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INSTRUMENTATION IN WASTE ROCK DUMPS: GOING DEEPER

S. Pearce and M. Barteaux
O'Kane Consultants Pty Limited, 1/11 Collingwood Street, Osborne Park, WA 6017

ABSTRACT

Instrumentation has been used for many years as part of the assessment and monitoring of cover systems on waste rock dumps, typically involving the use of instruments such as soil moisture probes placed to shallow depths to monitor factors such as net percolation rates. As a result a great deal of valuable information (practical field data) has been gathered from these monitoring programs regarding the performance of cover systems, which has greatly advanced the understanding of unsaturated zone hydrogeology within cover systems in general. However, to date the installation of instrumentation at greater depths within waste storage facilities is far more limited (with the notable exception of tailings dams). It can therefore be argued that our understanding of unsaturated zone hydrogeology and geochemistry within the waste rock mass is therefore (in comparison) biased more towards theory and standardised conceptual models rather than practical field data.

With the development of sonic drilling technology, there is however, considerable opportunities for placing instrumentation at depth within waste landforms. Instrumentation placed at depth can be used to provide the same kind of valuable field data as has been gathered for cover systems previously. In addition 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 90 instruments to depths of 40m within waste dump landforms 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 dump 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 hydrology 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. Data from instrumentation installed is presented herein which indicates that standard conceptual theories of dump hydrology such as "wetting fronts" may not be universally applicable.

1.0 INTRODUCTION

Waste rock dumps (WRD) are a consequence of most mining processes and usually consist of uneconomic low grade ore materials and non-mineralized "waste" materials as a result of resource extraction. Historically relatively little attention/effort has been afforded to the characterization of materials placed in WRDs, and to the construction process of forming them. As a result many significant environmental legacy issues have developed relating to WRDs ranging from structural failure (erosion) to acid and metalliferous drainage (AMD) discharges. As a result of these legacy issues having caused significant environmental/social impacts a large number of scientific studies have been completed to gain an understanding of mine waste material and related environmental risk factors resulting from placement in

WRDs. As part of this scientific research and development general conceptual models and theories have been developed to explain for example the causes of AMD from WRDs. Resulting from these generalised conceptual models and theories has been the development of legislative controls by government(s) as part of environmental management, and a better understanding in the industry of what “best practice” means with respect to waste management. This has seen a significant improvement in waste management practices in recent times. In general, engineering design and closure plans for WRDs generally address the concerns of long-term erosion stability as WRDs are considered increasingly as an “engineered landform”. In addition, the use of engineered “cover systems” for example has been widely adopted by the industry as a means to reduce net percolation rates into WRDs (thereby reducing the potential for AMD discharges). However, the success of ‘best practice” approaches has not been uniformly successful in reducing environmental liabilities caused by WRDs. Three common reasons for this ‘patchy” success include:

- The development of “best practice” in industry for WRD management and therefore construction is based on the assumption that the underlying conceptual models/theories regarding WRD structure and stability, hydrogeology, geochemistry, gas regime etc are sound. However the understanding of unsaturated zone hydrogeology and geochemistry within the waste rock mass is generally biased towards theory, standardised conceptual models, and predictive models/lab testing rather than from practical field data. This has resulted in engineering solutions being designed based on generalised conceptual WRD models that in some instances are not appropriate.
- In contrast to other waste management industries such as domestic landfill, WRDs are generally not subject to active monitoring by way of internal instrumentation being installed (with the exception of cover systems). This “walk away” approach has resulted in the creation of potential environmental hazards as processes like AMD take many years to develop and often will go undetected for decades until a significant AMD discharge occurs without warning.
- In addition (and again in contrast to domestic landfills), construction and regulator approval of WRDs commonly does not include detailed engineering specifications, as built drawings and QA/QC documentation. This has resulted in many WRDs being constructed poorly and often with limited planning/thought having been made with respect to materials management and placement (for example the prevalence of end tipping).

The third factor listed above can be considered purely an engineering design issue and therefore will not be addressed as part of this study; however, the preceding two factors are addressed herein as these relate to scientific study.

The study presented herein is based on a sonic drilling program of works completed as part of an investigation of decades old WRDs . The 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.

O’Kane Consultants Pty. Ltd. completed the installation of over 90 instruments to depths of up to 40m within waste dump landforms (from iron ore mining). 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.

2.0 INVESTIGATION OF AMD PRODUCING WRDS

A key data set that can be used to guide the development of a conceptual model of a WRD includes the investigation of WRDs that have produced AMD. Although not common, mining companies are now motivated to perform these detailed investigations of WRDs to gain an understanding of the internal hydrologic properties of the waste and evaluate how the *in-situ* waste material controls AMD production and potential release to the surrounding environment. By undertaking these investigations, an understanding of WRD hydrology such as recharge and underdrainage, and gas movement can be developed allowing to better understand the internal controls for AMD production.

A key feature of these investigations is that they allow the selection of material from within WRDs that has been *in-situ* for years, perhaps decades. Testing and characterisation of this material provides valuable data that can be used to retrospectively determine key processes operative in WRDs.

