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Coupled Atmospheric-Unsaturated Flow Modelling of Leached Ash Disposal in the Latrobe Valley, Australia

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Abstract

The Latrobe Valley region of Victoria, Australia, provides a significant proportion of Victoria's electricity through the combustion of brown coal. The principal waste product of this process is coal ash, and contains a small proportion of leachable salts and certain trace elements. In recent years, the method of managing and disposing of ash has shifted from a traditional tailings dam approach to excavating ash after a period of 6-12 months, and emplacing this within the adjacent overburden dump. To assess the environmental performance of this strategy, detailed leachability studies have been conducted in the laboratory and the field. Overall, these combined studies have demonstrated the low leachability of ash after excavation, and low mobility of most trace elements. In order to properly design and engineer the disposal of the ash within the overburden dump, an important issue is the ability to model the unsaturated flow behaviour of the ash coupled with atmospheric forcing conditions such as temperature, humidity, rainfall and wind. This paper presents the results of modelling work of field and laboratory studies on ash leaching using the VadoseW model. This is a unique approach and highlights the importance of correctly identifying the key processes which drive potential leachate generation and migration in waste disposal sites. Thus the paper will present both a useful case study and a rigorous approach to the theoretical aspects of modelling moisture flow at ash disposal sites.

Keywords: coal ash leaching, unsaturated flow, modelling, waste disposal

1. Introduction

The Latrobe Valley region of eastern Victoria, Australia, contains major brown coal resources which are used to provide base-load electricity from large-scale mining-power station complexes. At present there are three major open cut mining centres supplying four power stations totalling about 6,500 MW generation capacity. About 65 Mt of brown coal and 15 Mm^3 overburden is mined annually. A principal waste product of these operations is coal ash, usually <2% of coal, containing salts and trace elements.

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In recent years, there has been considerable research and focus on potential alternative waste management strategies to the traditional slurry pipelines and ash disposal ponds. At the Loy Yang power station complex, ash management has shifted from this traditional tailings dam-type approach to excavating ash after a period of 6-12 months and emplacing this within appropriately engineered facilities in the adjacent overburden dump. A major concern with this approach is the potential for leachate generation and consequent impacts on groundwater quality. To assess the environmental performance of this new strategy, detailed leachability studies have been conducted in the laboratory and the field, with a particular focus on assessing flow behaviour and leaching rates to allow modelling of the unsaturated flow behaviour of potential ash cells within an overburden dump environment. By validating models with such data, the model can then be used as both a design and an environmental assessment tool.
This paper presents the results of applying the relatively new Vadose/W coupled atmospheric-unsaturated flow model to the laboratory and field leaching studies. Overall, it demonstrates a unique approach to modelling waste disposal through a rigorous theoretical model which is well suited to unsaturated flow environments.

2. Methodology

2.1 Design of Laboratory and Field Leaching Studies

A series of three large column leaching studies have been conducted at various heights to assess possible scale effects. All columns had an internal diameter of 101 mm and were 300, 750 and 1,500 mm in height. Porous stones (6 mm thick) were sealed in place at the top and bottom of each column to ensure uniform flow distribution, with filter paper used to prevent any blockage of the bottom porous stone. All columns had top and bottom caps to ensure minimal evaporative losses. Inflow was delivered by a peristaltic pump, with outflow monitored for volume, flow rate and quality.
The field studies were conducted using two HDPE-lined cells 5x5 m in area and 3 m depth. A 15 mm gravel drainage layer was installed on the base of each cell to facilitate rapid drainage after exfiltration from the thicker ash layer. Due to the higher potential evaporation over rainfall for the region, the cells were operated as a “Wet Cell” with periodic irrigation to more actively leach the ash and a “Dry Cell” open only to rainfall to more closely mimic proposed waste disposal conditions in the overburden dump. The cells were monitored for a period of about 14 months, including a detailed water balance and leachate chemistry. The results are summarised in Mudd & Kodikara (2000) and Mudd *et al* (2004), and in detail by Mudd (2001).

2.2 Modelling Approach

There are numerous models available for unsaturated flow behaviour, each with various capacities and weaknesses (eg. SWIM, Seep/W, UNSAT1D, Hydrus, etc). The Vadose/W model (Geo-Slope, 2004), which explicitly models actual soil evaporation was selected for this study. Vadose/W is a two-dimensional unsaturated flow model coupled with heat and vapour transport to link soil hydraulic behaviour with atmospheric (or climatic) forcing conditions. It is based on the earlier one-dimensional SoilCover model. The principal reason for developing SoilCover and Vadose/W was the design of engineered soil cover systems for mine wastes and landfills, though it is also very useful for other applications such as groundwater recharge and irrigation modelling.

2.3 Theoretical Basis of Vadose/W

The theory of Vadose/W is described in detail by Geo-Slope (2004) and Wilson *et al* (1994). In brief, it couples Richard's equation (unsaturated flow) to atmospheric forcing conditions (temperature, rainfall, wind speed and relative humidity) through heat and vapour transport, using relative humidity to link the processes.

2.4 Calibration Approach

The calibration of the model was performed through a sensitivity analysis and visual observation. The column experiments were modelled first, varying the characteristic curve and the unsaturated hydraulic conductivity function to achieve a close fit between the experimental and modelled data. After a satisfactory correlation had been achieved, the same hydraulic properties were then used to model the Dry Cell. This paper does not report modelling results of the Wet Cell.

