Instrumentation of waste rock dumps as part of integrated closure monitoring and assessment

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Abstract

The understanding of unsaturated zone hydrology and geochemistry is of key importance when considering the design of landforms containing mineral waste(s). Poorly designed and constructed landforms have the potential to cause unwanted environmental impacts, such as Acid Metalliferous Drainage (AMD), saline drainage, erosion, along with the inability to meet closure objectives and the desired final land use(s). Good environmental outcomes over long time scales are more likely achievable with a thorough understanding of the waste materials properties, combined with early planning and design informed by in-situ data collection.

The installation of instruments within waste rock dumps (WRD) enables the conceptual understanding of unsaturated zone hydrology using recorded data. Instrumentation has been used for many years as part of the assessment and monitoring of cover systems on waste rock dumps. This commonly involves the use of soil moisture instrumentation, which is placed at shallow depths to monitor net percolation rates of water, and oxygen ingress. A large amount of field data has been gathered from such monitoring programs over time and has greatly advanced the understanding of unsaturated zone hydrogeology within cover systems.

Conversely, the installation of instrumentation at greater depths within waste storage landforms is less common (with the exception of tailings dams). The general understanding of unsaturated zone hydrogeology and geochemistry deeper in the waste rock dumps is typically based on academic theory and conjecture, rather than being derived from measured field data.

With the development of sonic drilling technology, there are considerable opportunities for placing instrumentation at depth within waste landforms. Instrumentation placed at depth can be used to provide the same kind of field data that has been gathered for cover systems previously. This instrumentation can provide field data for long term monitoring of waste dump hydrology, geochemistry, gas composition, temperature etc. which provides significant information for the prediction of AMD.

O’Kane Consultants Pty. Ltd. has completed the installation of over 150 instruments in waste rock dump landforms in the Pilbara, WA. The instruments were installed to depths of 100 m as part of a long term monitoring and assessment program. Instruments were installed using the sonic drilling technique and include galvanic oxygen probes, soil matric potential sensors, temperature sensors, and vibrating wire piezometers. The use of sonic drilling allowed the structure of the dumps to be assessed in detail during drilling which allowed the targeting of instrument placement in specific zones.

The gathering of data from the instrumentation allows the conceptual model of the hydrological and geochemical evolution of waste rock dumps to be both tested and refined, and there are opportunities for future predictive modelling to be better calibrated. Preliminary data from instrumentation installed is presented herein.

1 Introduction

Mining processes typically result in the construction of large man made landforms to store waste products in the form of waste rock dumps (WRD). These landforms are dynamic, in that hydrological, geochemical, and biological processes continually cause the landform to evolve with time. Engineering principles are utilised to limit or slow down the evolution of these landforms which are generally based on conceptual ideas of WRD hydrology, airflow and temperature conditions.
Significant work in cover system performance monitoring has resulted in a good understanding of unsaturated zone hydrology and controls of performance such as net percolation, oxygen flow, and moisture retention characteristics in the near surface (upper 10 m) of WRD landforms. There is however, less information regarding deep WRD conditions following placement of cover systems, or following landform closure. As such, the response of WRDs to atmospheric forcing including oxygen ingress, internal temperature, moisture, and pore-gas conditions which control acid metalliferous drainage (AMD) production, are rarely understood fully. As a result, many significant environmental legacy issues have developed relating to WRDs ranging from structural failure (erosion) to AMD discharges. By understanding the internal WRD conditions following waste placement, decisions on closure can be formulated based on actual monitoring data; for example net percolation rates estimated through cover system monitoring can be verified or improved which could lead to the reduction of cover system thickness requirements across the site. Temperature and oxygen monitoring can provide an indication of pathways through the dump which contribute to oxidation and potential AMD release.

The study presented herein is based on the completion of sonic drilling programs as part of the investigation of 12 WRDs in Australia. Sonic drilling allowed the installation of monitoring equipment (instrumentation) throughout the depth profile of a series of WRDs with the following objectives:

- To test conceptual ideas of WRD hydrogeology, structure, and gas flow in the vadose zone
- To provide a means for long term monitoring of the WRDs.
- To aid in the development of long term closure plans for WRDs
- To refine conceptual models of WRD controls on AMD production

O’Kane Consultants Pty. Ltd completed the installation of over 150 instruments in 12 WRD landforms up to 100 m depth. Instruments were installed using the sonic drilling technique and include galvanic oxygen probes, soil matric potential sensors, temperature sensors, and vibrating wire piezometers. The use of sonic drilling allowed the structure of the dump to be assessed in detail during drilling which allowed the targeting of instrument placement in specific zones. The installations were connected to a telemetry system so that automated and “real time” data collection could be achieved from the instruments.