3.0 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 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 utilized 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
- Effect of localized features related to dump structure such as rubble zones, underlying historical drainage pathways etc

As well as looking at what "has happened" the installation of instrumentation within WRDs allows future monitoring of WRD internal conditions. Instrumentation provides monitoring data that can be both fed into models for predictions of future developments, but also provides "real time" data that may aid with analysis of any significant events as they happen (for example unexpected seepage events)

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3.1 *In-Situ* Moisture Conditions

Dielectric water potential sensors (suction) MPS2 sensors 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 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 course 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.

VWPs installed within the WRDs will allow the evaluation of basal flow within the course 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.

3.2 *In-Situ* Gas Concentrations

ICT International ICT02 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 shale bands. 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.

3.3 *In-Situ* Temperature Monitoring

Temperature probes were installed throughout the WRD profile at various depths. The temperature probes, in addition to the temperature readings provided by the VWP and MPS2 sensors will allow for a temperature profile to be developed with depth. The oxidation of sulphide 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.

4.0 STUDY SITE

The presented study is a mine site in the Pilbara, Western Australia. The site is made up of multiple WRDs which have been constructed mainly by end dumping.

The WRDs do not have cover systems installed, and some surfaces of the WRDs comprise barren coarse waste rock. A significant proportion of the site is covered by relatively dense mature vegetation that appears to have established directly on the coarse waste rock surfaces (natural revegetation of many areas of the site appears to have been very successful).

The Pilbara region consists of 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.

4.0 WRD STRUCTURE & AMD PRODUCTION / RELEASE

Generic conceptual models for WRDs have been published by many authors, and many guidance documents contain “industry standard” schematics (MEND, INAP etc). However, what may appear to be a useful concise summary “picture” is potentially dangerous if these are assumed to be based on complete and robust technical models that accurately represent the hydrogeology/geochemistry/gas regimes pertaining to WRDs on a specific site. Some authors have attempted to incorporate field data and scaled laboratory experiments to make these models more technically robust (notably the work of Ward Wilson, e.g. Wilson 2011), however this approach has yet to translate to the more generic “industry standard guidance”.

Figure 1 is a reproduction from Ritchie, 1994, which is included in the Australian guidance (DITR 2007), which clearly shows the limits of a generic model. For example the oxidized zone is shown as a simple halo around the edges of the waste, and infiltration is indicated to be vertically uniform. Whilst potentially applicable to homogeneous waste materials such as tailings this model is not likely to be reflective of waste rock dumps. As will be demonstrated in this paper broad assumptions like these can be misleading.

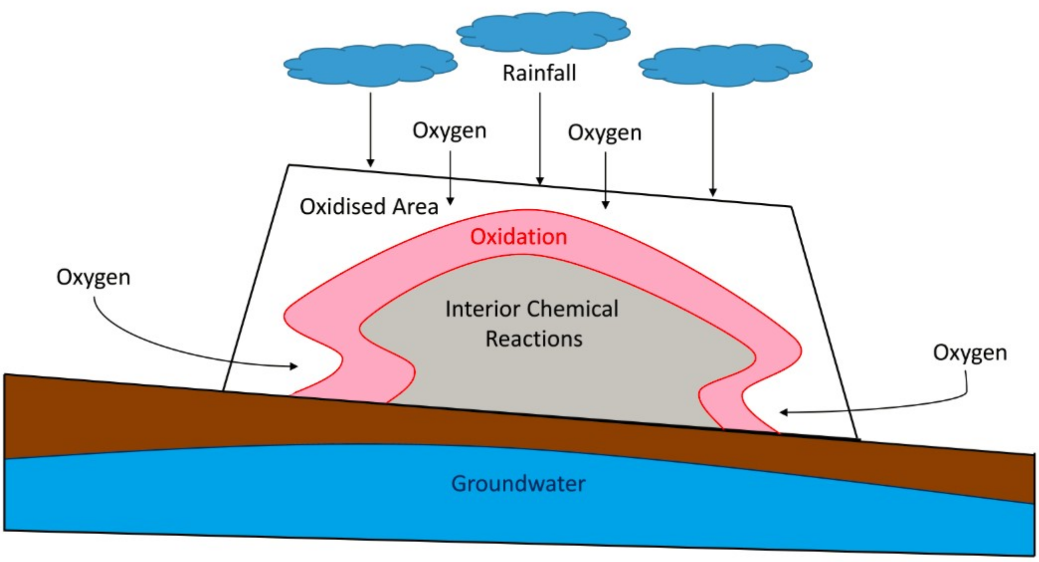

Fig. 1. Generic model of AMD production and contaminant migration from a waste rock dump after Ritchie 1994

An aspect of WRD construction that has been (and arguable still is) commonly overlooked is the internal structure created as a consequence of the prevalence of end tipping material, and the resulting hydrologic characteristics which control oxygen and water flow throughout the waste material (Wilson 2011). Given that oxygen and water flux are major controls in the production and release of AMD to the receiving environment, this is a major oversight in the conceptual model of WRDs and in their overall closure plan. Figure 2 is a conceptual model showing a cross section of a typical WRD constructed by end dumping material. The segregation of course and fine grained material into parallel bands along tip faces is a common feature of end dumped WRDs. The segregation of material as shown in Figure 2 has been confirmed by WRD excavations in the work of Wilson (2011).

