such materials appears to be low in the mining industry. This is not aided by the lack of suitable testing protocols to identify potentially unstable materials, and by the nature of the processes involved, which can, in some cases, take years to develop and create problems.

This review has been prepared to provide basic information on:

- the dispersion process;
- tunnel erosion;
- methods currently available for measuring dispersion potential;
- existing methods for controlling tunnel erosion; and
- potential applications of existing knowledge to the mining industry.

Two terms are used throughout this review to describe spoil material. They are:

**Potentially Tunnel Generating Material (PTGM):** This term applies to all materials that may form tunnels within a structure. This includes PDM (see below) and other material susceptible to tunnel failure (for example, structurally weak material that may tunnel through water movement).

**Potentially Dispersive Material (PDM):** This term applies to material with a clay fraction that may disperse when in contact with water. Both water quality and soil EC must be taken into account as PDM is potentially dispersive through the application of low EC water solutions following a change in soil solution EC.
2 DISPERSION

2.1 Mechanisms

Dispersion occurs when the individual particles in a soil are separated from each other when excess water is supplied. Sand and silt particles > 2 micron in size exist in the soil as individual entities, whereas clay particles (< 2 microns) normally clump together in both dry and wet conditions to form aggregates. If the aggregates are large enough, they incorporate the sand and silt particles.

Soils containing high levels of exchangeable sodium are widely recognised to be particularly susceptible to dispersion. In such soils, higher numbers of single-valency sodium cations surround the negatively charged area on the surface of clay crystals. To describe the effect of exchangeable Na on soil properties, it is necessary to define the following properties of the exchange complex and the associated soil solution (Sumner 1993):

Exchangeable sodium Percentage (ESP) = \(100 \times \frac{\text{Exchangeable Na}}{\text{Cation Exchange Capacity}}\)

Or \(\text{ESP} = 100 \times \frac{\text{Exchangeable Na}}{(\text{Exchangeable Ca}+\text{Mg}+\text{K}+\text{Na}+\text{Al})}\)

Sodium Adsorption Ratio of the soil solution or irrigation water (SAR) = \(\sqrt{\frac{[\text{Na}^+]}{([\text{Ca}^{2+}]+[\text{Mg}^{2+}])/2}}\), where \([\ ]\) are concentrations of cations

If the solution or irrigation water is in equilibrium with the soil, soil ESP can be calculated from SAR using relationships available for irrigation water and soil-water extracts (Sumner 1993).

Traditionally, a soil has been called “sodic” when soil physical behaviour is adversely affected by exchangeable Na. Various “threshold” values have been used, for example an ESP of 6 in Australia and 15 in the US, based on Hydraulic Conductivity (HC) measurements. However, a single threshold is not appropriate, and the “threshold” is actually highly dependent on the Electrolyte Content (EC) of the water used for HC measurement (Sumner 1993). As Quirk (2001) states “Since the permeability of a sodium affected soil is related to the EC of an irrigation water, there is no particular physical basis for division of soils into sodic and non-sodic classes at 15% ESP—or at any other ESP (authors note). In fact, (Sumner 1993) concludes that the term “sodic” is compromised, and that the set of properties associated with these soils, for example dispersion, should be substituted since they are less ambiguous. The term “Dispersive” is more appropriate in the case of tunnel formation.

At a fine scale, clay mineral crystal layers in soils are usually closely associated with each other to form structures known for different clay minerals as “domains” or “tactoids” (Quirk 2001). In such systems, dispersion can only occur if the individual mineral layers separate.

Quirk (2001) described this system using a simple “three plate model” in which individual clay crystals overlap to a certain extent, and slit-shaped pores form within the domain or tactoid where crystals do not overlap (see Figure 3).
Figure 3: A simple 3-plane model to describe the arrangement of clay crystals in a clay domain (modified from Quirk 2001)

This model is very useful for illustrating the dispersion process, and the effect of exchangeable sodium on dispersion. When water or an electrolyte solution is added to a soil, repulsive pressures (Pr), calculated from double layer theory 1, develop over the surface area of the larger slit-shaped pores, while an attractive pressure (Pa) associated with van der Waals forces operates over the surface area of the closely-aligned crystals. Dispersive cations such as Na tend to concentrate in the slit-shaped pores (Sumner 1993), and form extensive double layers (compared to smaller double layers for cations of higher valence), particularly if the salt concentration of the soil solution is low. Thus the repulsive force can more readily exceed the attractive force in soil systems containing Na, resulting in “spontaneous dispersion” when the soil is exposed to excess water at a low electrolyte concentration. When the repulsive force is nearly as large as the attractive force, dispersion will require the input of a threshold shear stress from flowing water or raindrops (Sherard et al 1976).

In soils, most of the focus has been on the effect of ESP and EC on excessive swelling and dispersion, and on the subsequent effects on HC and crust formation on drying. Quirk and Schofield (1955) and many others since that time (Quirk 2001) have used plots of ESP against Electrolyte Concentration (EC) to define regions of stable versus reducing hydraulic conductivity or soil flocculation versus deflocculation/dispersion. They investigated the permeability of a soil to solutions of different SAR and EC. The soil was first equilibrated with concentrated solutions at a range of SARs. For each SAR, the EC of the solution was then decreased (while maintaining a constant SAR and thus maintaining a constant soil ESP) until reductions in permeability and dispersed clay in the percolate were observed.

