COMPARISON OF MEASURED AND PREDICTED TRANSPORT PROCESSES CONTROLLING OXIDATION IN THE WASTE ROCK PILES AT THE HEATH STEELE MINE SITE[1]

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Abstract: The numerical model FIDHELM has been applied to waste rock pile 18B at the Heath Steele mine site in New Brunswick, Canada, with the aim of studying gas transport mechanisms related to the generation of acid drainage. FIDHELM includes the physics of gas, water and heat flow through a porous heap of oxidisable material in two spatial dimensions. Field measurements of oxygen diffusion coefficient, gas permeability and thermal conductivity were used as input data to the model. A range of typical values for the intrinsic oxidation rate (IOR) of waste rock were used. Measured average summer values of pore gas oxygen concentration distributions in pile 18B were used for comparison with the results of the modelling. Using homogenous material properties and constant boundary conditions, the FIDHELM output indicated that the oxygen profiles observed in part of the pile could be diffusion controlled. The runs could not however adequately represent the broad features of the measured oxygen concentration distribution. It has been suggested that air pressure differences at the boundary of the pile, produced by wind effects, and heterogeneous distributions of gas permeability and IOR in the pile may explain the observed oxygen concentration distribution. It is proposed that a further program of field measurement and FIDHELM modelling should be carried out to test these possibilities and assess their relative contributions.

Key Words: acid rock drainage, FIDHELM, modelling, intrinsic oxidation rate, oxygen diffusion coefficient, gas permeability, thermal conductivity.

Introduction

The oxidation of pyritic waste rock and the subsequent generation of acid rock drainage requires the supply of oxygen to the reaction sites. It is well-recognised that in many situations it is the oxygen supply rate which controls the oxidation rate, leading to the need to have a good understanding of gas transport mechanisms in waste rock piles in order to predict the behaviour of such systems. Acid rock drainage research under the Canadian Mine Environment Neutral Drainage (MEND) program has been undertaken at the Heath Steele mine site since 1988. The work described in this paper was part of the MEND project "Assessment of Gas Transfer - ANSTO Model at Heath Steele Mines" (1). The aims were: (a) to apply a numerical model which incorporated gas transport mechanisms to a particular waste

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rock pile, using measured parameters as input data, (b) to compare the results of the modelling with measured pore gas oxygen concentration profiles and (c) to evaluate the adequacy of the model to describe the behaviour of the system.

Background

The Heath Steele Mines site is located 50 km north of Newcastle in New Brunswick, Canada. The coldest months are January and February with mean daily temperatures of -12.5°C; July is the warmest month with a daily mean of 17.9°C. Mean annual precipitation is 1134 mm, of which 762 mm is rainfall. Winds are predominantly from the north-west.

Over more than 30 years of operations at least 756,000 tonnes of pyritic waste rock and reject ore have been dumped in more than 20 piles at the Heath Steele site. Pile number 18B which was chosen for this study has a volume of 8,300 m^3, with the bulk specific gravity of the rock estimated to range from 1.8 to 2.3. The surface area of the pile is 3,570 m^2 and the maximum thickness is 6.7 m. Sulphides are present as pyrite and pyrrhotite (each at 7-10%).

Instrumentation was installed in pile 18B at the end of 1988 to enable pore gas oxygen concentration profiles to be monitored on a regular basis. Figure 1a shows a plan view of the pile and the location of the probe holes. Figure 1b shows a cross-section through the pile, along the line of the probe holes numbered 1 to 6.

Numerical Model

Description

The computer model FIDHELM (2, 3) was produced by the Australian Nuclear Science and Technology Organisation (ANSTO) as a finite difference heap leaching model. It includes the physics of gas, water and heat flow through a porous heap of oxidisable material in two spatial dimensions. It can represent a two-dimensional vertical slice through a waste rock pile or, as was done in this study, a truncated cone using cylindrical coordinates.

Oxygen supply is considered in the model as a two-stage process whereby oxygen moves from the air through the pore space of the pile, and from there to the reaction sites within the solid particles. The model incorporates gas transport by diffusion (driven by concentration gradients) and advection (driven by pressure gradients). The pyrite oxidation reaction is described as the consumption of oxygen and sulphur and the generation of heat and sulphate. The version of FIDHELM used in this project did not allow for spatial heterogeneities in the physical and material properties of the pile. Nor was there provision for spatial or temporal variation in the boundary conditions applying at the surface of the pile, such as air temperature and air pressure caused by the wind.