2 Study Setting

The presented study includes 12 WRDs at mine sites in the Pilbara, WA. The mine sites are made up of multiple WRDs which have been constructed by various techniques including end dumping, and dumps incorporating encapsulation techniques. The majority of the WRDs in this study do not have cover systems installed, and some surfaces of the WRDs comprise barren coarse waste rock. One WRD included in the study did have a cover system test plot which is currently equipped with soil monitoring instrumentation dating back to 2001 to a depth of 4.5 m.

The Pilbara region experiences a climate classified as arid-tropical. Summers last from October to April and mild winters occur from May to September (Gentilli, 1972). Sporadic and intense thunderstorms are typical for the region from January to March, and tropical cyclones can result in daily rainfall amounts of up to 200mm over a 24hr period.

3 WRD Instrumentation

Significant work in the mine closure field has been completed in the performance monitoring of engineered cover systems over mine waste (O’Kane 2011). This includes the installation of detailed instrumentation equipment such as soil moisture sensors, temperature sensors, pore-gas and pore-water, etc. to monitor key processes such as:

- Net percolation
- Heat transfer
• Vadose zone gas composition and oxygen migration
• Salt uptake
• Soil water characteristic curves

With the advancement of sonic drilling technology the state of the art methodologies utilised at the near surface can be transferred deep into WRDs to evaluate:

• Internal hydrologic conditions and the response of the WRD to climatic variables such as incident precipitation and pressure;
• Internal processes such as heat generated through sulfide oxidation;
• Movement and replenishment of oxygen through dump structure; and
• Effect of localised features related to dump structure such as rubble zones, underlying historical drainage pathways etc.

By gaining an understanding of these WRD internal characteristics based on observed monitoring data, an assessment of potential closure options can be developed. Instrumentation also provides monitoring data that can be both fed into models for predictions of future developments, and also provides “real time” data that may aid with analysis of any significant events as they happen (for example unexpected seepage events).

3.1 WRD Data Acquisition System

In the installations constructed as part of this study, internal WRD conditions are continuously monitored with Campbell Scientific CR800 dataloggers which take readings from sensors every 60 seconds and output 20 minute averages. This high frequency data acquisition allows for detailed monitoring of changes in key parameters influencing potential AMD production within the WRDs. AVW200 vibrating wire interfaces are used in conjunction with the VWP sensors while AM16/32B multiplexers are used to expand the measurement capacity of the dataloggers. RF411 UHF radios allows for communication between the established monitoring stations while Hughes Inmarsat broadband global area network (BGAN) and SAM3G modems are equipped to central monitoring stations. Figure 1 shows a typical OKC DAS equipped with WRD monitoring instrumentation. Each DAS is powered with a 10W solar panel and rechargeable battery.

![Typical OKC DAS equipped with oxygen, VWP, MPS2, and temperature probes](image)

Data from the monitoring stations are sent to central dataloggers every 20 minutes through the site UHF radio network (Figure 2). Data is subsequently sent automatically to an online FTP server on a daily basis.
which allows for data quality assurance and system checks to be completed remotely. Given the remote nature of the sites, BGAN satellite monitoring systems were required to establish remote monitoring and allow online access to data.

![Figure 2 - Schematic of study site UHF radio network](image)

**Figure 2** Schematic of study site UHF radio network

DASs were installed as “low profile” stations, and tripod configured stations. Low profile stations were designed to limit the probability of lightning strike during cyclone events and also to supply additional stability during high wind conditions, while the tripod configured DASs were employed to allow for station relocation at sites currently undergoing WRD construction. Examples of tripod configured and low profile DASs are presented in Figure 3.

![Figure 3 - Low profile and tripod DAS with BGAN satellite modem](image)

**Figure 3** Low profile and tripod DAS with BGAN satellite modem

### 3.2 In Situ Moisture Conditions

Dielectric water potential sensors (suction) and multi-level vibrating wire piezometers (VWP) were installed at various depths within the WRD profile to measure matric suction/temperature, and pore-water pressure/temperature at different zones in the borehole, respectively. The soil suction sensors have a measurement range of -10 to -500kPa and the VWPs have the capacity to measure a positive pressure of 350 kPa (3.5 Bar) and also slightly negative pressure conditions.
Soil suction (MPS2) sensors are used in this study to monitor recharge in the WRDs and the propagation of the wetting front (if present) in response to rainfall events. Given the presence of both fine grained and coarse material bands within WRD construction, it is anticipated that the advancement of wetting fronts will be more pronounced within fine grained material. The locations selected for soil suction sensor placement will allow for a detailed evaluation of this hypothesis. The MPS2 sensor was selected given its small size and durability owing to the narrow and hostile installation environment of a borehole.

