The impact of co-disposal of sulphate brines on a fly-ash dam, a study of the physical-chemical influence on drainage patterns

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Abstract

The burning of pulverised coal in coal-fired boilers to generate heat causes the production of fly ash, water used in the process of cooling and turbine propulsion results in the production of high saline effluents. The high saline streams (ca. 20 % ash) are used for the hydraulic transport of ash to the dumping sites. The slurry that is pumped onto the wet dump area is allowed to settle. The water that has separated from the ash is skimmed off and re-circulated to transport more fly ash to the site.

In order to effectively manage the dam facility, a generalized conceptual model was required that incorporated the main physical and chemical process that occur at the site. The characterisation of the site included electrical resistivity surveys of the area, time-lapse electrical resistivity infiltration surveys, geohydrological classification of hydraulic properties, leach testing and recharge event impacts on the fly ash dam. Most of these studies were focused on post-production scenarios and the effect the site would have on the environment, i.e., total leachate production and identification of receptors in the environment.

Keywords: fly ash, time-lapse electrical resistivity, infiltration mechanism, transport

Introduction

The burning of pulverised coal in coal-fired boilers to generate heat causes the production of fly ash. The energy released from this process is converted from thermal energy into steam energy which can be used to generate electrical power through steam turbines. Petrik et al. (Petrik et al. 2007) reported that a low rank bituminous coal, consisting of a mixture of banded and sapropelic coal generally rich in volatile hydrocarbons (Kearey 2001) is generally used in gasification and combustion processes. Approximately 28 Mt of coal per annum (70 % of the coarse coal feedstock) is consumed by the gasification process at an industrial site which results in the production of about 7 Mt of gasification ash. The remaining 30 % of the coal utilised, a finer coal fraction, is combusted to produce steam and electric power. Coal ashes which comprise gasification ash and fly ash are the by-products of these processes. The industrial site uses ca. 0.25 l/day of fresh water for steam generation and process cooling in its coal to fuel and chemical processes. The high saline streams (ca. 20 % ash) are used for the hydraulic transport of ash (ca. 4.75 Mt/a) (Krüger 2003).

Current fly ash management options are based on two strategies, i.e., Disposal and Recycling. Disposal of fly ash in confinement areas remains the most practical and cost effective solution for South African industries. Typical disposal techniques include the construction of dumps or dams, similar to those employed within the mining sector. Fly ashes can either be dry dumped by means of truck loads or conveyor belts or it can be dumped as slurry in a so-called wet dump facility. Wet dumps are created when fly ash is mixed with a liquid, often also a secondary waste product produced by coal firing facilities to create the slurry. The slurry is then pumped and discharged onto the wet dump where density settlement separates reusable water from the slurry which is then left to dry over a time period. The water that has separated from the ash is skimmed off and re-circulated to transport more fly ash to the site.

Development of an Initial Conceptual Model

Typically disposal sites are conceptualised in such a manner that the flow of water is assumed to be from the top to the bottom, with evaporation and return water systems removing excess water from the pond located on the dam structure (Figure 1). However, there is a certain amount of uncertainty associated with this assumption since infiltration rates into the study waste disposal site presented in this paper does not seem to follow these general guidelines. Due to the layered structure of the dam (Figure 1) and the particle size of fly ash, it was proposed that a heterogeneous system with high anisotropy would be expected. The net effect of this would be that both vertical and horizontal flow paths would need to be investigated.