Data Requirements

A basic parameter required by the model is the rate of oxygen consumption by the material at any point in the pile under the conditions which apply at that point. This is called the intrinsic oxidation rate (IOR) and is generally expressed in units of $kg(O_2)\ m^{-3}\ s^{-1}$.

The IOR may depend on many parameters such as physical conditions (e.g. temperature, particle size distribution, type and form of sulphide mineral), chemical conditions (e.g. oxygen concentration, sulphur density, pH) and microbiology (e.g. bacterial type, bacterial density). In practice, only limited data are available for the dependence of IOR. In the version of FIDHELM used in this work the IOR is considered to be proportional to both oxygen concentration and sulphur density. The IOR is taken to be

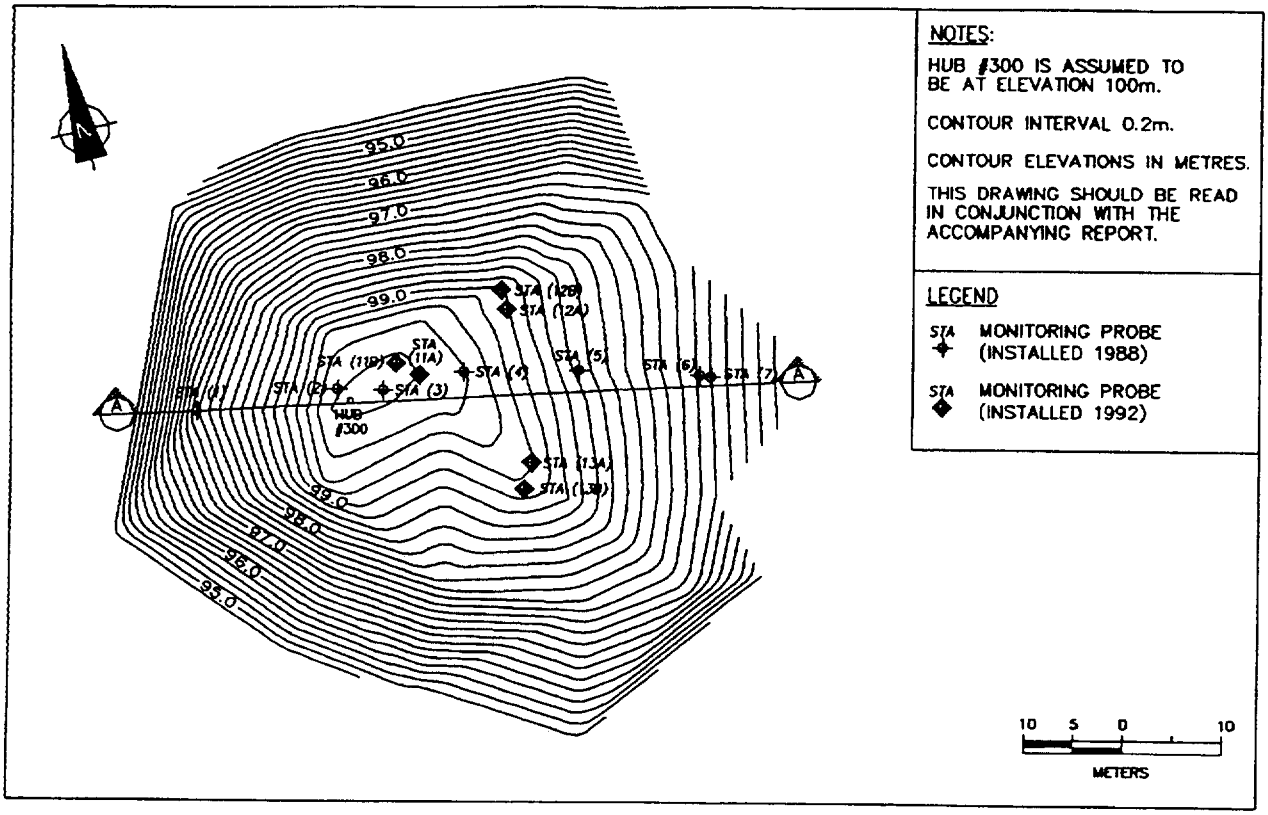

Figure 1a - Plan View of Waste Rock Pile 18B

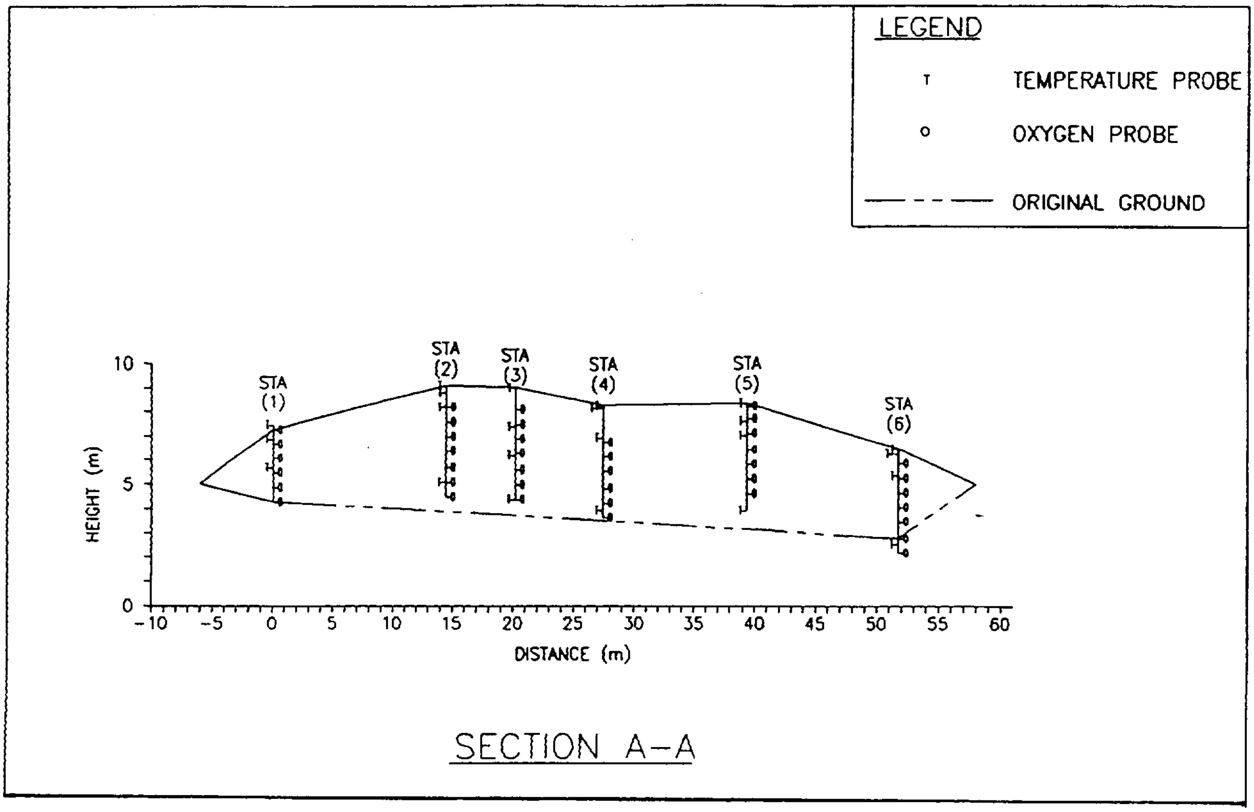

Figure 1b - Cross-Section through Waste Rock Pile 18B independent of temperature up to a value of 40°C, after which it decreases linearly due to the diminishing activity of the catalysing bacteria, until oxidation ceases at 50°C.

Three physical parameters required by FIDHELM, oxygen diffusion coefficient, gas permeability and thermal conductivity, were measured in pile 18B as described below. The oxygen diffusion coefficient is a term of proportionality relating oxygen flux to oxygen concentration gradient and therefore governs the diffusive transport rate of gas in the pile. The gas permeability of the material in the pile is a coefficient which relates the gas advective velocity to an applied pressure gradient (arising from density gradients produced by temperature differences, for example, in which case the mechanism is often referred to as convection). Thermal conductivity relates the heat produced by the oxidation reaction to the consequent temperature distribution in the pile.