VWPs installed within the WRDs will allow the evaluation of basal flow within the coarse grained material commonly found at the base of WRDs due to segregation during end dumping. VWPs installed throughout the WRD profile will give an indication of the development of perched water tables and seepage. Temperature values provided by the VWP and MPS2 sensors will also add to the overall temperature coverage at the WRD.

3.3 **In Situ Gas Concentrations**

ICT International ICT02 and Apogee SO-100 galvanic oxygen probes were installed within the boreholes to give an indication of oxygen levels within the WRDs. Given that oxidation is an oxygen consuming process, it is anticipated that a drop in oxygen levels will be observed following the advancement of wetting fronts. In addition, depressed oxygen levels may be observed within pyritic bands of material. Oxygen replenishment is thought to occur in coarse waste horizons, therefore installation of probes in these zones at various depths will allow this theory to be tested. Manual gas sampling ports were installed at the surface to provide additional gas monitoring and to verify readings made by the automated system.

Figure 4 shows an Apogee oxygen probe and mesh diffusion head. The mesh diffusion head is utilised to maintain an air space between the surrounding material and Teflon membrane to ensure that a sample is available for probe detection. Given the potentially acid environment which the sensor was to be installed, a low pH resistant ABS housing was selected to replace the standard aluminum probe housing.

![Figure 4 Apogee oxygen probe with mesh diffusion head and ABS housing](image)

The oxygen probes provide an absolute reading of oxygen concentration and were calibrated at the study site to provide relative readings of $O_2$. Site specific calibrations were required given the influence of atmospheric pressure on relative oxygen readings and were completed in the field prior to sensor deployment.

3.4 **In Situ Temperature Monitoring**

Temperature probes were installed throughout the WRD profiles at various depths. The temperature probes, in addition to the temperature readings provided by the VWP, Apogee oxygen probes, and MPS2 sensors will allow for a temperature profile to be developed with depth. The oxidation of sulfide materials is an exothermic process; therefore, it is anticipated that the introduction of meteoric water to the waste material will result in a temperature spike as the wetting front progresses through the WRD. Temperature
gradients within the WRD will also be evaluated in terms of introducing thermal gradients resulting in convective gas movement.

4 Internal WRD Monitoring System

OKC completed the installation of over 150 instruments within WRDs up to a depth of 100 m. The WRD monitoring systems were equipped with instrumentation to measure in situ moisture, pore-gas concentrations, pore-water pressure and in situ temperature within the WRDs. In addition to automated instrumentation, groundwater sampling wells and manual gas sampling ports were also installed at selected locations. Figure 5 shows a cross section from a study site WRD with the conceptual layout of monitoring equipment. Fully automated data acquisition systems (DAS) were installed and commissioned in 2013 and 2014, and are equipped with 3G and BGAN satellite modems to enable remote communications which allow real time monitoring of internal WRD conditions.

![Conceptual cross section of WRD monitoring equipment placement](image)

**Figure 5** Conceptual cross section of WRD monitoring equipment placement

4.1 Borehole Drilling and Sensor Installation

Sonic drilling was utilised to construct the boreholes at the study sites due to the ability to collect accurate, continuous, and relatively undisturbed core samples in unconsolidated material (Barrow 2007). Drill holes comprised of 150 mm diameter holes (outside casing diameter) and 100 mm core with depths ranging from 5 m to 100 m. Because of the ability of sonic drilling to produce (relatively) undisturbed core samples, this allowed the internal structure of the WRDs to be assessed in detail and depths for sensor installation to be chosen based on observations in the field; targeting specific zones such as bands of coarse or fine grained material.

Table 1 shows the rationale for sensor installation at particular depths. In general sensors were installed in the following horizons:

- Shallow depths to monitor oxygen, temperature and moisture content conditions
- Mid depths to monitor oxygen, temperature and moisture content conditions (including pyritic shale bands)
• Deep sensors to monitor basal drainage and toe seepage.

Sensors were installed surrounded by a 1-2m thick pack of 1-2mm clean silica sand on the outside of the centralized 42mm PVC casing (used to route cables). Sensor installations were isolated with a bentonite pellet backfill. The top of the boreholes were sealed with a cement grout mixture. Details of a typical borehole installation can be seen in Figure 6.