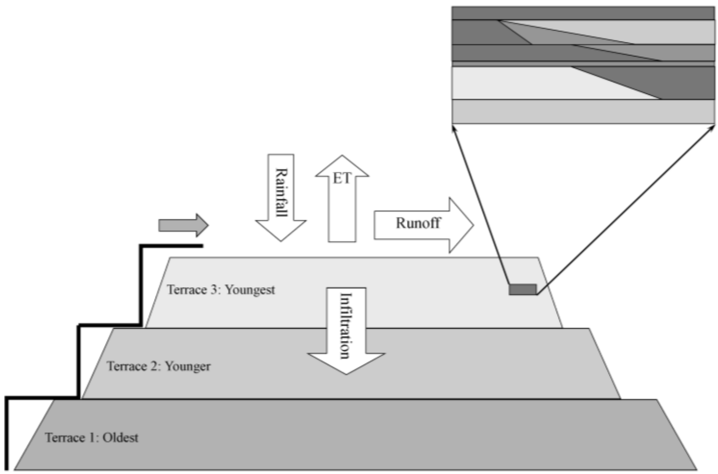


***Figure 1** Construction and initial conceptual model of fly ash dam, showing the hydrological processes.*

Physical properties of fly ash on site

Two types of particles shapes have been identified from the fly ash present at the study site. The more abundant particle morphology is a spherical shape which is either solid or hollow glassy (amorphous) particles. In contrast the carbonaceous particles are more angular in shape and cubic. The particle sizes are comparable to that of silt (less than 0.075mm). The fly ash produced from sub-bituminous coal combustion is generally slightly coarser than that observed for higher grade coals (U.S. Department of Transportation 1998). The specific gravity (Cairncross, 2004) of fly ash ranges form 2.1 – 3.0. The specific surface area may range from 170 – 1000 m^2/kg (U.S. Department of Transportation 1998). The colour of the fly ash is highly dependent on the source and effectiveness of the coal-fired boiler used. Typically, the darker the ashes, the higher the unburned carbon content, which is a direct indication of boiler efficiency. Lighter shades of grey can be associated with higher quality of ash as found in the industrial site (U.S. Department of Transportation 1998). In Figure 2 a 200 μm by 100 μm is shown, particle size distribution seems to vary from 20 μm to less than 1 μm. Furthermore, larger particles are in part composed of a conglomerate of smaller particles.

Lithology effects

The layering of the subsurface zone or the lack of it can play an important role in the hydraulic movement of water in the subsurface. Firstly, the porosity of the medium can determine the absorption rate and transport through the medium. Considering only the porosity of a system, the movement will be much higher in coarse media than fine grained particles under saturated conditions. The behaviour of water in the subsurface is to follow the path of least resistance. Furthermore, if preferred pathways exist in the subsurface then the infiltrating water will be transported from the surface zone to the groundwater level at a significantly enhanced rate.

Secondly, the local water level gradient in the area in combination with the lithology of the subsurface can either act as a barrier or a preferential pathway. In contrast soluble components would move in the direction of groundwater flow and would experience typical hydrodynamic dispersion and eventually occur in low concentrations in the down gradient areas of the aquifer.

Finally, the homogeneity of the subsurface will also play an important role in the movement of water. Considering the type and extend of no-flow boundaries and aquitards in an area can have a significant effect on the distribution of water and solutes in the subsurface.

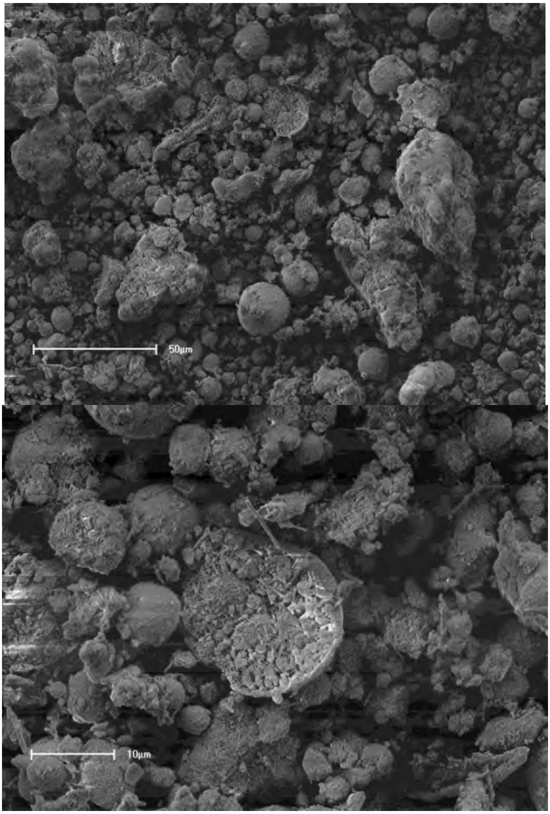


Figure 2 *Scanning electron microscopy (SEM) photos of industrial fly ash at 50 and 10 micron meters, respectively.*

Geophysical classification

The geophysical characterization of the ash impoundments was done in order to map the subsurface salts and moisture content using Electrical Resistivity method. Compare geophysics profiles of two different time periods to evaluate the likely movement of salts and water through the impoundment sites. Electrical resistivity methods can benefit the investigation of the ash dump and its sustainability by:

- Providing a fast non-intrusive method to characterise and map salt distribution and water content; which eliminates the need to drill boreholes which may cause additional preferential pathways through the ash dump to the underlying aquifer system.
- Mapping of salt distribution and water content in the unsaturated part of the ash dump. Electrical resistivity varies between different geological environments and depends mainly on variations in water content, dissolved ions and the composition of the matrix. Time dependent

surveys can help to identify whether there are changes in the salt and water content in the ash dump over time;
- Mapping zones in the underlying geology where potential contaminants will preferentially infiltrate the groundwater system.