Methods

Site Installations

Three pairs of monitoring probes were installed in pile 18B in May 1992 to allow the measurement of the physical parameters described above. At each of the locations, numbered 11, 12 and 13 on Figure 1a there were two monitoring probes spaced about 1.5m apart (labelled A and B on the figure). The three locations were distributed to allow the variation of the measured parameters in the pile to be estimated.

An air rotary percussion hammer, 150 mm diameter, was used to drill through the full depth of the waste rock pile, following which a prepared PVC liner was inserted into the drilled hole. Nylon tubes (3 mm internal diameter) were attached to the outside of the liner to allow the gas measurements to be made. A pair of tubes extended to each metre depth and were attached to opposite sides of the liner. The hole was then backfilled with a layer of gravel around the open ports of each pair of gas tubes, and sand and bentonite sealing layers were placed between the pairs of ports to prevent preferential flow of gas along the liner during measurements. Each of the six probe holes was sealed at the surface with 300 to 400 mm of bentonite to prevent the preferential entry of surface water and air into the backfill.

Oxygen Diffusion Coefficient

The oxygen diffusion coefficient of pile 18B was determined by the injection and subsequent monitoring of the movement of a tracer gas, sulphur hexafluoride (SF_6). SF_6 is an inert, non-native gas which is insoluble in water and is not consumed in the pile. SF_6 was injected into the pile through one of the installed gas tubes. Samples of pore gas were periodically withdrawn from the pile and analysed for the tracer gas using a portable gas chromatograph. Each measurement was made over a period of about 24 hours to allow time for the tracer to diffuse over the distance of at least 1.5 m between pairs of monitoring probes.

These measurements produced values for the diffusion coefficient of SF_6 in the pile which were converted to oxygen diffusion coefficients, on the basis that both gases diffuse through a background gas which can be approximated as air.

Gas Permeability

To make the gas permeability measurements, dry compressed air was injected into the waste rock pile through one of a pair of pressure tubes. The second pressure tube, fixed on the other side of the liner, was used to monitor the consequent pressure rise in the gravel-filled chamber. The air flow was measured using a mass flow meter and pressure transducers monitored the pressure rise. The instruments were interfaced to a laptop computer. The gas permeability of the pile at the measurement position was found by applying a theoretical relationship between air flow, pressure rise, chamber geometry and backfill permeability.

Thermal Conductivity

The measurement of thermal conductivity involved placing a linear heat source at some depth in a one of the monitoring probe holes and recording the temperature in the liner over a period of about 10 hours with the heat source switched on and then for a further 10 hours after it was switched off. The two data sets obtained in this way were fitted with theoretical curves to obtain estimates of the thermal conductivity allowing for the geometry and thermal properties of the liner and backfill.

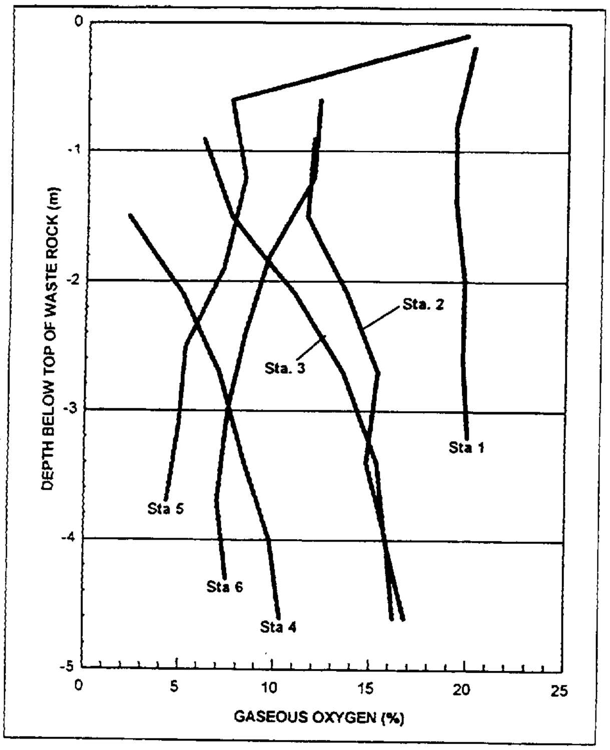

Figure 2 - Measured Pore Gas Oxygen Concentration Profiles, Average of Summer Values