The conceptual cross section shows that the infiltration of water enters the WRD at the top of the pile, percolating down through areas of fine grained materials due to their ability to retain water and the low air entry value of course grained material. During heavy rain events such as cyclones, water will also enter the WRD in coarse grained sections quickly percolating to depth. Oxygen ingress primarily will enter the WRD at the bottom of the pile moving upwards through the free draining course material layers by the process of thermal advection.

The presented conceptual internal structure of WRDs constructed by the common practice of end dumping is an ideal scenario for the production of AMD given the ample supply of atmospheric oxygen and water.

The conceptual model shown in Figure 2 is an improvement over that shown in Figure 1 as some elements of structure are considered; however, some of the concepts are based on limited field data. Some areas of uncertainty include:

- How efficient the oxygen replenishment is within the dump
- The presence of a “wetting front” within the dump
- The dominance of fine or coarse grained materials with respect to seepage transfer to the base
- The influence of “underdrainage” where dumps are constructed on old drainage pathways or on natural slopes (e.g. escarpments)

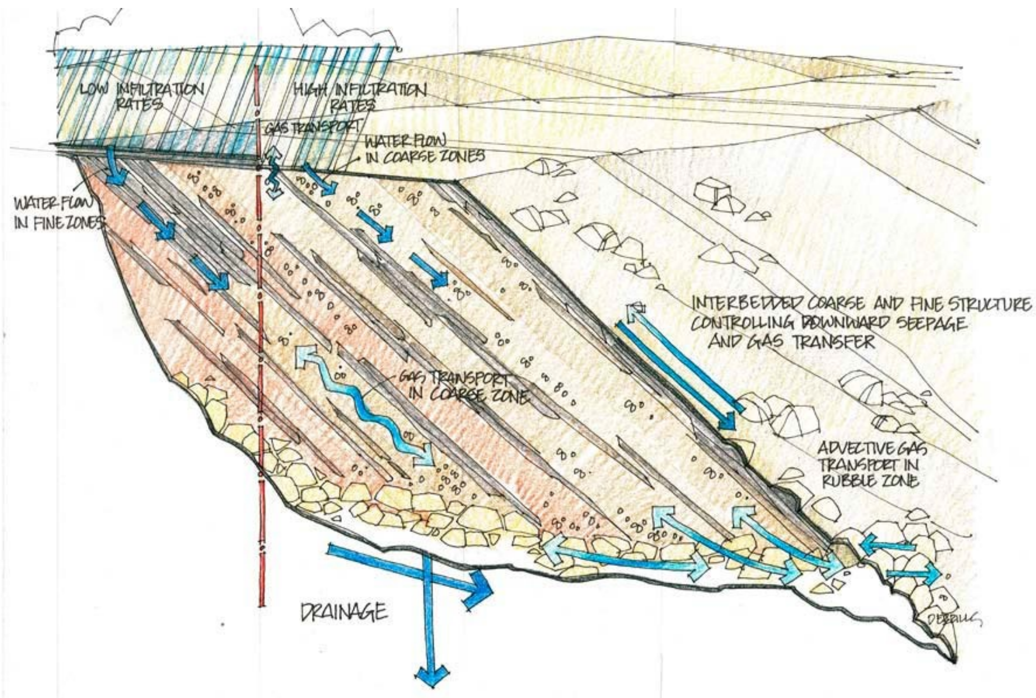

Fig. 2. Conceptual cross section of end dumped WRDs illustrating oxygen and water transport

5.0 SITE MONITORING SYSTEM

OKC completed the installation of over 90 instruments within the WRDs up to a depth of 40m. The site monitoring system includes 19 boreholes equipped with instrumentation to measure *in situ* moisture, pore-gas concentrations, pore-water pressure and *in situ* temperature within the waste rock piles. In addition to automated instrumentation, groundwater sampling wells and manual gas sampling ports were also installed at selected locations. A conceptual layout of the monitoring equipment is shown in Figure 3. Instrumentation was installed in conjunction with a sonic drilling program for material and site characterisation. Fully automated data acquisition systems (DAS) were installed and commissioned in 2013 and are equipped with remote communications to enable real time monitoring of internal WRD conditions. DASs were installed as “low profile” stations to limit the probability of lightning strike during cyclone events, and also to supply additional stability during high wind conditions.