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1 Double layer theory was developed to explain the swelling of clay pastes in solutions with different cation types and total salt concentrations. At the mid-point between clay particles, the cation concentration is the same as the bulk solution in which the particles are bathed. As we approach the clay particle, the concentration of cations increases. The thickness of the double layer depends on cation type and electrolyte concentration. Potential Double Layer thickness (and the repulsive force if solution uptake is limited) follows the order Na/K>Mg>Ca>Al, for different exchangeable cations, while potential thickness is decreased by increasing electrolyte concentration.
They defined **three** threshold electrolyte concentrations:

- **“Threshold concentration”** = “the salt concentration for a given solution SAR at which the permeability was decreased by 15%”, presumably due to excess swelling
- **“Turbidity concentration”** = “The salt concentration for a given solution SAR at which the dismantling of soil microstructure is indicated by the appearance of dispersed particles in the percolate”
- **“Flocculation concentration”** = “The salt concentration for a given solution SAR at which a dispersed soil suspension will flocculate

Quirk and Schofield found that “turbidity concentration” is approximately 25% “threshold concentration”, and about 12% of the “flocculation concentration”. This shows that dispersion and flocculation are not reversible, and that flocculation tests cannot be used to predict dispersion.

An illustrative version of an ESP-EC diagram is shown in Figure 4. The diagram shows threshold concentrations for both permeability and clay dispersion. The actual threshold values will depend on a number of factors including clay mineral type, organic matter content, other cations present, and input of mechanical energy (Sumner 1993). The principles in Figure 4, and the difference between Threshold concentration and Turbidity concentration, have significance for formation of tunnels, and this will be discussed in Section 4.

*Figure 4: A plot of Soil ESP versus EC of the equilibrium solution, showing threshold curves for decreased permeability and clay dispersion (Note: points anti-clockwise from the threshold lines represent instability: points clockwise from the threshold lines represent stability)*
2.2 Distribution of Dispersive Soils

The Australian Soil Classification (Isbell, 1996) defines Sodosols as “Soils with strong texture contrast between A horizons and sodic B horizons which are not strongly acid”. It also notes that Australia is noteworthy for the extent and variety of sodic soils. Figure 5 shows the approximate distribution of Sodosols within Australia, illustrating that they are widespread in all states except the Northern Territory.

Figure 5: Distribution of Sodosols in Australia (from “Concepts and rationale of the Australian Soil Classification, Isbell et al. 1998”)
3 DEFINITION, MORPHOLOGY, AND PROCESS OF TUNNEL EROSION

Tunnel Erosion is best defined in terms of tunnel morphology and processes of formation. Both these aspects are well illustrated in Figure 6.

![Diagram illustrating the processes of tunnelling and the morphology of tunnels](image)

**Figure 6:** Diagram illustrating the processes of tunnelling and the morphology of tunnels

Formation of a tunnel requires the following conditions:

- Free water or a positive pore water pressure at the depth of tunnel initiation.
- Areas for entry of concentrated runoff flows through the surface soil horizon. In Figure 6, water entry from the surface is via an old root line, but other mechanisms are listed later.
- Sufficient land slope to develop a hydraulic head to drive water through the soil.
- Massive failure of the soil matrix, for example clay dispersion or soil liquefaction, at this point. Tunnelling resulting from liquefaction is normally associated with materials dominated by the silt and fine sand components (typically >70%). In such materials inter-particle bonds are so weak that they are readily destroyed by flowing water when the material is wet. Moving water increases the area of weakness within the soil structure, causing tunnels and surface collapse above the tunnels. Slaking, or the breakdown of aggregates to a size commonly greater than 0.05 mm due to uneven swelling and air entrapment in macro-aggregates, is probably not sufficient to initiate tunnelling. Firstly, the micro-aggregates would tend to block the soil porosity. Secondly, sub-surface soil is usually too wet (above wilting point) to slake.
- An exit point for the tunnel where a sediment fan accumulates at the surface.

Sherard et al. (1976) note that the importance of dispersive clays was first noted by engineers in Australian investigations of failed clay dams in the early 1960s, and that the role of sodium clays in erosion of structures was recognised from the mid 1930s.
Crouch (1976) noted that in a number of surveys of tunnel erosion in soils of NSW, tunnel erosion was more common on soils high in sodium, though there were areas of dispersive soils that did not tunnel.

The need for an hydraulic gradient to aid water flows through the soil is to be expected. It is interesting to note that Lynn and Eyles (1984) reported that tunnel erosion in New Zealand occurred mainly at land gradients of 16-25 degrees, as many current rehabilitated landforms in Western Australia have batter slopes of 20 degrees gradient.

A common feature of tunnels is the occurrence of “pipes” where the surface soil collapses into the tunnel. If the collapse is extensive, a gully may form, and this form of erosion was called tunnel-gully erosion (Schafer and Tragmar 1981).

In undisturbed agricultural soils, tunnels tend to occur mainly in Duplex soils (which have a relatively sandy A-horizon overlying a clay B-horizon) and in 2 locations associated with soil cracking (Crouch 1976): The role of cracking in both surface and sub-surface layers has been widely noted. Jones (1981) notes that both clay type (swelling clays such as smectites) and clay content have associated with development of tunnel erosion. Crouch (1976) considered that seasonality of rain and loss of vegetative cover may also predispose a site to cracking and tunnel development.

- At the bottom of the A-horizon, where soil either disperses or liquefies under the influence of water at positive pressures when water ponds on the surface of the impermeable B-horizon.
- In the lower layers of the B-horizon, where similar positive pore water pressures initiates dispersion along the edges of cracks.