Results

Oxygen Concentration Distribution

Monthly measurements of pore gas oxygen concentration profiles have been made since 1988 at station numbers 1 to 6. Average values between June and September inclusive have been calculated at each measurement port using the entire data set. The average oxygen concentration profiles for the six stations are presented in Figure 2. These data are represented in Figure 3 as iso-value contours on the cross-section which runs roughly west-east through the pile (section A-A on Figure 1a). These average summer values will be used for comparison with the modelling results because the version of FIDHELM used in this study does not allow for seasonal temperature variations.

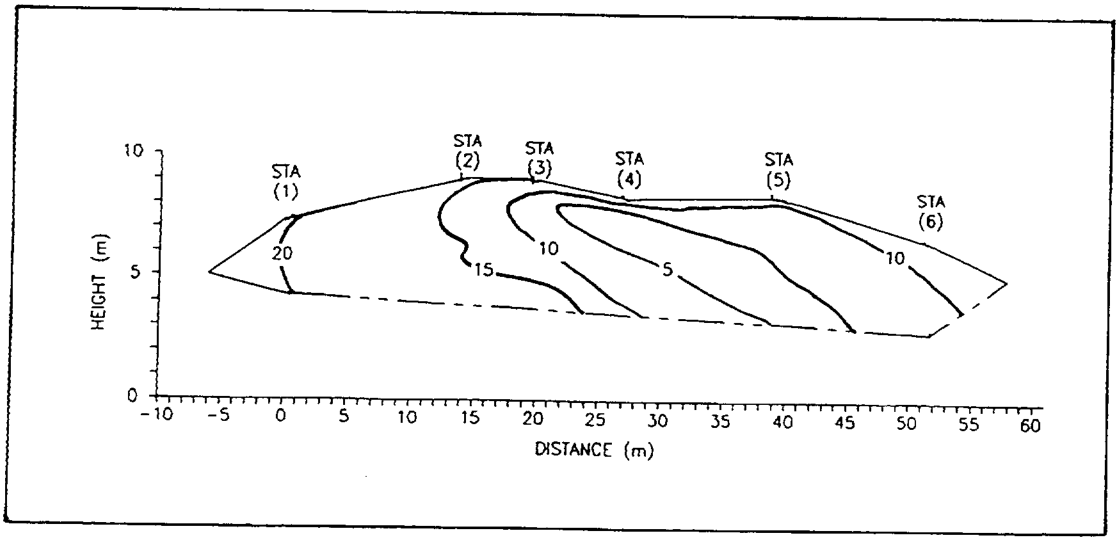

Figure 3 - Inferred Pore Gas Oxygen Concentration Contours (%), Average of Summer Values.

Field Measurements

Measured oxygen diffusion coefficients ranged from 2.1×10^{-6} to 3.6×10^{-6} m^2 s^{-1}, with an average value of $(3.0 \pm 0.5) \times 10^{-6}$ m^2 s^{-1}.

The measured gas permeability ranged from a minimum of $(1.6 \pm 0.1) \times 10^{-10}$ m^2 to a maximum of $(1.7 \pm 0.7) \times 10^{-8}$ m^2, with a mean value of 2.9×10^{-9} m^2, averaged over 24 measurements.

Thermal conductivities measured at three locations had an average value of 1.17 ± 0.11 W m^{-1} K^{-1}, corresponding to an estimated average thermal diffusivity of $(5.2 \pm 0.5) \times 10^{-7}$ m^2 s^{-1}.

Modelling

A list of the parameters used in the FIDHELM modelling is presented in Table I. The table indicates which values have been measured, which were estimated and those that are physical constants.