Electrical resistivity (ER) is a direct current (DC) resistivity technique that measures electric potentials generated by a current source either on the earth's surface or in the subsurface. These potentials are indicative of porosity, the amount and connectivity of pore fluid, and the pore fluid chemistry. The measured potential gives an image for the difficulty of the current flow through the subsurface. Data from resistivity measurement are customarily presented and interpreted in the form of values of apparent resistivity. Apparent resistivity is the resistivity of an electrical homogeneous and isotropic half-space that would yield the measured relationship between the applied current and the potential difference for a particular arrangement and spacing of electrodes.

The resistivity of any earth material generally depends on the interstitial water of resistivity, porosity, and saturation, and is linked via the general form of Archie's law which is given as:

$$R_t = \frac{R_w}{\Phi^{\mathrm{m}} S_w^n} \qquad (1)$$

Where R_t is the observed resistivity of the sample, R_w is resistivity due to the fluid in the sample, Φ is the porosity of the medium, S_w is the electrical conductivity due to salt concentration, m is the cementation exponent, which is a property of the medium and n is the salt saturation exponent.

An Abem SAS 4000 terrameter and ES 10-64 switching unit was used for the field survey. Four multi-core cables and stainless steel pegs were used with the "roll-along" surveying method. Measurement of the resistivity of the ground is carried out by transmitting a controlled current (I) between two electrodes pushed into the ground, while measuring the potential (V) between two other electrodes. Direct current (DC) or a very low frequency alternating current is used.

The RES2Dinv version 3.52-inversion program was used to invert the measured data. The 2-D model used by this program divides the subsurface into a number of rectangular blocks that will produce an apparent resistivity pseudo section that agrees with the actual measurements. A forward modelling subroutine is used to calculate the apparent resistivity values, and a non-linear least-squares optimization technique is used for the inversion routine. The optimization method basically tries to reduce the difference between the calculated and measured apparent resistivity values by adjusting the resistivities of the model blocks. A measure of this difference is given by the root-mean-squared (RMS) error. However the model with the lowest RMS error can sometimes show large and unrealistic variations in the model resistivity values and might not always be the "best" model from a geological perspective.

Results and Discussion

Three traverses were done at the site ranging from 800 meters to 1 100 meters in 2006. It was assumed that the site is underlain by a Karoo dolerite sill and that no ash was dumped north of the existing dump in the past. Modelled resistivities between 3 and 10 Ohm.m (approximately), can be associated with highly weathered dolerite (clay) as well as ash (Figure 2 and Figure 3).

In Figure 2 a low resistivity zone is observed in both the fly ash dam and the surface strata of the surrounding area. Irregular zones of slightly higher resistivity values can be observed in the fly ash as indicated by green/yellow areas in the figure. Most likely the cause of these areas might be the evaporation of water from the surface, causing an increase in conductivity measurements. The presence of less weathered to fresh dolerite in the subsurface is indicated by the higher resistivity measurements (red-brown contours), this was also confirmed by an extensive drilling program. The extension of the geological formation under the ash dam is observable as seen from the light and dark green contours under the ash dam. However the approximate elevation of the weathering zone should be considered only as an indicative range since the measurement spacing's were not varied to compensate for the change in elevation. No significant decrease in resistivity could be observed from the movement of salt-bearing water into the geological formation as indicated in the lower section of Figure 2. The presence of less weathered to fresh dolerite in the subsurface decreases the movement to deeper levels in the immediate vicinity of the fly ash dam.