### Table 1 Typical profile through WRD and rationale for placement of sensor

<table>
<thead>
<tr>
<th>Core photograph</th>
<th>Depth, material info</th>
<th>Placement of sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Core photograph" /></td>
<td>1-2m&lt;br&gt;Gravely sand of mainly BIF</td>
<td>MPS2: 2m&lt;br&gt;Sensor placed to determine shallow depth moisture conditions</td>
</tr>
<tr>
<td><img src="image" alt="Core photograph" /></td>
<td>4-4.5m&lt;br&gt;Clayey gravel with cobbles; black pyritic clay</td>
<td>O2/Temp: 4m&lt;br&gt;Sensors placed to determine shallow oxygen concentrations and temperature in sulfide zone.</td>
</tr>
<tr>
<td><img src="image" alt="Core photograph" /></td>
<td>15.5-16.5m&lt;br&gt;Gravely clay; BIF with grey shale</td>
<td>VWP/MPS2: 16m&lt;br&gt;Sensors placed to determine pore pressure and moisture conditions changes in finer grained clayey zones</td>
</tr>
<tr>
<td><img src="image" alt="Core photograph" /></td>
<td>35-36m (base zone WRD)&lt;br&gt;Silty sandy gravel with cobbles; Hematite, BIF, black shale;</td>
<td>O2/VWP: 35m&lt;br&gt;Sensors placed to determine oxygen flow and pore pressure in course waste near base of dump</td>
</tr>
<tr>
<td><img src="image" alt="Core photograph" /></td>
<td>36.5-37.5m&lt;br&gt;Silty clay with cobbles; Sandstone;</td>
<td>VWP: 36.5m&lt;br&gt;Sensor placed to determine seepage though natural ground from base dump</td>
</tr>
</tbody>
</table>
4 Data Analysis/Interpretation

Preliminary data sets are presented in this section. Significant amounts of data are collected from the study sites; however, only selected data has been chosen for inclusion in this analysis.

Figure 7 presents temperature data from one WRD from October 2013 to April 2014. Temperatures measured at shallow depths (2 m – 9 m) show a higher range in comparison to sensors installed to deeper depths. This is due to the influence of ambient atmospheric temperatures and infiltration of meteoric waters following rainfall. Sensors below 9 m depth showed a relatively constant temperature over the six month monitoring period.

A sharp increase in temperature was observed at DHID15, 4 m depth (installed in a coarse zone of cobbles) in early January, which saw temperatures increase from 35°C to 47°C over the course of several weeks; temperatures continued to rise to the end of March.
Figure 7  *In situ* Temperature measurements from selected WRD

Figure 8 and Figure 9 show oxygen concentrations and airflow estimates measured at DHID15 which saw the rapid increase in temperature observed (see Figure 7); no change in oxygen concentration was noted during this time frame. This suggests that the change in temperature at this location is a result of air movement from another location in the WRD; most likely a result of convective, density dependent airflow. As the air moved from the location in which oxidation was occurring to the monitored location, it likely mixed with other air within pore space, resulting in no measured change in oxygen while still registering a change in temperature. PSD profiles from down-hole sampling profiling indicates that from 4-5m the material is predominantly coarse and comprises mostly cobble size or above materials. The WRD was end tipped and therefore this zone of material is likely to be present in an inclined layer of indeterminate depth extent. The data indicates that the coarse zone of material is acting as a ‘chimney’ and is acting as a conduit for the advection (or venting) of higher temperature air from depth in the WRD.
Figure 8  Oxygen concentrations and temperature at DHID15 drill hole

Figure 9  Airflow estimates at DHID15 drill hole

Figure 10 shows the soil suction profile measured by MPS2 dielectric soil suction sensors at a selected borehole location. Suction data from 2 m (most shallow) and 25 m (deepest sensor) indicate that water potential is approximately 10 to 20 kPa. The shallow sensor is located in a finer textured material, and as such, suctions in the observed range are not unexpected given the moisture retention characteristics.