Ritchie (4) has reviewed five sets of measurements made in waste rock and found IOR values ranging from <0.3 to about 9.0×10^{-8} kg(O_2) m^{-3} s^{-1}. In this work 10^{-8} kg(O_2) m^{-3} s^{-1} was used as a typical value; values of 10^{-9} and 10^{-7} kg(O_2) m^{-3} s^{-1} were also used in some simulations to investigate the effect on gas transport of possible broad scale inhomogeneities of IOR in the pile.

Figures 4 and 5 show the pore gas oxygen mass fraction distribution in pile 18B after a modelled period of ten years. Both figures present the oxygen distribution for the three values of IOR set out above. The FIDHELM runs shown in Figure 4 used the average measured value of gas permeability and Figure 5 used a value close to the maximum measured.

Discussion

Figure 3 shows that the pore gas oxygen concentration profiles in the pile are asymmetric across the pile. At the eastern end of the pile, around stations 5 and 6, the profiles show the monotonic decrease in concentration from the surface which is characteristic of diffusion into a material with uniform IOR. From the centre of the pile towards the west, however, oxygen concentrations increase at depth, which can suggest that oxygen is being supplied by some advective mechanism.

The FIDHELM output at 10 years using the average values of measured parameters, with a gas permeability of 2.9 x 10^{-9} m^2 and an IOR of 10^{-8} kg (O_2) m^{-3} s^{-1} (Figure 4), represents the features of the measured oxygen concentrations in the eastern end of the pile fairly well. It is clear however that the same runs do not adequately describe the features observed in the western half of the pile.

The FIDHELM output presented in Figure 5 was produced using close to the highest gas permeability measured. This was to promote the convective supply of oxygen in the pile in an attempt to reproduce the observed increase in oxygen concentration with depth. At an IOR of 10^{-8} kg(O_2) m^{-3} s^{-1} there is some increase in concentration with depth around 6 m from the centre of the pile. Using a higher IOR of 10^{-7} kg (O_2) m^{-3} s^{-1} had a similar effect, but at 10 years the higher oxygen concentration with depth is only seen around 10 m from the centre. In neither case is the effect nearly as pronounced as in the field measurements.

The inability of these FIDHELM runs to reproduce the oxygen contours observed in the field, even though both gas transport mechanisms of diffusion and advection were included in the model, suggests that some additional features of the system need to be considered.

Table I - FIDHELM Parameters for Pile 18B

Parameter	Values	Type *
ambient temperature (°C)	3	M
intrinsic air density (kg/m^3)	1.2	C
acceleration due to gravity (m/s^2)	9.8	C
air permeability (m^2)	2.9×10^{-9} 10^{-8}	M
viscosity of air (kg/(m.s))	1.9×10^{-5}	C
thermal coefficient of volume expansion (K^{-1})	3.47×10^{-3}	C
oxygen diffusion coefficient of oxygen in air (m^2/s)	2.26×10^{-5}	C
parameter in particle oxidation model ($m^3/(kg.s)$)	1.354×10^{-9}	E
bulk density of solid (kg/m^3)	2200	M
specific heat of solid ($m^2/(s^2 .K)$)	866	E
specific heat of air ($m^2/(s^2 .K)$)	1.06×10^3	C
thermal diffusivity (m^2/s)	5.0×10^{-7}	M
heat of oxidation reaction per mass of reactant oxidised (J/kg)	2.2×10^{-7}	C
mass fraction of oxygen in air	0.22	C
mass of oxygen used per mass of reactant in oxidation reaction	1.746	C
solid volume fraction	0.763	M
density of reactant (kg/m^3)	118	M
maximum intrinsic oxidation rate (kg (O_2)/m^3/s)	10^{-9} 10^{-8} 10^{-7}	E
infiltration rate (m/y)	1.134	M
viscosity of water (kg/m s)	0.001	C
intrinsic water density (kg/m^3)	1000	C
specific heat of water ($m^2/(s^2 .K)$)	4.184×10^3	C
temperature at which micro organisms cease to be effective at catalysts (°C)	50	E
temperature above which the micro organism catalytic activity diminishes	40	E
tortuosity factor	0.59	M
radius of pile (m)	34	M
hight of pile (m)	6.7	M
side slope angle of heap (radians)	0.245	M