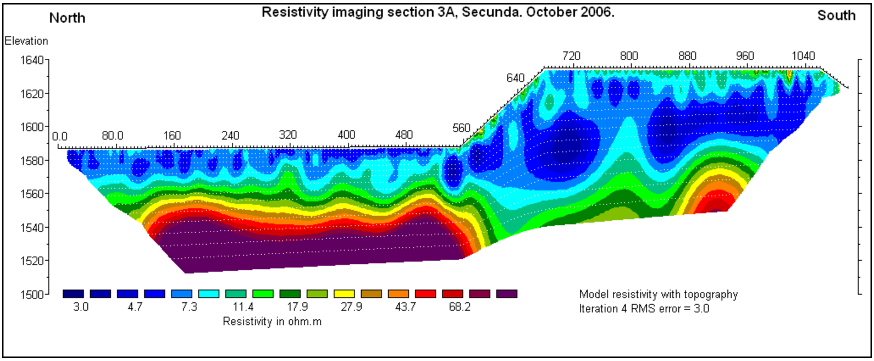


Figure 2 *Resistivity imaging of section of the surrounding area and the fly ash dump was done over a one kilometre area. On the left side of the image the surrounding area is mapped while on the right-hand side the fly ash dam influence is shown.*

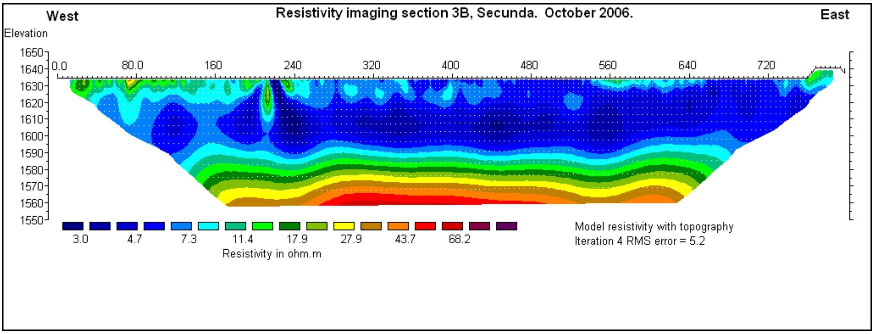


Figure 3 *Resistivity imaging of a section of the surface area of the fly ash dam.*

Figure 3 represents a traverse over only the fly ash dam surface, and the presence of the underlying geological formations can be clearly observed at 40 – 50 meters below the dam. The extent of this area is reasonably uniform and of consistent composition. A clear stratification of contour layers can be seen in Figure 3, indicating a dual resistivity model. In the top fly ash section low resistivities are observed, indicating a wet and/or highly brine saturated zone. The surface clearly shows areas in which high resistivity regions exist, which are either a result of evaporation and/or leaching of conductive salts. The lowest resistivity areas in Figure 3, is most likely associated with saturated and/or highly salt loaded regions which occur ca. 30 meters below the surface.

Combining the observations of Figure 2 and Figure 3 into a conceptual model, it can be postulated that the low resistivity zones are locked in the middle of the ash dam – indicating either highly saturated conditions and/or highest concentration of salts present in this area. The presence of high resistivity areas above and below the saturated and/or high salt concentration areas clearly points to a confined system. Due to the nature of the observation method and temporal scope no movement of water and/or salts could be observed.

Infiltration ERT study

The survey geometry employed during the time-lapse ERT surveys on the Ash Dam is depicted graphically in Figure 4. An injection pit was dug into the ash at the selected position. Time-lapse ERT data were recorded along two profiles (west/east and north/south), both centred at the injection pit. The time-lapse ERT survey on the Ash Dam was conducted using the Lund Imaging System with a Wenner geometry and a standard electrode spacing of 1 m in order to record resistivity data with a high spatial resolution. Due to surface constraints (an embankment and an access road) the north/south profile was limited in its length, extending 12 m to the north and 14 m to the south as measured from the centre of the injection pit. The west/east profile extended 20 m in each direction from the centre of the injection pit. The maximum separation of 40 m between the electrodes on this profile allowed a maximum depth of investigation of approximately 7.5 m (compared to approximately 4.3 m on the north/south profile). A photograph of the survey setup is shown in Figure 5.