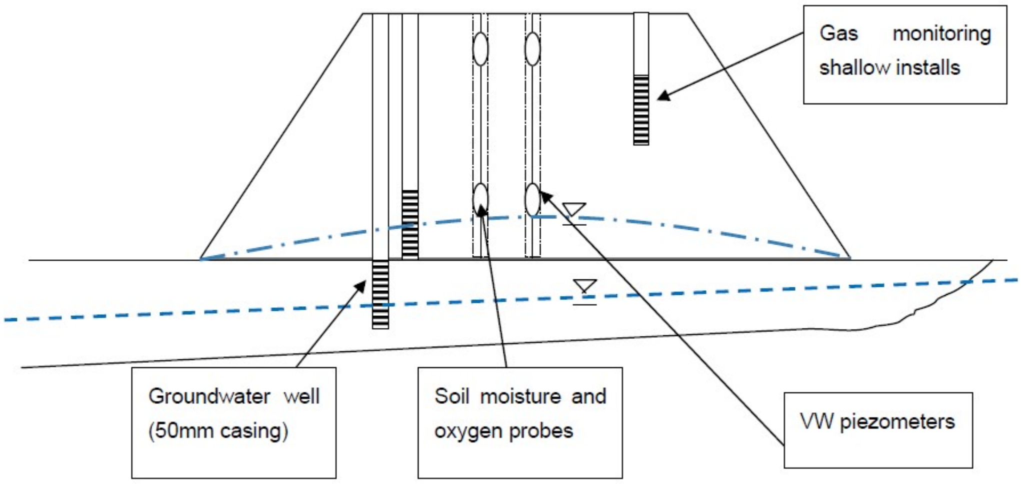

Fig. 3. Conceptual layout of monitoring equipment

5.1 Borehole Drilling and Sensor Installation

Sonic drilling was utilized to construct the boreholes onsite due to the ability to collect accurate, continuous, and relatively undisturbed core samples in unconsolidated material (Barrow 2007). Drill holes were comprised of 150mm diameter holes (outside casing diameter) and 100mm core with depths ranging from 5m to 42m. 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 course or fine grained material.

Figure 4 shows a typical profile through the dump based on data gathered from sonic drilling. The following observations are made with respect to this data:

- A coarsening of materials towards the base of the dump is noted
- Natural ground is identified by sharply higher fines content under the rubble zone (clay underlies the dump)

- Moisture contents are low through the profile and do not show an obvious wetting front

The data from the drilling indicates that the dumps are generally dry throughout the profile indicating that the much hypothesized “wetting front” has not developed even though the dumps have no cover and are decades old. However, seepage is noted at the base of the dumps therefore an infiltration mechanism must be active. Given this observation instrumentation was installed to test a theory that seepage relates to fast drainage through coarse layers rather than through “slow drainage” through finer materials as a vertically migrating wetting front.