Tunnel erosion has long been recognised as a serious problem in agricultural soils, and research has been carried out in Australia for at least the last 50 years, particularly in Victoria (for example, Downes 1946) and NSW (Ritchie 1965). Charman (1969) identified two types of tunnel. In drier areas, the tunnel seemed to be initiated from the surface through uneven infiltration and water concentration at some point in the subsoil (inlet initiated). In wetter areas, tunnel initiation seemed to occur mainly in natural flow lines or depressions through removal of saturated clay layers along the edge of the flow line (outlet initiated). Soil cracks along the edge of the flow line or gully act as a focus for concentrated flow when the soil profile is rewet by rainfall, and the outlet of the tunnel erodes back into the subsurface layers. Examples of these two types of tunnels are shown in Fig 1 and Fig 5 of Crouch (1976).

### 3.1 Factors Involved in Initiation and Extension of Tunnel Erosion

Crouch (1976) lists a set of processes that can lead to tunnelling. They are:

- Surface cracking due to desiccation
- Rapid infiltration down the cracks, and super-saturation of a subsurface layer
- Dispersion of the super-saturated layer
- Movement of the dispersed particles in soil water due to a hydrostatic gradient that produces lateral flow. Generation of a "subsurface rill" or tunnel results from this movement. Over time and with increased flow volumes the tunnel will increase in size and may merge with other tunnels. The size of tunnels is limited by the strength of the upper layer, which will collapse once the tunnel achieves a certain size to form a tunnel-gully.

- Expansion of the tunnel inlet and outlet. Tunnel inlets typically start as small holes generated below subsurface cracks. Progressive collapse may cause this inlet point to become a large depression although the tunnel inlet size may remain small (Figure 7) depending on the volume of water concentrated at this point.

- Tunnel outlets are formed through the continued progress of tunnelling below the surface layer finding an outlet (an existing gully or point of weakness such as surface cracking). In some cases, exits form as "blowholes" resulting from the hydraulic pressure forcing its way through the surface layer at a lower point in the landscape.

![Figure 7: Collapsed and rilled area above small tunnel inlet.](image)

Crouch et al (1986) briefly reviewed the occurrence of tunnelling on a worldwide scale. Tunnelling has been observed in all climates, with wide variations in temperature, rainfall and seasonality of rainfall. There is also a wide variety of soil types, ranging from Duplex/Texture Contrast through silty loess soils to soils that are clayey throughout the profile. Clay type does not appear to be an important variable, with tunnelling occurring in soils containing both montmorillonite (highly expansive) and kaolinite.

As a result of the above variations in soil and climatic conditions, different reasons are given for tunnel formation. In general, tunnels are associated with less permeable soils, and in particular those with an impermeable layer. In such soils, a
perched water table may form above the impermeable layer. However, there are reports of tunnelling in permeable soils, associated with zones of very high permeability. The unifying concept in this case appears to be spatial variability in permeability within the soil profile. This results in preferential flow paths, allowing flow concentrations that increase the erosion/dispersion levels.

Shrinkage cracks, either at the tunnel entrance or at the tunnel outlet (see for example Charman (1969) and Crouch 1976) are common features of tunnel initiation, as are dispersive soils containing significant levels of exchangeable sodium. However, Crouch et al (1986) report situations where tunnels are not related to soil cracks, and are “outlet initiated” in permeable layers between zones of relatively impermeable, dispersive soil. An hydraulic gradient forms in the permeable material, and the tunnel erodes back from the gully edge. This example illustrates the importance of both spatial variability and availability of a tunnel exit in tunnel erosion.

Tunnels can extend the influence of erosion at inlet points by generating a feedback effect causing rill generation above the tunnel inlet. This continuing rill generation upslope of the inlet point provides an additional source for concentrating flow into the tunnel, continuing the cycle of increasing erosion rates.

Crouch et al (1986) conclude that tunnels appeared to be formed by a number of different mechanisms. However, there are a number of principles or factors involved, and these are considered in the sections below.

1) Seasonality of rainfall

In climates with distinct seasonality of rainfall, the action of drying and wetting cycles has an important effect on soil structure. Main processes affected are the slaking of soil exposed to evaporative drying and the formation and closure of shrinkage cracks. Shrinkage cracks generated by soil drying provide inlet areas for water, and expose dispersive sub-surface clays to free water. This process can initiate tunnel formation.

Floyd (1974) observed climatic conditions and tunnel formation over a 16-year period, and applied a range of treatments to control tunnelling. Referring to occurrence of tunnels over time, he stated “it is apparent that other factors, particularly rainfall, override soil and agronomic treatments”. Floyd noted that, although tunnelling was extensive in years with higher summer rainfall, it was not in particular associated with high rainfall years, nor with high winter rainfall. Floyd worked in the Riverina area of NSW, where high summer temperatures (and high soil evaporation) are associated with intense summer storms. He proposed that the extensive summer tunnelling was due to formation of shrinkage cracks, which act as foci for excess infiltration and dispersion of subsoil layers.

Crouch (1976) concluded that, although shrinkage cracks would be larger in soils containing expansive clay minerals such as montmorillonite, enough shrinkage can occur in lighter textured surface soils or in kaolinitic clays (Crouch et al 1986) to provide entry points for overland flows if desiccation is sufficient
2) Heterogeneous surface infiltration

Crouch (1976) reports the work of Downes (1946) who found that infiltration rates into the surface of tunnelling areas can vary by up to 50 times (Floyd 1974). A significant impact on the formation of tunnels in an earthwork construction or in the field is any factor allowing concentration of water and causing uneven infiltration rates into the soil. Features identified as causing a concentration of water to influence tunnel formation include:

- soil cracks formed by construction works or wetting drying cycles;
- animal burrows (rabbit burrows are mentioned significantly in many articles from NSW agricultural regions, although it is uncertain as to which came first-the tunnels or the rabbits (Floyd 1974)),
- holes from root system and rock outcropping and their removal; and
- small depressions.