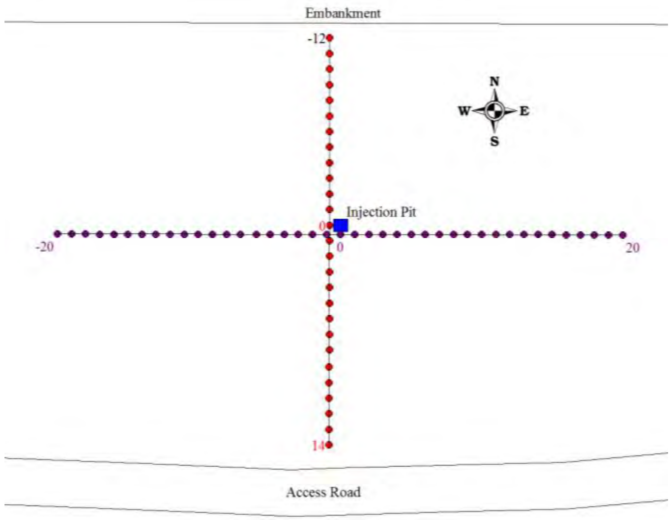


Figure 4 *Survey geometry employed during the ERT investigations.*

The time-lapse ERT survey was conducted over three phases, namely a background investigation phase, and a constant head injection phase followed by a recovery phase. The background investigation phase consisted of ERT surveys on both the west/east and north/south profiles prior to brine injection. The purpose of the background investigation phase was to yield models of the resistivity sections along the two profiles against which the constant head and recovery profiles could be evaluated to investigate the fluid flow patterns through the ash. During the constant head injection phase, the brine level in the injection pit was kept constant at the surface level of the ash by continuous injection of brine (see Figure 5). The constant head injection phase lasted 282 minutes (4 hours, 42 minutes). During this time period, 14 sets of ERT data were recorded, i.e., 7 sets for the respective west/east and north/south profiles. The recovery phase commenced after brine injection was terminated. Sixteen sets of ERT data were recorded along each of the west/east and north/south profiles. The recovery phase of the investigation lasted 2,880 minutes (48 hours). After acquisition, the recorded ERT data were inverted to obtain models of the subsurface resistivity distribution. Model blocks with widths of half the standard electrode spacing were employed during inversion to model the spatial distribution of resistivities.

Figure 5 *Photograph of the survey setup (view towards the south-east). A constant head level with the ash surface is maintained in the injection pit during the injection phase.*

A time variance resistivity experiment was performed on a smaller area using a mass infiltration system. A zero baseline of the site was taken and is shown in Figure 6. A general analysis of this figure indicates two different zones; (1) the top zone which is the area from 0.0 – 2.7 meters and (2) the bottom zone is located from 2.7 – 7.0 meters below surface.

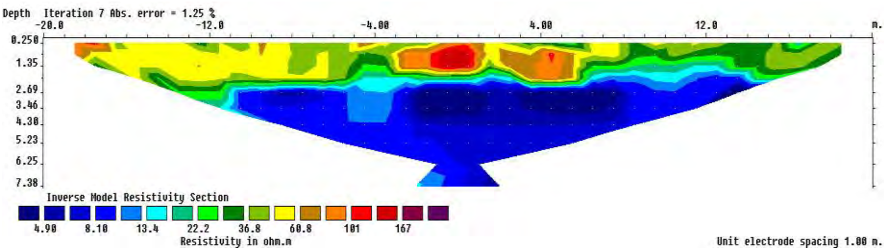


Figure 6 *Resistivity imaging of the top section of the fly ash dam. A cross-profile of the surface area of the fly ash dam is presented. A hole was dug at position 0 (centre of figure) which was 1 m x 1 m in extent and 0.5 m in depth. The impact on the resistivity measurements can be seen in this area, with an elevated resistivity reading*.

The top zone in Figure 6 can be attributed to the weathering of the fly ash, creating a higher resistivity zone which might be due to the absorption of carbon dioxide to form carbonates in this zone. The bottom zone most likely is in a higher saturation phase and unweathered. The chemical composition between these two zones probably differs. From Figure 6 differences in resistivity can be observed in each layer indicating a heterogeneous composition of the zones. Although it should be kept in mind that at the top at zero meters (centre) a hole was dug (0.5 m deep) which created an artefact due to high resistivity. It can be observed that the top layer differs significantly on the left and right-hand sides of Figure 6. The difference in resistivity can be attributed to the deposition method employed by the company in constructing the fly ash dam.

In order to investigate the hydraulic properties of the dam an infiltration test was done to elucidate possible movement of water in the subsurface. In the following paragraphs preliminary results of the test are discussed. Experimental procedure is as follows: A constant head (nearly level with surface) was maintained in the 1 m x 1 m x 0.5 m hole over a period of ca. 5 hours. Resistivity measurements were done over 3 day time frame and only the initial section.