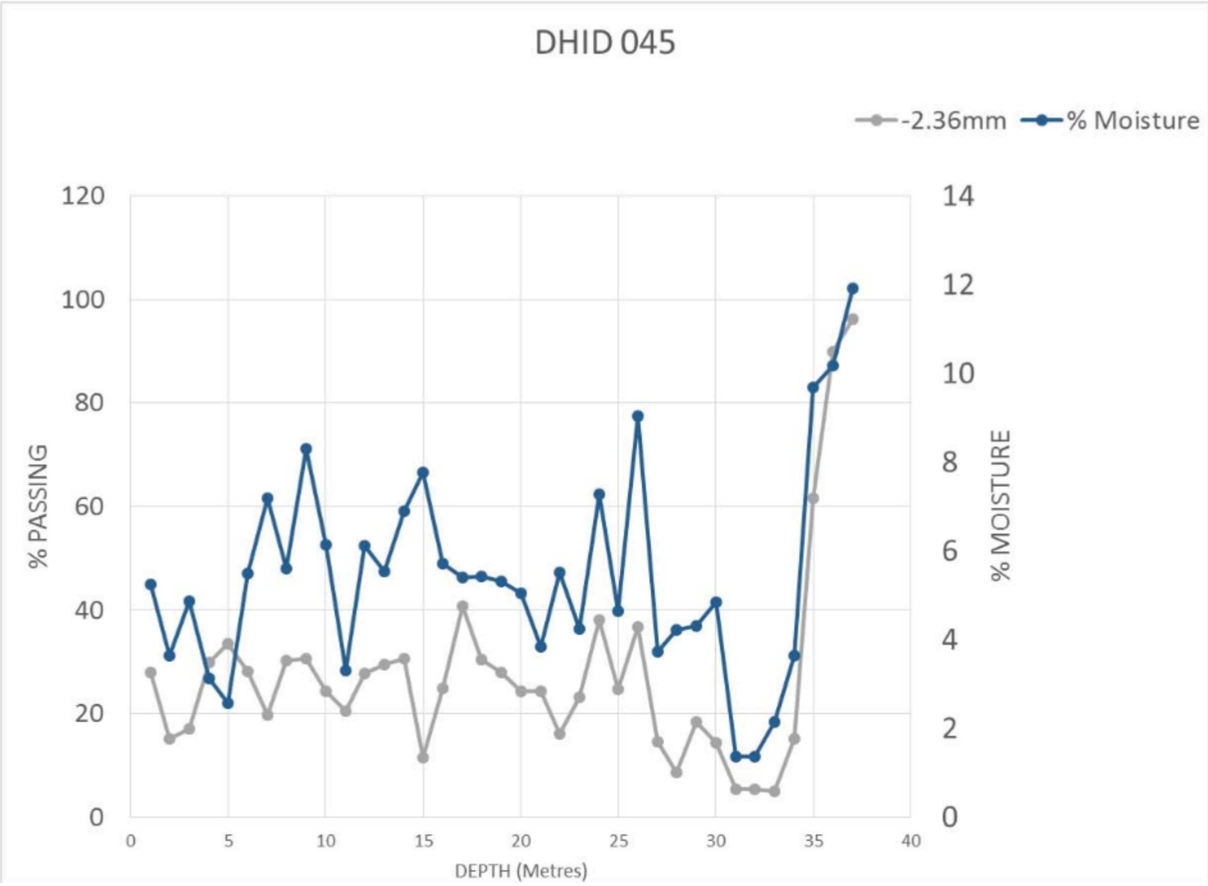

Fig. 4. Typical moisture content, grain size profile though waste dump

Core logging summarized in Table 1 (and PSD data shown in Figure 4) clearly shows the alternating coarse/fine grain horizons present in the dumps resulting from end tipping. In addition material type segregation is noted throughout the profile with bands of shale/BIF/dolerite noted, bands range from as little as 5cm to 6m in thickness. Table 1 shows the rational 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)

Table 1. Typical profile through dump and rational for placement of sensors

Core photograph	Depth, material info	Placement of sensor
	1-2m Gravely Sand of mainly BIF	MPS2: 2m Sensor placed to determine shallow depth moisture conditions
	4-4.5m Clayey gravel with cobbles; black pyritic clay	O2/Temp: 4m Sensors placed to determine shallow oxygen concentrations and temperature in sufide zone.
	8.5-9.5m Sandy gravel with cobbles. BIF and hematite	O2/Temp/MPS2: 9m Sensors placed to determine oxygen concentrations, temperature and moisture conditions in coarse material zones
	15.5-16.5m Gravely clay; BIF with grey shale	VWP/MPS2: 16m Sensors placed to determine pore pressure and moisture conditions changes in finer grained clayey zones
	35-36m Silty sandy gravel with cobbles; Hematite, BIF, black shale;	O2/VWP: 35m Sensors placed to determine oxygen flow and pore pressure in course waste near base of dump
	36.5-37.5m Silty clay with cobbles; Sandstone;	VWP: 36.5m Sensor placed to determine seepage though natural ground from base dump

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 betonite 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 5