Many of these features exist on mine waste dumps, with added influences caused by waste dump construction design and requirements, for example the construction of level berms. Constructions formed through the use of differing materials (particularly with differing hydraulic conductivities) on the surface may also serve to increase subsurface flow levels at certain points of the construction. Increasing infiltration rate at one point will drain the ponding water on a nearby less permeable material increasing the flow through the area of higher permeability. Floyd (1974) found tunnelling to be less severe for bank construction when graded banks were constructed, and where ponding did not occur.

3) Tunnel exits and entrances

Tunnels require a suitable exit so that mobilised sediment can continue to be removed from the tunnel. Tunnel or tunnel/gully erosion provides a localised point of high erosion rates with large shear and high flow rates removing significant levels of material. Hence, water emerging from the exit of tunnel and tunnel/gully formations is typically turbid, with a high suspended load which may be transported to local water courses. If a landscape “flattens” below a tunnel or tunnel/gully a sedimentation zone typically forms downstream due to settling of eroded material and stream flow losing potential to carry high sediment loads passing out of system. The alluvial fan produced by this provides a source of poor vegetation establishment (water and “soil” quality not amenable to growth) and a zone of highly mobile, unprotected material.

In addition, inlet points to tunnels generate a feed back effect by concentrating flow and causing rill generation above the tunnel inlet.
4) Hydraulic conductivity of subsurface horizons

Soil pore size influences the rate of movement of water through the soil structure (Rosewell 1970) (soil permeability). Higher permeability of the soil structure (due to factors such as low density, resulting from poor soil compaction in structures) will allow movement of any dispersed clay through soil and enhance erosion rates of dispersed material from the soil matrix. Increasing compaction levels to reduce the permeability of the soil structure restricts the movement of water and dispersed clay through the soil body, decreasing the severity of dispersion in the soil and restricting tunnel formation. A non-compacted dispersive layer above an impermeable layer is particularly susceptible to tunnel erosion since positive hydraulic pressures can build up in this layer (Crouch 1976).

5) Factors involved in the dispersion of soil layers subjected to water flow

Rosewell (1970) studied methods of controlling tunnelling of farm dams due to “post-construction deflocculation”. This type of tunnelling is strongly analogous to that occurring in natural soils or mine spoils, in that free water stored upstream of the dam wall is in direct contact with dispersible or potentially dispersible material in the dam wall.

The mechanisms for dam wall tunnelling are complex, and depend on a number of factors, including:

- The rate of filling of a structure (dam or in the case of mines a berm) containing potential dispersive material (PDM)
- The rate of flow of stored water through a dam wall construction material (as discussed in (4) above)
- The potential dispersibility of the material (determined largely by the ESP)
- The electrolyte content of the soil solution (which may maintain the material in a flocculated condition), and
- The electrolyte concentration in the stored water (which can maintain the electrolyte concentration in the soil material above the “turbidity concentration” defined by Quirk and Schofield (1956), and shown in Figure 4. An addition of rainwater to storages or structures decreases the stored water EC resulting in the potential for soil solution electrolyte concentration to fall below the turbidity concentration.

The way in which all these factors interact in determining the probability of tunnel formation is probably best described using Figure 8, which is a variant of Figure 4. Figure 8 shows the changes in EC and ESP in different types of spoil or soil materials and wetting rates when rainwater containing low levels of salt is added.
Figure 8: Changes in EC and ESP for different types of spoil and wetting conditions when rainwater containing low levels of salt is added (paths for situations B and C join the square box and the asterisk).

For tunnelling to occur, Rosewell (1970) concludes that two conditions must be met. Firstly, the soil must disperse into the water flowing through the soil; and secondly, the soil permeability must be great enough to ensure that any dispersed clay will pass through the soil without causing a blockage.

On this basis, Figure 8 identifies three potential situations:

1. Situation A: ESP-EC of the material in the “Dispersion” or “reduced permeability” zones, rapid wetting.
2. Situation B: ESP-EC of the material in the “Flocculation, high permeability” zone, rapid wetting.
3. Situation C: ESP-EC of the material in the “Flocculation, high permeability” zone, slow wetting.

According to Wood et al, quoted by Rosewell (1970), tunnelling will occur in situation A if permeability of the material is greater than about 4 mm/hr. If permeability is less than this value, the spontaneously dispersed clay will be trapped as a “gel” structure within the soil pores. For situations B and C, the probability of tunnelling depends also on the rate of wetting of the material, and the chances that the soil will become dispersive. When water permeates through material with relatively high EC, salt is leached out. If wetting is rapid, EC will be reduced as shown for situation B in Figure
8, and the soil will enter the “Dispersion” zone. This explains the failure of earth
dams when they are rapidly filled by rainfall runoff.

In situation C, if wetting and reduction in EC is slow, ESP will also reduce slowly as
the soil equilibrates with the flowing water. More importantly, if the soil crosses the
“threshold concentration” permeability will be decreased and salt leaching may stop.
In this situation, the soil may never enter the “Dispersion” zone, and tunnelling will
not occur. In this situation, Swelling and dispersive clays may inhibit tunnelling due
to restrictions in pore spacing caused by swelling of the soil structure. If the rate of
swelling exceeds the rate of dispersive erosion through small tunnels, the flow path is
cut off preventing further erosion. If the rate of swelling is slower than the removal of
clay through the generating tunnels, the tunnel system can progress and may be
exacerbated by the restriction in other areas of the soil mass diverting flow to the
developing tunnel spacing.