Figure 7 indicates a resistivity measurement after 28 minutes with a constant head at the surface at a position of 0 m. The heterogeneity in the resistivity can be observed across the profile of the contour map with a highly conductive zone present at the infiltration hole position and below 2 meters. A preliminary percolation can be observed below the infiltration point with a decrease in resistivity. Zones of high resistivity are present on the sides of the infiltration zone and could be a product of saturation and mobilization of salts. In Figure 8 the expansion of the lower resistivity zone around the infiltration zone can be observed, although resistivity decrease seems to occur in both the horizontal and vertical directions. This trend is continued if one considers the 1 hour and 46 minutes (Figure 9) and 4 hours and 22 minutes (Figure 10) contour figures.

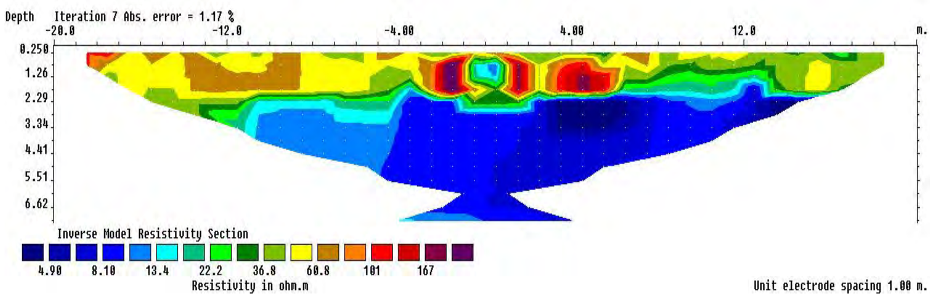


Figure 7 *Constant head resistivity measurement after 28 minutes.*

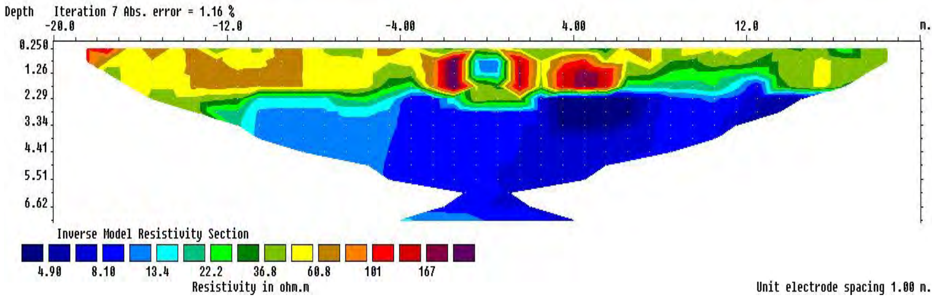


Figure 8 *Constant head resistivity measurement after 1 hour and 8 minutes.*

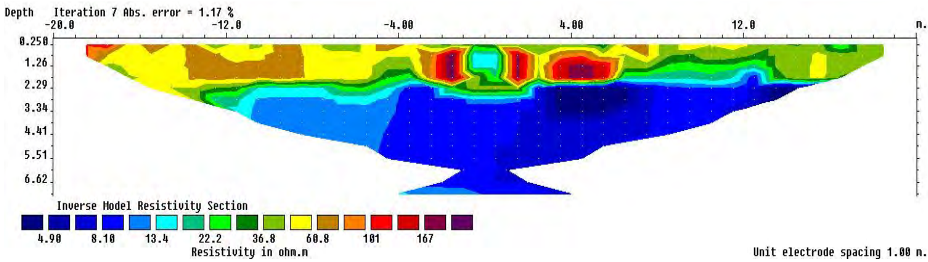


Figure 9 *Constant head resistivity measurement after 1 hour and 46 minutes.*

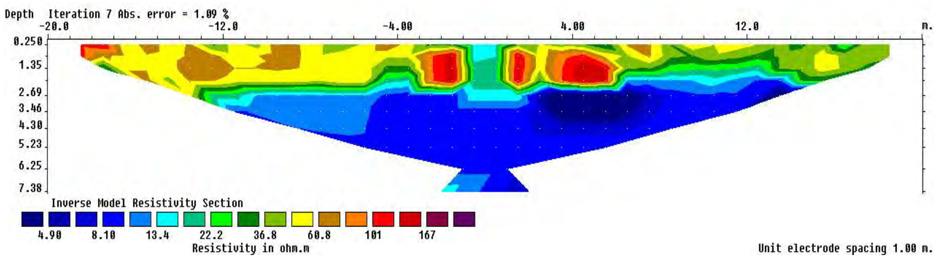


Figure 10 *Constant head resistivity measurement after 4 hour and 22 minutes.*

Clearly the infiltration of water in this system will follow both the horizontal and vertical flow direction paths.