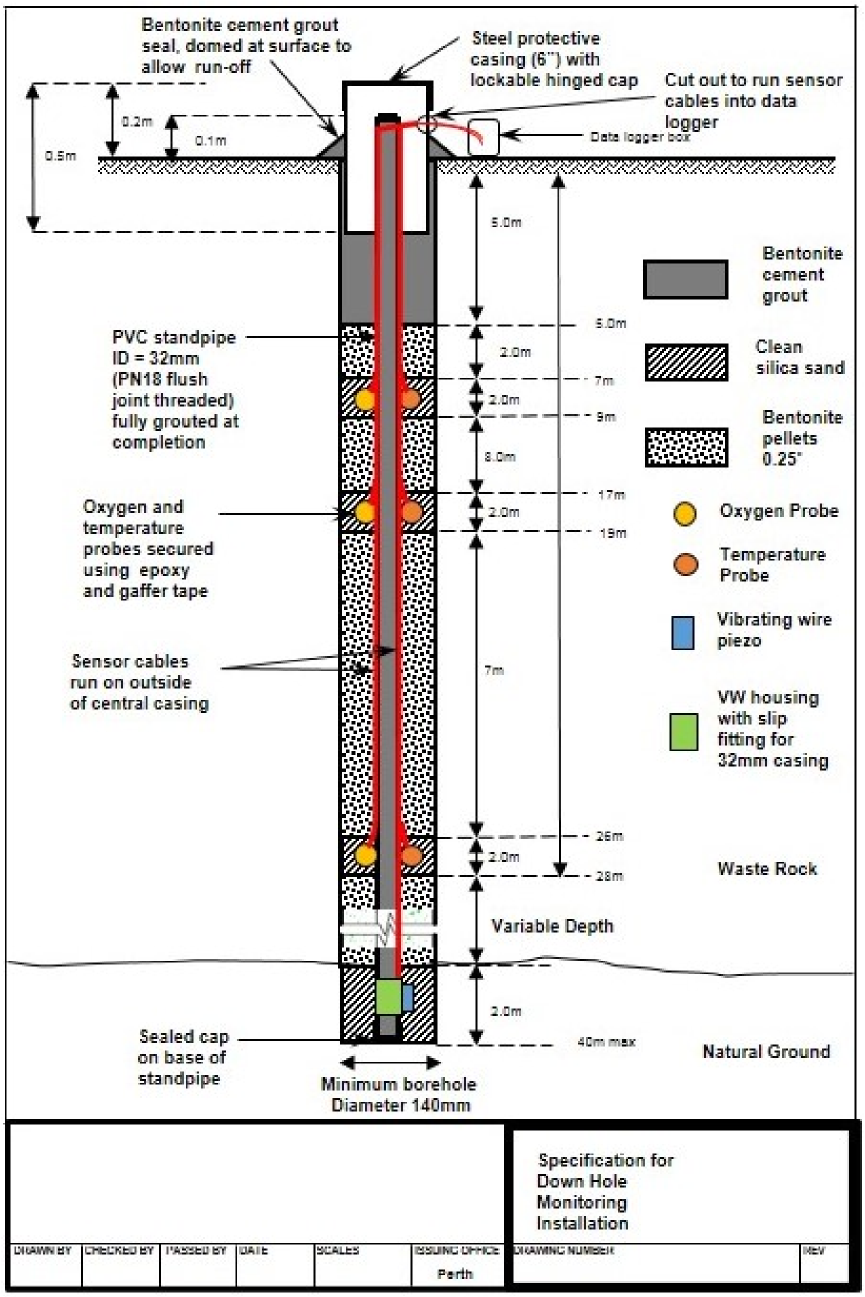

Fig. 5. Typical borehole installation

6.0 DATA ANALYSIS / INTERPRETATION

Preliminary data sets are presented in this section. Significant amounts of data are collected from the study site; however, at this time limited data is available for inclusion in this analysis. Selected data is presented as an initial review with long term monitoring planned for the future.

Figure 6 presents temperature data measured within the waste rock at a selected borehole location. Temperature readings are available from November 1st to November 19th. Temperature in the upper 2 m of the waste has increased fairly constantly over the 19 day monitoring period rising from 33.6°C to 34.8°C, while temperatures from 8 m – 25 m have remained relatively constant between 30 – 32 degrees Celsius. The data indicates the following:

- Temperatures are increasing at shallow depths, this is likely related to increase in ambient air temperatures due to move from spring to summer period
- Temperatures are lowest close to the base of the dump, this is not unexpected as temperature gradients are expected to be inversely proportional to depth given advective forces
- Temperatures are consistent through the middle of the dump and are relatively high. 31 degrees Celsius is a relatively high ambient temperature for the core of the dump and likely explains the low moisture contents given high potential for moisture loss due to evaporation. The consistent temperature profile with depth indicates a high level of convective heat flow through the dump which likely relates to high levels of interconnected advective gas flow

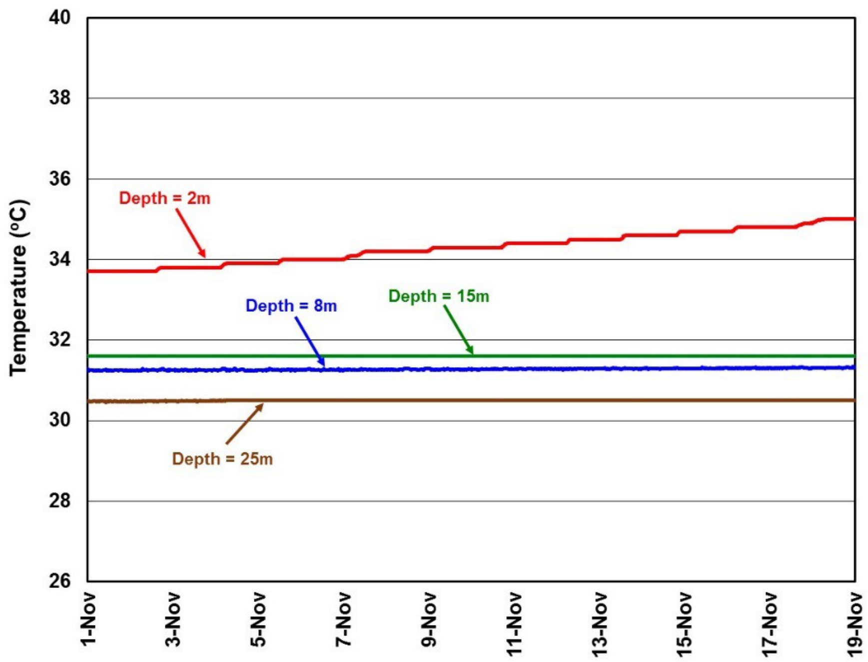

Fig. 6. Temperature profile within the waste rock at selected borehole location

Figure 7 shows the soil suction profile measured by MPS2 dielectric soil suction sensors at a selected borehole location. The reading of 100,000 kPa results from material which is air dry, indicating that the sand pack which the sensors at 8 m and 15 m are installed in are completely dry. The reading of 12 kPa and 21 kPa for sensors at 2 m and 25 m, respectively, shows that these sensors have moisture present within their sand pack. It should be noted that the sand packs were installed dry so any water is likely a result of migration post installation.

Moisture present at 2 m is not unexpected given the influence of precipitation at the near surface. Moisture readings at 25 m however, gives an indication that water is present and is being replenished at the base of the waste rock pile. The fact that the MPS2 sensors are reading air dry in the middle of the pile would suggest that:

- Water has not percolated uniformly from the top of the pile to the base, but has reached the base through basal seepage or preferential flow paths.
- Supports the evidence from moisture content profiles through the dump that show a "wetting front" has not developed
- Supports the temperature data that indicate that high levels of moisture loss may be occurring due to evaporation as a result of advective gas flows through the core of the dump