4 IDENTIFICATION OF SPOILS SUSCEPTIBLE TO TUNNELLING

Dispersion tests are the most useful laboratory tests for identifying the susceptibility
of a soil to tunnelling, though it should be noted that tunnel formation is not entirely
confined to dispersive materials. The three main types of dispersion test are:

- Emerson test (AS 1289.3.8.1 – 1997)
- Pinhole test (AS 1289.3.8.3 – 1997)
- Dispersion Index test

The Emerson test (Emerson 1967) initially measures both slaking and spontaneous
dispersion of an air-dry soil aggregate immersed in excess water. If spontaneous
dispersion is “slight to nil”, the soil is remoulded at near maximum field water content,
and dispersion is again observed. Finally, if soil does not disperse after remoulding,
the soil is shaken in water.

Soils that disperse spontaneously are susceptible to tunnelling, and are responsible
for dam failure by “piping”.

In the Pinhole Test the mechanical input is via water flow through a small hole
(pinhole 1.07mm diameter, Schafer 1978) placed in a compacted soil specimen.
Distilled water is passed through the pinhole, with an initial mean velocity 0.4 to 0.8
m/s, and measurements are taken of the water turbidity and flow rates exiting the
pinhole. Visual inspection of the pinhole is carried out after testing is complete
(Schafer 1978). The Pinhole test is specifically designed to identify dispersive soils
susceptible to tunnelling. Dispersive clay soils produce turbid water with a rapidly
eroding hole, whereas non-dispersive clay soils result in clear water at the outlet and
little change in pinhole size (Sherard et al. 1976).

The Dispersion Index test has been widely used in Australia in the detection of soils
susceptible to tunnelling, and applies mechanical energy through end-over end
shaking. Soil is shaken in distilled water for 2 hrs, and the % particles < 2 micron (A)
is measured. This % is compared with the % particles < 2 micron (B) measured after
the soil has been shaken with dispersant, and clay dispersion is considered
complete. The Dispersion Index is calculated as the ratio (B/A). Ritchie (1965)
classified soils with DI<3 as “susceptible to tunnelling”. This classification is the same as that used by the Soil Conservation Service in the USA. They used a Dispersion Ratio, calculated as (A/B), and set a threshold value of DR at > 0.33.

Ritchie’s (1965) classification was confirmed by further field studies (Charman 1969). All soil layers that showed tunnelling in the field had a DI<3. However, not all soils with DI<3 exhibited tunnelling, and this confirms that a range of climatic and site factors, in addition to soil dispersion (as indicated in Section 3), are involved in tunnel initiation.

5 CONTROL OF TUNNELLING IN AGRICULTURAL SOILS

There are three basic strategies available to control the initiation and expansion of tunnels. They are:

1. Reducing the amount of water that flows onto and accumulates on areas of PTGM material

Hosking (1967), quoted by Crouch (1976) concluded that the only practical way of preventing tunnel development was to divert water away from the catchment areas of the tunnels. In similar vein, Floyd (1974) recommends that, if an area of non-susceptible soils occurs upslope of a tunneled area, banks and gully control structures should be built on the stable soil to divert water safely away from dispersible soils.

Floyd specifically recommends that “care should be taken not to build extensive bank systems, especially level absorption banks, on dispersive soils”. This comment is particularly significant for the construction of level berms on mine waste dumps.

2. Compacting the soil that is susceptible to dispersion or tunnelling to reduce the rate of water flow.

Pore spacing and degree of compaction are obviously interrelated. Higher compaction rates reduce the volume and continuity of pore spaces within the soil structure. Dispersive soils need a volume of pore space around clay particles to allow water contact with the dispersive clay components, continuity of pore spaces to allow mechanical dispersion to remove dispersed material and allow cleaner water to enter allowing further dispersion. Reducing the pore space and continuity of pore spaces reduces the potential for dispersion to occur and reduces the rate that water can remove dispersed material from the soil structure. Low levels of compaction allow dispersion to occur and assist in the removal of dispersed clay in solution from the soil structure. Large pore space with high continuity of pore spaces allow more rapid movement of water through the soil structure increasing the rate of removal of dispersive material, rapidly increasing the size of pores through the soil structure and accelerating the growth of tunnels and internal erosion of the soil structure.

Ritchie (1965) studied the effect of compaction methods on tunnelling failure of farm dams. Materials were compacted to dry densities of 0.8-1.5 t/m$^3$, and 100% dam failure was noted at a density of 0.8 t/m$^3$. Rosewell (1970) found that tunnelling
failure in PDM can be prevented by compaction of the earthwork to 85% of the Proctor maximum. This represented a dry density of about 1.5 t/m$^3$. This is beyond the compaction capacity of a crawler tractor. For non-dispersive materials compaction to 70-75% of Proctor maximum should be sufficient, and this is readily obtained using conventional earthwork construction techniques.

3. **Use of chemical amendments so that the soil is less dispersive (to reduce the potential for a PDM to disperse).**

One standard technique for the reclamation of Sodic Soils (Sumner 1993) is to reduce or remove the exchangeable sodium. There are many strategies available, but most concentrate on two approaches:

i) Increase or maintain electrolyte concentration of soil so that the soil remains in the flocculated region shown in Figures 4 and 7. Once this is achieved, the EC of the leaching water is slowly reduced so that both ESP and EC of the soil are reduced, ensuring that the ESP/EC combination for the soil remains in the flocculated region. In this way, the ESP of the soil may be reduced to near zero while maintaining the soil in a flocculated condition. This is known as the **high salt water dilution technique**.

ii) Addition of beneficial ions (normally Ca) to replace Na in the exchange complex. In this approach, two types of strategies can be used:

- Addition of more soluble Ca sources such as Gypsum to increase Ca concentrations in the soil solution
- Addition of acidifying agents such as elemental sulphur, sulphuric acid, iron pyrites or acid dairy whey to the soil to mobilise soil Ca in soils containing lime

By-product gypsum is moderately soluble, compared with mined gypsum or lime which are probably too insoluble to supply Ca at a sufficient rate for soil amelioration. However, in clay soils in particular, very large amounts of gypsum would be required to remove all the exchangeable sodium, and the price of by-product gypsum at $85/tonne probably means that this approach is not feasible in most agricultural situations.