Time lapse infiltration results for West-East Profile

To assist in visualising the migration of the brine plume, the background resistivity model was subtracted from the models of the injection (Figure 11) and recovery (Figure 12) phases.

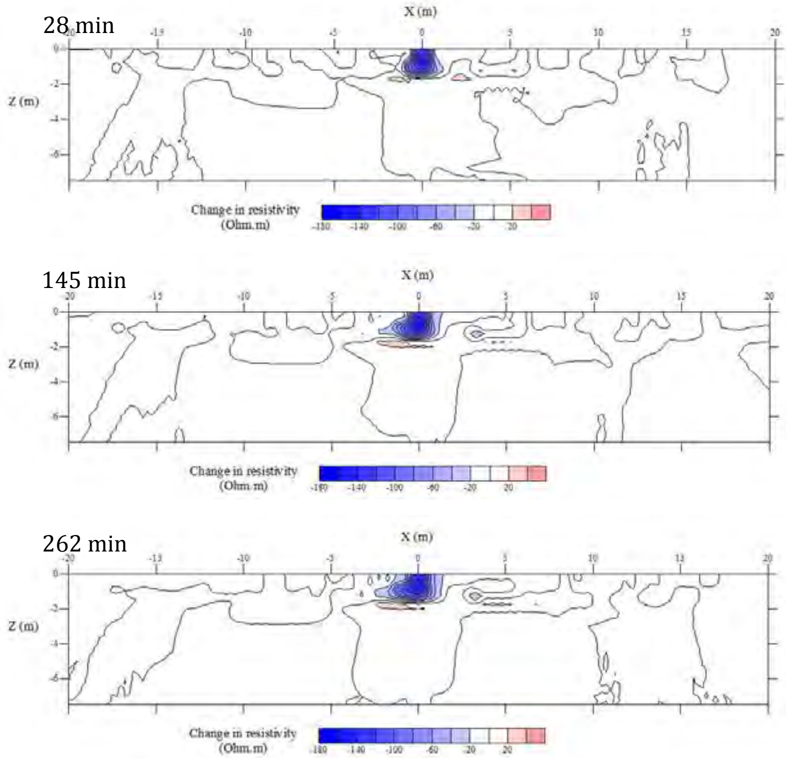
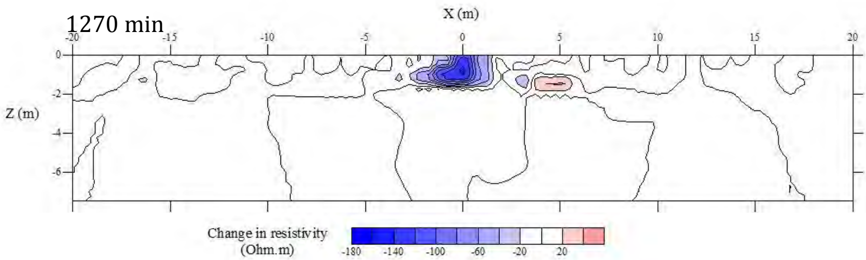


Figure 11 *Changes in the modelled resistivity values (as compared to the background values) along the west/east profile at specified time intervals after brine injection commenced (under constant head conditions).*