* E: estimated
C: constant
M: measured

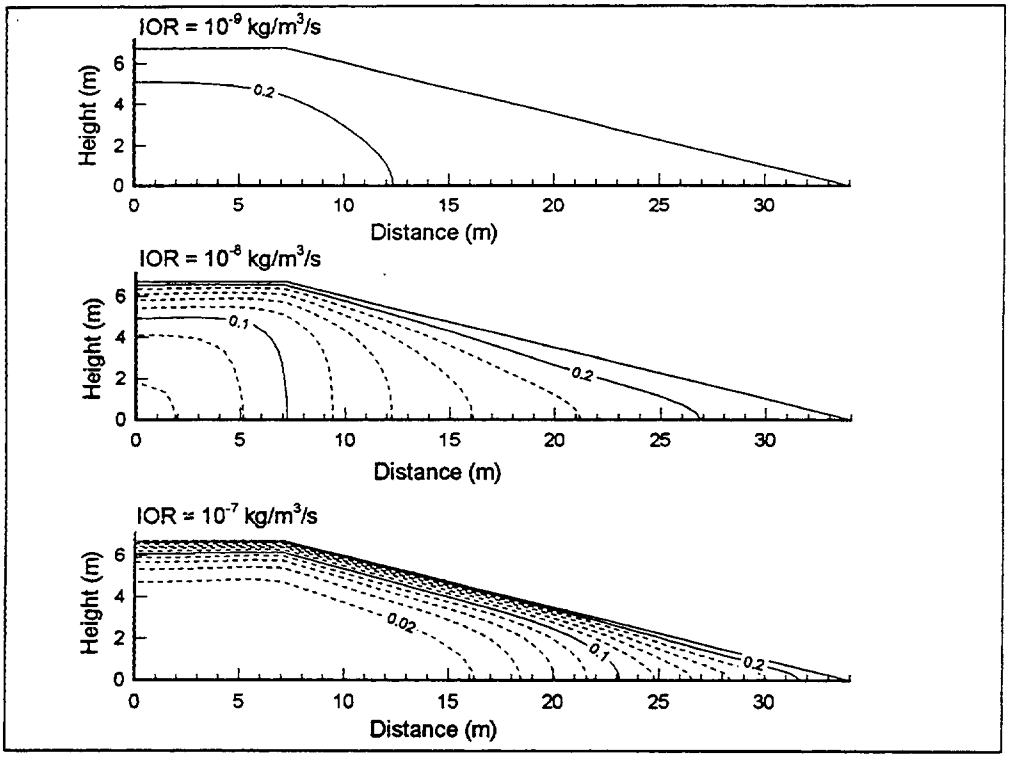

Figure 4 - FIDHELM Results: Pore Gas Oxygen Mass Fraction Iso-Values ($\Delta = 0.02$), $K = 2.9 \times 10^{-9}\ m^{-2}$, Time = 10 years