Alternatively, Ca amendments may be used mainly to increase the EC of the soil solution, and this requires much smaller amounts of gypsum. For the control of tunnelling in agricultural soils Floyd (1974) recommended gypsum application rates of 4-16 t/ha, incorporated to the depth of potential tunnelling. The amount of gypsum required to maintain the soil in a flocculated condition will depend on exchangeable Mg, ESP and dispersion index. Alternatively, Rosewell (1970) recommended the incorporation of 2% hydrated lime in dispersive material to be used in construction of earth-wall dams.
6 RELEVANT REFERENCES


## APPENDIX 2: Material Characteristics

**Table 1:** Soil properties of samples collected on original site inspections (materials in blue selected for complete tunnelling potential testing)

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<tr>
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<th>pH</th>
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<th>ESP (%)</th>
<th>Ca:Na</th>
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Table 2: Higginsville pit materials EC data, Emerson Test (ET) results and description based on texture and similarity to original dump samples (materials in blue selected for complete tunnelling potential testing)

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<th>Post-leach ET</th>
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<td>orange-yellow material - similar to HVS14</td>
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<td>1</td>
<td>red(pink)-white material - very similar colour and structure to HVS9</td>
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<td>1</td>
<td>orange material - similar colour and structure to HVS3</td>
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<td>HVS15</td>
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<td>1</td>
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Table 3: Field texture and mineralogical composition of received samples (prepared by UWA Centre for Land Rehabilitation)

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<td>Clayey sand</td>
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<td>&lt;5</td>
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</tr>
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<td>CPS 7</td>
<td>Clayey sand</td>
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*Iron oxides include haematite and goethite.
### APPENDIX 3: Leaching Column Data

**Table 1:** Short leaching column data for Coppabella, Jundee and Telfer (low salinity materials).

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Table 2: Short leaching column data for Higginsville and St Ives (high salinity materials).

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<td></td>
<td>12.06</td>
<td>9 165</td>
<td>2.22</td>
<td>51 405</td>
<td>37.5</td>
</tr>
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<td>76 995</td>
<td>0.12</td>
<td>87 900</td>
<td>77.0</td>
</tr>
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<td>SIS5</td>
<td>6.90</td>
<td>16 380</td>
<td>1.52</td>
<td>20 906</td>
<td>45.5</td>
</tr>
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<td></td>
<td>12.59</td>
<td>23 160</td>
<td>3.00</td>
<td>10 494</td>
<td>33.2</td>
</tr>
<tr>
<td>SIS8</td>
<td>6.7</td>
<td>285</td>
<td>85.0</td>
<td>23 958</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>840</td>
<td>38.5</td>
<td>19 553</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>24.2</td>
<td>6 180</td>
<td>7.8</td>
<td>12 105</td>
<td>12.0</td>
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<td></td>
<td>38.5</td>
<td>86 505</td>
<td>0.6</td>
<td>10 058</td>
<td>6.8</td>
</tr>
</tbody>
</table>

A Sediment concentration includes leached salt
Table 3: Long leaching column sediment data for Coppabella, Jundee and Telfer samples (Higginsville and St Ives produced no measurable sediment data due to extensive sealing of samples).

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>BD (g/cc)</th>
<th>Leachate depth (mm)</th>
<th>Steady infiltration (mm/hr)</th>
<th>Sediment load (g/L)</th>
<th>Final Sediment mass (g)</th>
<th>Sed. mass / Sample mass (%)</th>
<th>Reps measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPS1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>1.66</td>
<td>48.7</td>
<td>NM</td>
<td>19.2</td>
<td>5.3</td>
<td>0.56</td>
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</tr>
<tr>
<td>Rewetting</td>
<td>1.66</td>
<td>100.6</td>
<td>NM</td>
<td>12.2</td>
<td>7.0</td>
<td>0.74</td>
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<td>CPS3</td>
<td>1.84</td>
<td>141.3</td>
<td>18.0</td>
<td>0.6</td>
<td>0.4</td>
<td>0.04</td>
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</tr>
<tr>
<td>CPS5</td>
<td>1.69</td>
<td>49.4</td>
<td>NM</td>
<td>17.9</td>
<td>5.0</td>
<td>0.52</td>
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</tr>
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<td>CPS6</td>
<td>1.77</td>
<td>85.6</td>
<td>39.1</td>
<td>3.3</td>
<td>1.6</td>
<td>0.16</td>
<td>4 of 4</td>
</tr>
<tr>
<td>CPS7</td>
<td>1.7</td>
<td>85.7</td>
<td>46.0</td>
<td>5.4</td>
<td>2.6</td>
<td>0.27</td>
<td>4 of 4</td>
</tr>
<tr>
<td>JDS1</td>
<td>1.55</td>
<td>148.3</td>
<td>106.5</td>
<td>4.1</td>
<td>3.5</td>
<td>0.40</td>
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<tr>
<td>JDS2</td>
<td>1.47</td>
<td>79.3</td>
<td>53.0</td>
<td>7.5</td>
<td>3.4</td>
<td>0.41</td>
<td>2 of 4</td>
</tr>
<tr>
<td>JDS3</td>
<td>1.57</td>
<td>66.4</td>
<td>NM</td>
<td>15.0</td>
<td>5.6</td>
<td>0.63</td>
<td>1 of 4</td>
</tr>
<tr>
<td>JDS4</td>
<td>1.86</td>
<td>148.0</td>
<td>14.7</td>
<td>0.6</td>
<td>0.5</td>
<td>0.05</td>
<td>4 of 4</td>
</tr>
<tr>
<td>JDS5</td>
<td>1.55</td>
<td>20.7</td>
<td>0.7</td>
<td>23.4</td>
<td>2.8</td>
<td>0.31</td>
<td>1 of 4</td>
</tr>
<tr>
<td>TFS2</td>
<td>1.34</td>
<td>121.6</td>
<td>50.9</td>
<td>4.0</td>
<td>2.7</td>
<td>0.36</td>
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</tr>
<tr>
<td>TFS4</td>
<td>1.38</td>
<td>142.4</td>
<td>1197</td>
<td>17.2</td>
<td>13.9</td>
<td>1.78</td>
<td>4 of 4</td>
</tr>
<tr>
<td>TFS5</td>
<td>1.33</td>
<td>143.7</td>
<td>1285</td>
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<td>10.5</td>
<td>1.39</td>
<td>4 of 4</td>
</tr>
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<td>81.8</td>
<td>4.2</td>
<td>3.2</td>
<td>0.42</td>
<td>4 of 4</td>
</tr>
<tr>
<td>TFS7</td>
<td>1.3</td>
<td>147.1</td>
<td>2346</td>
<td>11.4</td>
<td>9.5</td>
<td>1.29</td>
<td>4 of 4</td>
</tr>
</tbody>
</table>