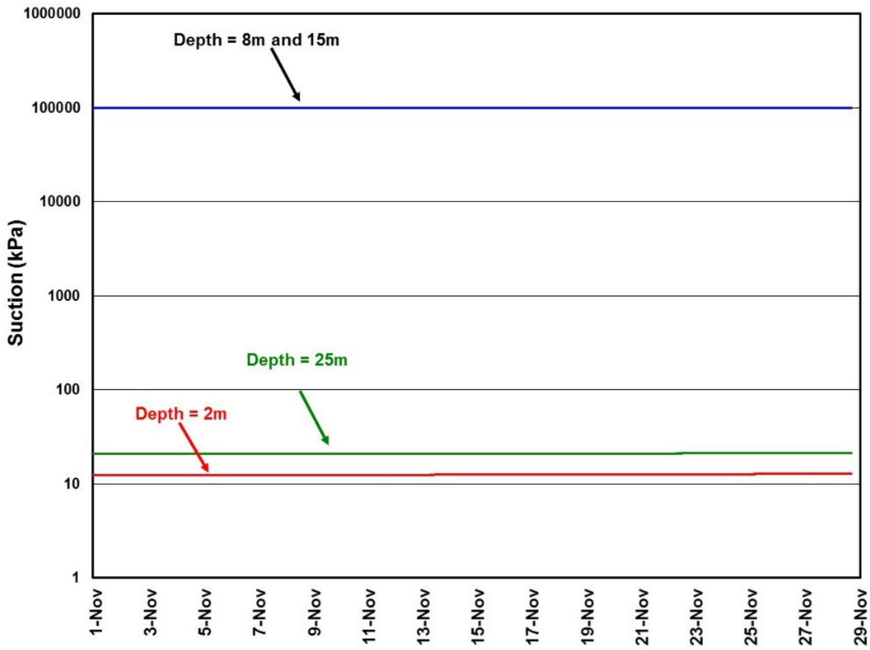

Fig. 7. MPS2 soil suction profile at selected borehole location

Figure 8 shows positive pore-water pressure measured by VWP sensors at a borehole in close proximity to the MPS2 data presented in Figure 7. Data was available at this borehole from October 18th to November 25th. The VWP data shows positive pressure (to a maximum of 10 KPA) conditions developing near the base of the WRD (sensor is installed in the rubble zone just above the contact with natural ground) at a depth of 27m. VWP sensors at 12m and 9m remain relatively unchanged during this time period (readings indicate unsaturated conditions as negative pore pressures are recorded); however, a slight increase in pressure can be seen on November 1st at 9m. The sudden drop in pressure at 27m on November 10th can be attributed to influences on the VWP during initial wetting. A decrease in pore-water pressure can be observed starting November 17th as the waste begins to de-saturate. In total, the time from initial pressure increase (October 28th) to when decreases in pore-water pressure were observed is 20 days. This is notably a fairly rapid response of the base of the dump to a seepage event.

The MPS2 soil suction data in combination with the VWP pore-water pressure results show that wetting is not occurring uniformly with depth (i.e. wetting front is not developing). Rainfall data from a meteorological station in proximity to the study site reported 26mm of rainfall on October 17th likely leading to the pore-water pressure observed (11 days later on the 28th October). Initial trends in the data suggest that the interior of the WRD is remaining relatively dry while the upper and lower extremities experience changes in moisture. The increase of positive pore-water pressure at the base of the dump gives an indication of potential basal seepage which may be occurring, while the time from initial pressure increase to de-saturation can give an idea of seepage rates. The collection and analysis of a larger data set will allow for a more detailed examination of the WRD response to incident precipitation.

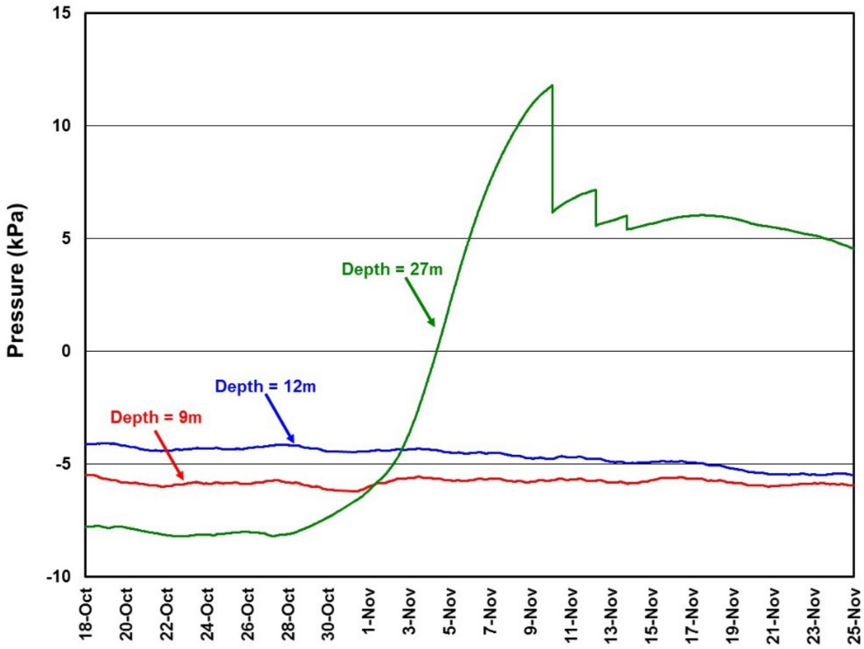

Fig. 8. Pore-water pressure recorded by VWP sensors at selected borehole

Figure 9 shows oxygen concentration with depth at a selected borehole from October 11th to October 29th. The oxygen concentration is slightly depressed in comparison to atmospheric (20.9%) at all depths; however, oxygen levels are above 17% at all depths. The relatively high oxygen levels present throughout the dump profile indicates that significant oxygen replenishment is occurring within the dump. This supports the temperature and moisture data which indicates a high level of air movement (convection/advection) through the dump is occurring

