STRATEGIES TO REDUCE TUNNELLING ON DISPERSIVE MINE SPOIL MATERIALS

C.A. Vacher[A], S.R. Raine[B] and R.J. Loch[A]
[A] Landloch Pty Ltd, Toowoomba, Australia.
[B] National Centre for Engineering in Agriculture, University of Southern Queensland, Toowoomba, Australia.

Abstract

A general requirement of mine site closure is that waste rock dumps, generated by the excavation of large quantities of overburden in open cut mines, should be rehabilitated to create stable, sustainable landforms. However, many factors affect the success or failure of attempts to stabilise and rehabilitate waste rock dumps. Dump “failure” (where major erosion has occurred at points on the landform) is often associated with the erosion of unstable and dispersive materials. The presence of these materials in waste rock dumps commonly results in the development of tunnel erosion, causing failure of berms at points where tunnels develop, creation of relatively unsafe landforms with widespread tunnels immediately below the soil surface, development of large gullies once tunnels collapse, and instability of rock drains overlying dispersive materials. This paper provides information on the factors leading to the initiation of tunnelling and the potential for both changes in spoil properties through time and waste dump design to influence tunnel erosion risk. Waste rock dump design and management practices are reviewed and recommendations are made on the usefulness of alternative prevention and control strategies for tunnel erosion of unstable and dispersive spoils.

Additional Keywords: mine rehabilitation, erosion, sodic, gullies

Introduction

Open-cut mining activities typically excavate large quantities of overburden or spoil to gain access to the mineral that is sought. Overburden is usually placed in above-ground waste rock dumps, which are commonly 10-40 m high, and may have outer batter slopes at gradients of 25-40%. This paper reports on current research directed at characterising the risk of tunnelling failure on the basis of soil physical properties and dump design.

In general, the development of tunnel erosion is normally associated with 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. However, tunnelling also occurs due to soil liquefaction which is normally associated with materials dominated (typically >70%) by silt and fine sand components. 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 soil collapse above the tunnels.

Stabilisation of mine site waste rock dumps is a major component of mine site rehabilitation works. The presence of materials susceptible to tunnelling or piping a large impact 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) (Schafer and Tragmar 1981). 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.

Factors Involved in Tunnelling

Material properties

Soil materials susceptible to tunnel erosion (and selected for study) broadly fall into three main groups: (a) non-saline sodic, (b) saline sodic; and (c) non-saline, non-sodic, silty materials. These groups have distinctly different patterns of tunnel erosion under field conditions and hence, will require different management strategies. For classification purposes, measurements were taken on all materials collected from 5 sites for electrolyte content (EC), exchangeable cations, particle size distribution (clay, silt, fine and coarse sand categories) and clay mineralogy (using X-ray diffraction). A total of 5 materials from each site were tested covering a wide range of material properties (Table 1).

Figure 1. Tunnel developed from a berm on a waste rock dump constructed of sodic spoil.

Figure 2. Tunnels collapse forming a large gully.

Table 1. Summary of material properties used in testing

Mine site	EC (mS cm^{-1})	ESP (%)	Sand (%)	Silt (%)	Clay (%)	Mineralogy
Coppabella	0.1-1.9	20 - 36	51 - 90	6 - 21	5 - 34	Quartz, Kaolinite
Jundee	0.06 – 0.76	10 - 35	44 - 78	4 - 42	17 – 33	Quartz, Kaolinite
Higginsville	7.5 – 12.8	38 - 56	15 - 31	7 - 10	59 – 76	Quartz, Kaolinite, Smectite, Ilite
St Ives	4.9 - 46	25 – 89	19 - 83	8 – 60	8 – 22	Quartz, Kaolinite, Smectite, Ilite
Telfer	0.1 – 1.9	3 – 7.2	40 - 68	26 - 54	5 - 12	Quartz, Kaolinite, Ilite

The Coppabella (central Queensland coalmine) and Jundee (central Western Australia gold mine) materials are largely non-saline, sodic, dispersive and mostly sandy.

The Higginsville and St Ives (both from Western Australia Goldfields near Kalgoorlie) materials 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 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. The St Ives materials are highly sodic and saline, with salinity levels varying considerably. The St Ives materials varied greater than the Higginsville materials with 1 markedly different from the other materials, being primarily a sandy material and non-dispersive.

The Telfer (northern Western Australia gold mine) materials 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.

Tunnel mechanisms

There are a variety of mechanisms that influence the formation of tunnels within a material. These include; rainfall seasonality, heterogenous surface layer infiltration, exits/entrances, hydraulic conductivity of subsurface horizons and dispersion of soil layers subject to water flow (Couch *et al*., 1986). 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 (particularly associated with swelling clay materials). Shrinkage cracks generated by soil drying provide inlet areas for water, and expose dispersive sub-surface clays to free water.

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 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. 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 rock 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.