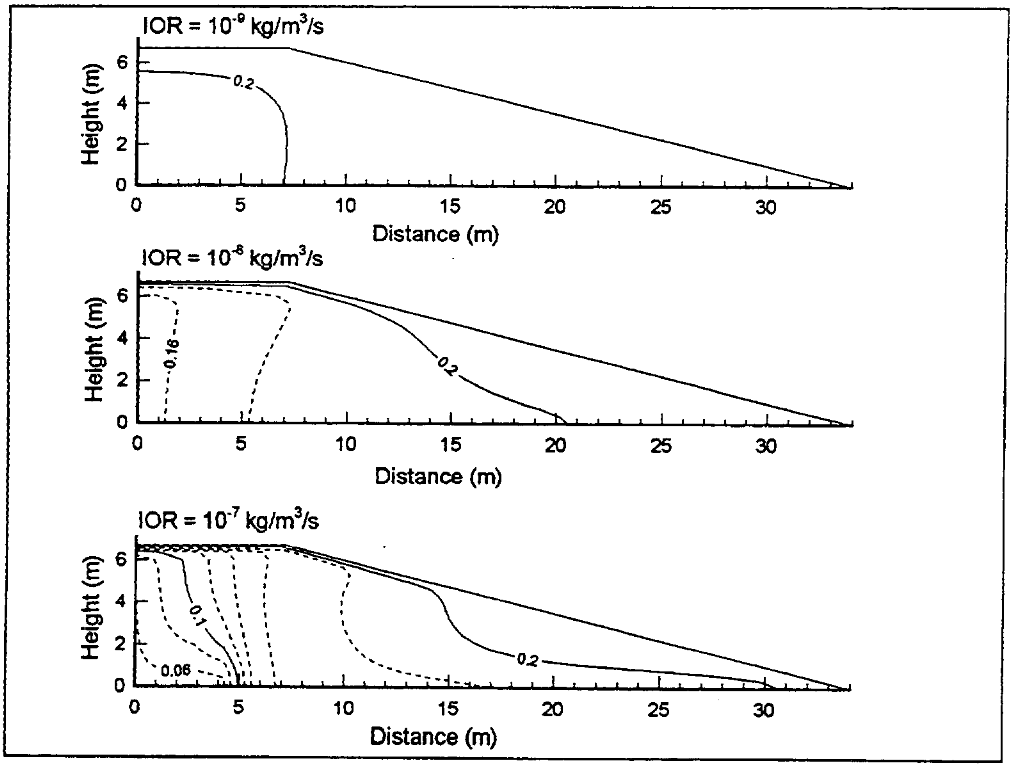

Figure 5 - FIDHELM Results: Pore Gas Oxygen Mass Fraction Iso-Values ($\Delta = 0.02$), $K = 1.0 \times 10^{-8}\ m^{-2}$, Time = 10 years

One possibility is that air pressure differences across the surface of the pile produced by wind effects might enhance advective gas transport through the pile. This would seem to be supported by the observation that higher oxygen concentrations have been measured in the western half of the pile and the prevailing wind is from the north-west. A further program of site measurements and modelling would be needed to ascertain whether wind-driven advection can be a significant gas transport mechanism in pile 18B.

The FIDHELM modelling in this project assumed that the input parameters are constant throughout the pile and in particular that the gas permeability and the IOR do not vary with position. This is not necessarily the case in a real pile which may have been constructed with material of different types being dumped at different times. In a pile as small as 18B a few truck-loads of a particular type of material could produce a significant feature in the composition of the pile. Modelling should be undertaken to investigate the effect that heterogeneities in the gas permeability in the pile may have in enhancing the contribution of the wind effect described above.

It seems reasonable to suggest that the region of the pile bounded by the 5 percent oxygen concentration profile seen in Figure 3 might represent material having some characteristic different from the rest, particularly if the pile had been constructed in a single lift. This is further supported by the observation that the feature lies at an angle of about 13 degrees to the horizontal, consistent with waste rock having been pushed down a slope.

Bennett and Pantelis (5) have shown that an increase in pore gas oxygen concentration with depth can arise from the presence of a relative small volume of material having a high IOR in a waste rock pile, being surrounded by material with a much lower IOR. It was found that measured oxygen concentration profiles in a waste rock pile could be explained by a model which included diffusion as the only gas transport mechanism but allowed for a heterogeneous distribution of IOR in the system. Oxygen diffused towards the high pyrite zone from the sides and top surface of the pile. The much higher oxidation rate in the high-IOR zone resulted in a reduced penetration of oxygen into that zone, as indicated by a steep oxygen concentration gradient near the boundary of the zone. Oxygen was able to diffuse much further through the low-IOR material, leading to relatively high oxygen concentrations in the bulk of the pile, and even directly below the high-IOR zone.

It would be worthwhile modelling pile 18B with the IOR represented as a heterogeneous distribution, to test the suggestion that the observed oxygen profiles can be explained by the presence of a diagonal band of high-IOR material. An analysis of the field data could provide estimates of the IOR of material in the pile for use in the modelling.

Conclusions

Modelling of pile 18B with FIDHELM, incorporating the gas transport mechanisms of diffusion and advection and assuming homogeneous material properties and boundary conditions, was unable to describe adequately the observed distribution of pore gas oxygen concentrations.

The suggestions made to explain the discrepancies (air pressure differences at the boundary and heterogeneous distributions of gas permeability and IOR in the pile) should be tested by a further program of field measurement and FIDHELM modelling, and their relevant contributions assessed.

Acknowledgments

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