It is noted that the oxygen concentrations oscillate with a daily frequency. These oscillations are more pronounced at 4m depth while at 9m and 16m changes are more subtle. The muted oscillations in the 9m and 16m readings seem to ‘mirror’ those at 4m in that increases in oxygen concentrations at depth are accompanied by a decrease at 4m. Core log information shows that the oxygen probe at 4m is located in a zone of black clay which is highly weathered pyritic black shale. It is worth noting that temperature data does not show significant levels of daily fluctuation as is seen on the oxygen data. This indicates that the loss/gain in oxygen at 4m is not likely to be directly related to daily variations in the supply/consumption of oxygen and rate of oxidation of pyrite in the shale as temperature and moisture conditions are constant. Rather the fluctuations are more likely to be a function of air flow.

The regular (day/night) changes in oxygen levels indicate the dump is ‘breathing’, however the causes of the ‘breathing’ mechanism have not been determined. Some observations are noted as follows. During the night time oxygen levels appear to be increasing at shallow depths indicating the dump may be breathing out (venting to the surface) as a result of convective gradients (due to internal dump temperature being higher than ambient air temperature) bringing higher oxygen air from depth to the surface. During the daytime oxygen levels decrease at shallow depths indicating the flow upwards of air in the dump is stagnated/reduced (as a result of reduced thermal gradients due to higher ambient air temperatures than dump temperatures driving convective air flow) and consumption may be occurring as a result of pyrite oxidation.

It is important to note that air flows within the dump will be complicated by factors such as the stack effect which depends on local wind conditions therefore this breathing model should be viewed as a high level concept of oxygen flows at this time until more data is gathered.

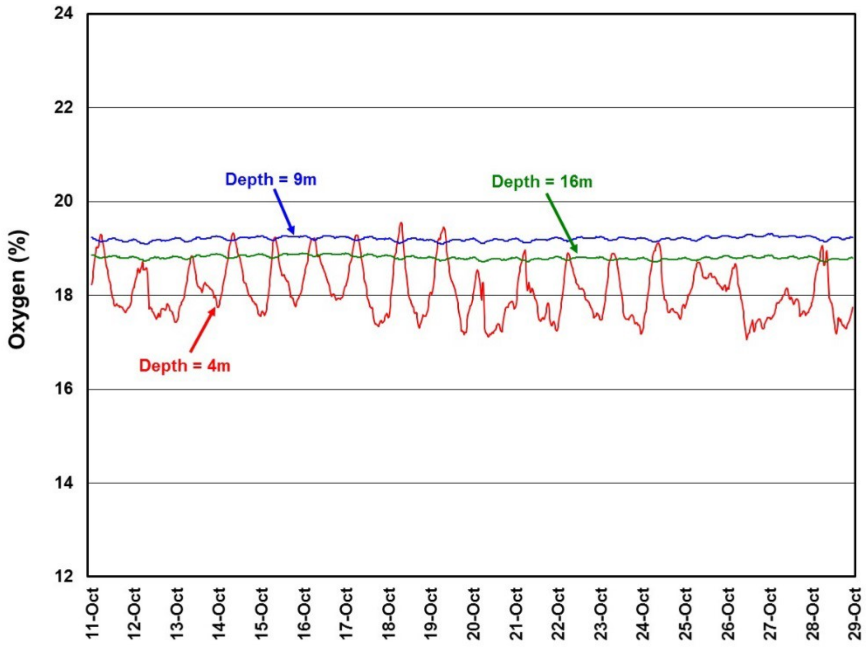

Fig. 9. Oxygen concentration at depth within a selected borehole

7.0 SUMMARY

A monitoring system comprised of 90 sensors was installed and commissioned in a number of WRDs in the Pilbara, Western Australia in 2013. The monitoring system records temperature, oxygen concentration, matric potential and pore water pressure data at depth within the waste rock. 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. The monitoring system in conjunction with detailed logging of WRD structure allows for an understanding of WRD hydrology to be further developed, and for controls of AMD production to be understood as well as releases to the surrounding environment to be predicted. Remote communications allows the real time monitoring and evaluation of the WRDs response to climatic forcing and the effect this has on AMD production.

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

- Wetting of the WRD’s is not occurring uniformly throughout the waste, i.e. a 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
- 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 significant size wetting front from developing
- The WRD’s appear to be breathing as a result of the response of the dump internally (convection/advection) to daily ambient temperature fluctuations
- Basal seepage is occurring as a result of fast drainage of infiltrating waters through coarse waste horizons (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.

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