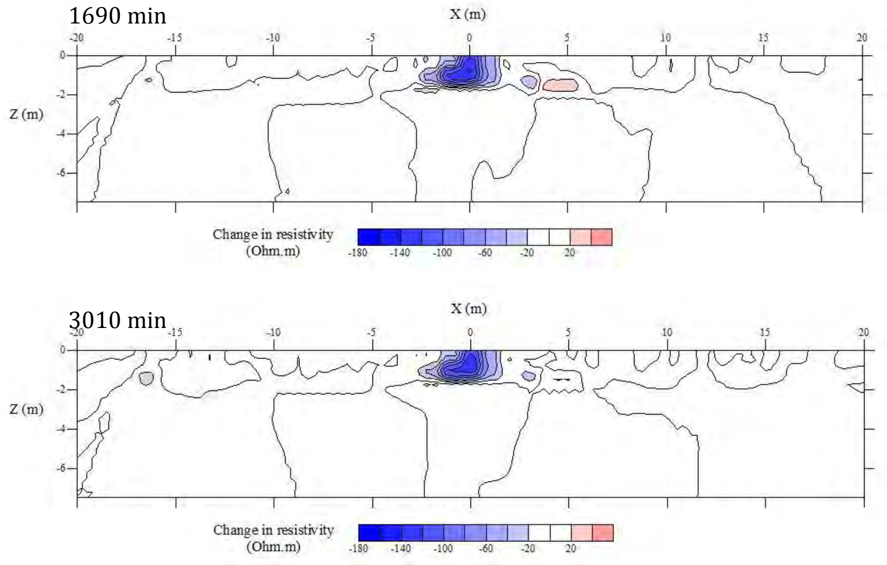


Figure 12 *Changes in the modelled resistivity values (as compared to the background values) along the west/east profile at specified time intervals after brine injection commenced and removal of constant head.*

A similar profile was recorded for the north/south traverse at the test site and showed a similar type of infiltration pattern as the west/east profile system.

Estimation of horizontal and vertical flow rates

Estimation based on flow distances

By considering the flow distance observed over the time period spanning the time-lapse ERT surveys, an upper estimate of the brine flow rates through the ash may be obtained. Since horizontal flow is seen to dominate over vertical flow, yielding measurable changes over distance and time, the estimation is only done for horizontal flow. These values correspond to average flow rates of between 0.70 and 1.1 m/day. Since the flow rate can be expected to decrease with distance from the injection pit, these estimates of the flow rates may be considered as the upper estimates of the average horizontal flow rate.

It should be appreciated that the apparent horizontal distances travelled by the brine plume are to a larger extent dependent on the effects of contouring the resistivities at adjacent model cells with widths of 0.25 m. There is therefore much uncertainty as to the true distances travelled by the plume. The above estimated flow rates should therefore be seen as very crude estimate at best.

Estimation of flow direction

In this section the flow direction of the brine or moisture front in the subsurface can be estimated using the two north/south (Figure 13) and west/east (Figure 14) ERT profiles.

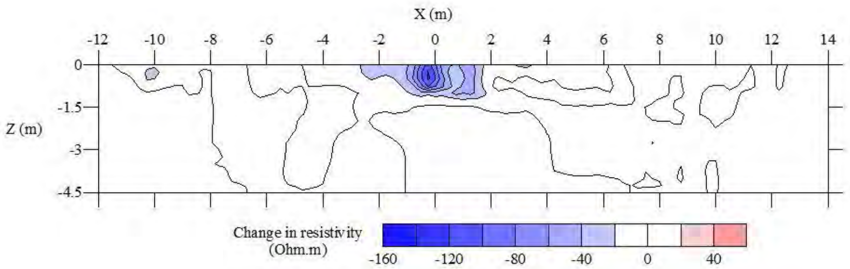


***Figure 13** Changes in the modelled resistivity values (as compared to the background values) along the north/south profile 3160 min (52 hr, 40 min) after brine injection commenced (2880 min after removal of constant head).*

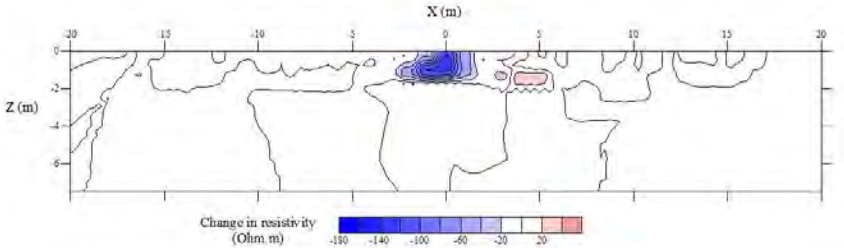


***Figure 14** Changes in the modelled resistivity values (as compared to the background values) along the west/east profile 3130 min (52 hr, 10 min) after brine injection commenced (2850 min after removal of constant head).*

Combining the two profiles and assuming a radial vector interaction the estimated flow direction is in south-western direction. This could indicate that during the depositional construction of the dam, a fan type structure could have existed at this point. It should also be noted that the flow is mostly horizontal.

Conclusion

The differences in hydraulic properties were clearly evident and the application of ERT type measurements assisted in the elucidation of flow paths and brine dispersion in the fly ash dam. A horizontal flow model could be verified for this area on the dam structure which would indicate a rapid lateral flow path and over time and a steady percolation to deeper zones if the water is not removed from the structure.

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