The deep sensor at 25 m is located at the base of a deep (10 m) cobble zone. From the conceptual model of WRD hydrology, one would expect suctions to be very high due to the effects of advective drying; however, low suctions are observed. The lower suctions measured at 25 m indicate the presence of a wet zone or water table in this location. Sensors in the middle of the WRD (8 m and 15 m) indicate a moisture condition at or near the residual water content supporting the evidence that water has not percolated uniformly through the WRD, but has reached the base through basal seepage or preferential flow paths.
Figure 10 MPS2 soil suction profile at selected borehole location

Figure 11 shows VWP data from a selected WRD. Positive pore-water pressures were recorded at a number of locations. The sensor at a depth of 21 m in DHID35 shows a rapid increase in pore-water pressure in mid-March, likely responding to Jan/Feb rainfall events. The material at this location is gravelly but is located above a few finer-textured layers that may be slowing down the vertical movement of water. The deeper sensors at both DHID35 and DHID30 indicate saturated or near saturated conditions. These positive pore-water pressures indicate the potential for toe seepage at the WRD.

Figure 11 Pore-water pressure recorded by VWP sensors from multiple boreholes at a selected WRD
Figure 12 illustrates the response of near surface MPS2 soil suction sensors to wetting and drying and also the variability in response given different material textures. The soil suction sensor at DHID41, 2 m remains at or near saturation for the entire monitoring period and is located in a silty material, while at DHID44, 3 m and 7 m sensors were placed in an area with gravel and cobbles, resulting in lower moisture retention.

Figure 12 MPS2 soil suction from multiple boreholes at a selected location.

Figure 13 presents a 1D plot of oxygen concentration with depth at a selected borehole location. A region of low oxygen concentration can be observed from 10 m-18 m depth throughout the monitoring period which begins to increase in width from April to June 2014. Depressed oxygen levels are likely to result from oxidation of pyritic minerals within the waste.

Figure 13 1D plot of oxygen concentration with depth at selected borehole
Figure 14 presents preliminary temperature data from a selected borehole containing both banded iron formation (BIF) material and black shale. Black shale contains pyritic minerals which readily oxidize in the presence of oxygen and water, producing AMD products and heat as a by-product of the exothermic reaction, while BIF is relatively benign. Temperatures recorded by sensors installed within the black shale zone range from 80°C - 86°C, while sensors installed lower within the borehole profile fall in the range of 53°C - 58°C.

Continued monitoring of temperatures within the borehole, accompanied by in situ moisture and oxygen data will allow internal WRD conditions to be analysed in terms of the AMD producing potential of the WRD, and also indicate potential modes allowing oxidation reactions to occur.

![Temperature profile from selected borehole illustrating large temperature difference between BIF and black shale waste](image)

**Figure 14** Temperature profile from selected borehole illustrating large temperature difference between BIF and black shale waste

### 5 Conclusions

Internal WRD monitoring systems were installed in multiple WRDs in the Pilbara, Western Australia consisting of over 150 instruments installed to depths of up to 100 m in 2013 and 2014. The monitoring systems continuously monitor in situ oxygen concentration, temperature, and moisture conditions at depth within waste rock dumps while allowing “real time” data analysis through the application of 3G and BGAN satellite telemetry systems. Installation of the monitoring system equipment utilised sonic drilling which allowed for a detailed log to be recovered of the internal structure of the WRDs and specific zones to be selected for sensor installation. By monitoring deep within WRDs, a detailed understanding of the waste materials response to site specific atmospheric conditions can be developed such as oxygen ingress rates, internal moisture conditions (determining if “steady state” conditions have been reached), and temperature fields. Conceptual models of WRD hydrology, airflow, and temperature can be verified or improved upon, leading to increased positive outcomes in terms of long term closure results.

A preliminary review of monitoring system data indicates that sensors are responding as anticipated, and are producing valuable data. Initial trends suggest that:

- The response of the WRD internally to rainfall events is relatively rapid, suggesting internal drainage through preferential pathways is occurring
• Wetting of the WRD’s is not occurring uniformly throughout the waste, i.e. a uniform wetting front is not present as would be suggested by typical WRD conceptual models

• The core of the WRD’s have a high internal air flow which is providing ample supply of oxygen to the whole waste rock profile

• Interconnected pathways for air movement within the WRDs have been identified that allows the transfer of both oxygen and heat to occur through the depth profile, the process is akin to venting through ‘chimney’ structures.

• Elevated internal dump temperatures and high (and connected) internal air flows are resulting in effective air drying of the waste mass throughout much of the profile preventing a uniform size wetting front from developing

• Internal temperatures of over 80 degrees Celsius have been recorded suggesting the heat generated from pyrite oxidation is a significant contributor to internal WRD dynamics

• Basal seepage is occurring as a result of fast drainage of infiltrating waters through coarse waste horizons (and possibly as a result of underdrainage)

On-going monitoring of the study site will provide a unique dataset for the assessment of end dumped course waste rock piles and the production of ARD under site specific climatic conditions.

References