Waste rock dump design

During initial site visits, a strong difference was observed between the patterns of tunnel erosion at Coppabella (non-saline/sodic) and Higginsville (saline/sodic) Mines. At Coppabella, tunnels were extremely frequent on waste dump batter slopes, tended to be relatively small (up 50 cm diameter), and developed at depths of 50-70 cm in the soil. In contrast, at Higginsville, tunnels developed almost entirely on dump tops and berms, were relatively large (up to a metre or more in diameter), and relatively infrequent (spacings of 50 m being common in some areas).

When spoils are first excavated at Higginsville, they are actually non-dispersive, due to their high salt content. However, if leached, their salt content reduces, and they then become highly dispersive. Therefore, leaching of salt from the spoil is a major factor in making the soil dispersive. Most of the leaching occurs at points where water is ponded - on dump tops and berms. This ponded water then also provides the driving force for the tunnel erosion process. So, where spoils are initially saline / sodic, ponding water on them is a guaranteed way to create tunnels. This indicates that the traditional water-retaining waste dump profiles (flat tops, berms), are a major cause of the tunnelling of these sorts of spoils.

For non-saline / sodic spoils like Coppabella, clearly the tunnelling process can start immediately, and at any point on the landscape, and this seems to be consistent with the observations. For saline / sodic spoils it is plain that waste rock dump design is a major issue for tunnelling on this group of spoils and there are a range of issues to consider for spoil instability. Quirk and Schofield (1955) and many others since that time (Quirk, 2001) have used plots of ESP (sodicity) against Electrolyte Concentration (EC) (salinity) to define regions of stable *versus* reducing hydraulic conductivity or soil flocculation *versus* deflocculation/dispersion.

Results and Discussion

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. Laboratory tests for the 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.

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 (Sumner, 1993). 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 Coppabella 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^{-1} 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^{-1} 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: (a) loosely placing the material to a depth of 100 mm, and (b) 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.

Design options to control or avoid tunnel erosion problems on waste rock dumps have generally not been considered. From the outset of this research, 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.

Conclusions

This research has highlighted a number of issues related to the assessment of the risk associated with tunnelling problems on a mine site. 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. Firstly, it has shown the importance of soluble salt content in some spoils, and the need to manage salt content to maintain stability. Where water is ponded over saline sodic spoil, with leaching of salt by the ponded water, resulting 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. 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 considered.

The three groups of materials susceptible to tunnel erosion are saline sodic, non-saline sodic, and fine, non-sodic materials of low cohesive strength.

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.

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:

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

The problem with existing unstable waste rock 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. For existing dumps subject to tunnel erosion, remediation and repair appears to be difficult in some cases and often impossible. Access on waste rock dumps for appropriate equipment to perform remedial works (eg. to remove unstable material and replace it with a more stable spoil) is difficult and potentially dangerous due to the presence of existing tunnel-gullies and/or un-collapsed tunnels. Therefore, the importance of early diagnosis of potential tunnelling problems (identifying potentially tunnel generating materials) and adoption of strategies to prevent long-term instability is essential for successful mine closure.

Acknowledgements

The contribution of spoil samples and funding for the project by Australian Premium Coals Pty Ltd, Resolute Mining Ltd, Gold Fields, Newcrest Mining Ltd, Newmont Australia Pty Ltd through the Australian Centre for Mining Environmental Research is gratefully acknowledged.

References

Crouch, R.J. (1976). Field tunnel erosion – a review. *Journal Soil Conservation New South Wales* 32, 98-111.

Crouch, R.J., McGarity, J.W. and Storrier, R.R. (1986). Tunnel Formation Processes in the Riverina Area of N.S.W., Australia. *Earth Surface Processes and Landforms* 11(2), 157-166.

Downes, R.G. (1946). Tunnelling erosion in North-Eastern Victoria. *Journal of Council of Science and Industrial Research, Australia* 19, 283-292.

Emerson, W.W. (1967). A classification of soil aggregates based on their coherence in water. *Australian Journal of Soil Research* 5, 47-57.

Floyd, E.J. (July 1974). Tunnel erosion--a field study in the Riverina. *Journal Soil Conservation New South Wales* 30(3), 145-156.

Quirk, J.P. (2001). The significance of the threshold and turbidity concentrations in relation to sodicity and microstructure. *Australian Journal of Soil Research* 39, 1185-1218.

Quirk, J.P. and Schofield, R.K. (1955). The effect of electrolyte concentration on soil permeability. *Journal of Soil Science* 6, 163-178.

Schafer, G.J. (1978). Pinhole test for dispersive soil – suggested change. GT6 Technical Notes June 1978, p. 760-765.

Schafer, G.J. and Trangmar, B.B. (1981). Some factors affecting tunnel gully erosion Soil mechanics and foundation engineering. *Proc. 10th International Conference, Stockholm, June 1981*. Vol. l, (A.A.Balkema) p. 481-486.

Sherard, J.L., Dunnigan, L.P. and Decker, R.S. (1976). Identification and nature of dispersive soils. *Journal of the Geotechnical Engineering Division, ASCE* 102, 287-301.

Sumner, M.E. (1993). Sodic soils: New perspectives. *Australian Journal of Soil Research* 31, 683-750.