A Sample CPS1 measurement for rewetting applied following a drying cycle with measurements taken for the samples not sealing (tunnelling occurred on the 2 reps that did not seal).

B Steady infiltration rate of NM indicates values not measurable due to sealing and/or tunnelling during testing.

C Reps measured indicate the number of repetitions that produced leachate data (sealing of long column test samples produced unmeasurable results).
APPENDIX 4: Pinhole Test Data

Table 1: Pinhole test data including average moisture content (MC) and dry bulk density (BD) of each material tested.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Rating</th>
<th>MC (%)</th>
<th>Dry BD (g/cm³)</th>
<th>Size (F/I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPS1</td>
<td>D1</td>
<td>13.0</td>
<td>1.85</td>
<td>2.3</td>
</tr>
<tr>
<td>CPS3</td>
<td>D1</td>
<td>10.0</td>
<td>1.80</td>
<td>13.3</td>
</tr>
<tr>
<td>CPS5</td>
<td>D1</td>
<td>12.4</td>
<td>1.87</td>
<td>5.0</td>
</tr>
<tr>
<td>CPS6</td>
<td>D1</td>
<td>11.6</td>
<td>1.86</td>
<td>8.3</td>
</tr>
<tr>
<td>CPS7</td>
<td>D1</td>
<td>11.7</td>
<td>1.79</td>
<td>8.3</td>
</tr>
<tr>
<td>HVS13</td>
<td>D2, D1, PD2</td>
<td>31.4</td>
<td>1.27</td>
<td>1.9</td>
</tr>
<tr>
<td>HVS15</td>
<td>D1</td>
<td>36.7</td>
<td>1.17</td>
<td>3.0</td>
</tr>
<tr>
<td>HVS16</td>
<td>D2, D2, ND2</td>
<td>35.9</td>
<td>1.11</td>
<td>1.3</td>
</tr>
<tr>
<td>HVS17</td>
<td>D2, D1, D1</td>
<td>41.8</td>
<td>1.03</td>
<td>2.8</td>
</tr>
<tr>
<td>HVS18</td>
<td>D1, D2, D1</td>
<td>30.7</td>
<td>1.29</td>
<td>1.7</td>
</tr>
<tr>
<td>JDS1</td>
<td>D1</td>
<td>30.3</td>
<td>1.31</td>
<td>5.2</td>
</tr>
<tr>
<td>JDS2</td>
<td>D1</td>
<td>32.1</td>
<td>1.23</td>
<td>5.5</td>
</tr>
<tr>
<td>JDS3</td>
<td>PD1, D1, D1</td>
<td>30.3</td>
<td>1.35</td>
<td>2.7</td>
</tr>
<tr>
<td>JDS4</td>
<td>D1</td>
<td>12.1</td>
<td>2.00</td>
<td>4.7</td>
</tr>
<tr>
<td>JDS5</td>
<td>D1</td>
<td>28.3</td>
<td>1.36</td>
<td>6.0</td>
</tr>
<tr>
<td>SIS1</td>
<td>D1</td>
<td>27.3</td>
<td>1.40</td>
<td>3.3</td>
</tr>
<tr>
<td>SIS2</td>
<td>ND2</td>
<td>25.2</td>
<td>1.41</td>
<td>2.6</td>
</tr>
<tr>
<td>SIS4</td>
<td>PD1, D1, D1</td>
<td>26.5</td>
<td>1.46</td>
<td>2.4</td>
</tr>
<tr>
<td>SIS5</td>
<td>ND2</td>
<td>23.9</td>
<td>1.50</td>
<td>1.5</td>
</tr>
<tr>
<td>SIS8</td>
<td>PD2, D1, D1</td>
<td>34.7</td>
<td>1.27</td>
<td>3.3</td>
</tr>
<tr>
<td>TFS2</td>
<td>D1</td>
<td>22.8</td>
<td>1.52</td>
<td>4.9</td>
</tr>
<tr>
<td>TFS4</td>
<td>D1</td>
<td>26.1</td>
<td>1.39</td>
<td>5.7</td>
</tr>
<tr>
<td>TFS5</td>
<td>D1</td>
<td>26.2</td>
<td>1.38</td>
<td>4.1</td>
</tr>
<tr>
<td>TFS6</td>
<td>D1</td>
<td>24.3</td>
<td>1.45</td>
<td>5.5</td>
</tr>
<tr>
<td>TFS7</td>
<td>D1</td>
<td>26.7</td>
<td>1.39</td>
<td>5.6</td>
</tr>
</tbody>
</table>

A Multiple rating values provided for differing results between reps, single rating values for same results for all 3 reps.
B Size is measured by a ratio of the final hole size (F) to the initial hole size (I).
### APPENDIX 5: Erodibility Data

#### Table 1: Rill erosion measurements for dispersive spoils material.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Kr</th>
<th>Tau_c</th>
<th>R²</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPS1</td>
<td>1.3E-03</td>
<td>3.0</td>
<td>0.90</td>
<td>Tunnelling occurred during test</td>
</tr>
<tr>
<td>CPS3</td>
<td>7.7E-03</td>
<td>10.0</td>
<td>0.19</td>
<td>Rills undercutting and collapsing, roots within sample</td>
</tr>
<tr>
<td>CPS5</td>
<td>9.0E-03</td>
<td>6.1</td>
<td>0.25</td>
<td>Rills undercutting and collapsing</td>
</tr>
<tr>
<td>CPS6</td>
<td>3.1E-03</td>
<td>3.8</td>
<td>0.62</td>
<td>Rills undercutting and collapsing</td>
</tr>
<tr>
<td>CPS7</td>
<td>1.2E-03</td>
<td>4.1</td>
<td>0.53</td>
<td>Rills undercutting and collapsing, blue rock armouring</td>
</tr>
<tr>
<td>HVS13</td>
<td>6.2E-03</td>
<td>6.5</td>
<td>0.69</td>
<td>Quickly formed Deep narrow rill</td>
</tr>
<tr>
<td>HVS15</td>
<td>3.5E-03</td>
<td>5.2</td>
<td>0.70</td>
<td>Narrow rill, undercutting, terraced rill line, tunnels</td>
</tr>
<tr>
<td>HVS16</td>
<td>4.9E-04</td>
<td>0.2</td>
<td>0.85</td>
<td>Minimal rilling, gouge points on plot</td>
</tr>
<tr>
<td>HVS17</td>
<td>8.4E-04</td>
<td>7.6</td>
<td>0.10</td>
<td>Minimal rilling, gouge points on plot</td>
</tr>
<tr>
<td>HVS18</td>
<td>4.2E-03</td>
<td>12.8</td>
<td>0.46</td>
<td>Rill formed quickly, undercutting of rill walls</td>
</tr>
<tr>
<td>JDS1</td>
<td>1.7E-03</td>
<td>11.2</td>
<td>0.71</td>
<td>Deep narrow rill, some armouring, undercutting</td>
</tr>
<tr>
<td>JDS2</td>
<td>8.8E-04</td>
<td>6.8</td>
<td>0.41</td>
<td>Narrow rill with armouring present</td>
</tr>
<tr>
<td>JDS3</td>
<td>9.0E-04</td>
<td>3.9</td>
<td>0.87</td>
<td>Rill undercutting and armouring</td>
</tr>
<tr>
<td>JDS4</td>
<td>1.2E-03</td>
<td>7.7</td>
<td>0.55</td>
<td>Broad shallow rill, undercutting</td>
</tr>
<tr>
<td>JDS5</td>
<td>1.5E-03</td>
<td>0.8</td>
<td>0.55</td>
<td>Deep narrow rill, undercutting</td>
</tr>
<tr>
<td>SIS1</td>
<td>9.4E-04</td>
<td>6.6</td>
<td>0.99</td>
<td>Defined rill formed, gouge points present</td>
</tr>
<tr>
<td>SIS3</td>
<td>6.3E-04</td>
<td>4.3</td>
<td>0.97</td>
<td>Wide spread flow, little rilling over surface</td>
</tr>
<tr>
<td>SIS4</td>
<td>2.5E-04</td>
<td>4.6</td>
<td>0.52</td>
<td>Strong surface crust, minimal rilling, some rock armour</td>
</tr>
<tr>
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<td>9.2E-05</td>
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<td>0.82</td>
<td>No rilling, some of flows disappeared through holes</td>
</tr>
<tr>
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<td>2.7E-03</td>
<td>7.3</td>
<td>0.67</td>
<td>Very sharp rill formed</td>
</tr>
<tr>
<td>TFS2</td>
<td>7.5E-04</td>
<td>2.7</td>
<td>0.75</td>
<td>Armouring of rill line stabilising rill</td>
</tr>
<tr>
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<td>1.2E-03</td>
<td>3.7</td>
<td>0.84</td>
<td>Very sharp rill formed, water disappearing down holes</td>
</tr>
<tr>
<td>TFS5</td>
<td>2.5E-03</td>
<td>5.7</td>
<td>0.90</td>
<td>Very sharp rill formed, rock armouring</td>
</tr>
<tr>
<td>TFS6</td>
<td>5.9E-04</td>
<td>2.6</td>
<td>0.44</td>
<td>Very defined rill, rock armour</td>
</tr>
<tr>
<td>TFS7</td>
<td>8.7E-04</td>
<td>2.8</td>
<td>0.54</td>
<td>Very defined rill, undercutting of rill wall, rock armour</td>
</tr>
</tbody>
</table>