3. Results

3.1 Leaching

For completeness, the leaching dynamics of salt loads (as TDS) over time of the columns and field cells are given in Figure 1. The clear wash-off of soluble salts (primarily sodium sulfate with minor chloride) can be observed in the first pore volume of leachate passing through the ash, with pH relatively stable around 8.5 to 10. The behaviour of leachable metals is often variable, but can show a similar declining trend.

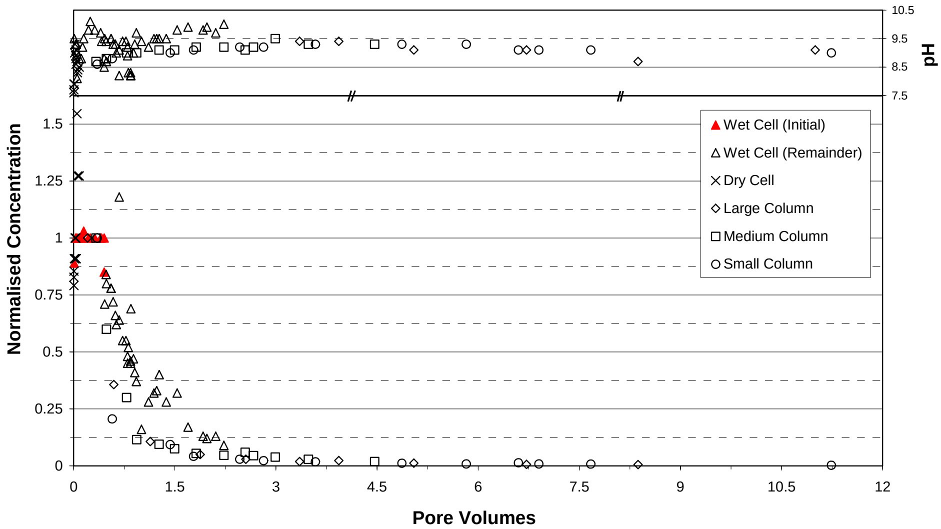

Figure 1. Leached ash – Salinity and pH versus pore volumes (Mudd et al., 2004)

3.2 Hydraulic Properties

The principal hydraulic properties of the leached ash, the characteristic curve and unsaturated hydraulic conductivity function, are given in Figure 2. These results are based on the laboratory testing of Mudd (2001) and La Motta *et al* (2003) and the calibrated property functions derived from sensitivity analyses of model runs. They correspond well to the observed and expected behaviour of the ash as a porous, fine-grained soil.

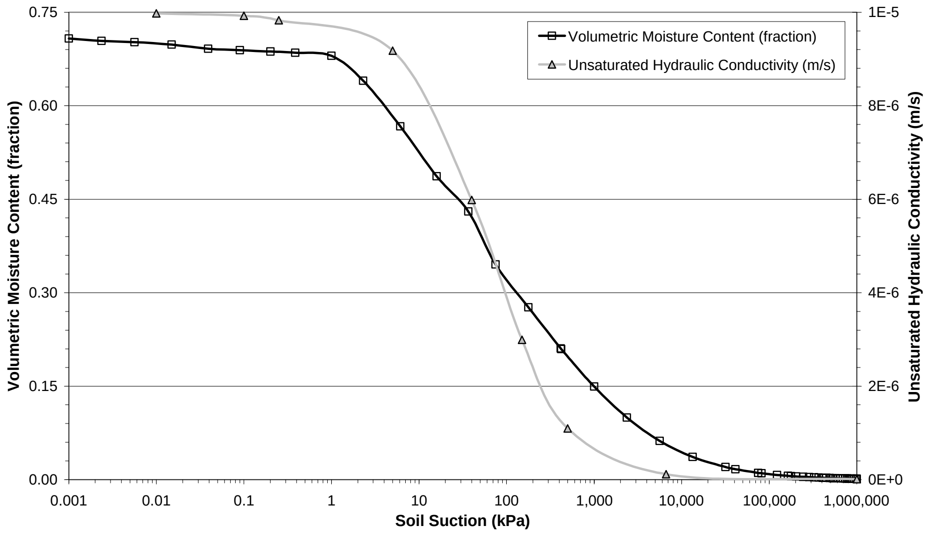

Figure 2. Adopted Unsaturated Hydraulic Properties of Loy Yang Leached Ash

3.3 Results – Small, Medium and Large Columns

The model results of the cumulative water balances for the small, medium and large columns are shown in Figures 3 to 5.

The inflows demonstrate an excellent calibration in all columns. The outflows generally show a very close calibration, though sometimes slightly over or under the measured experimental data. Importantly, the slopes are identical and the points of change (eg. start or end of inflow) are matched well by the model.

3.4 Results – Dry Cell

The model results of the cumulative water balances and changes in soil moisture storage for the Dry Cell are shown in Figure 6, with climate data shown in Figure 7.

The inflow shows an excellent calibration. The modelled outflow was difficult to calibrate accurately to the field data. For the early period of operation (days 0 to 90), the observed volume of discharge was minor, often being a very slow drip rate, and was most likely due to self-weight consolidation and equilibration of pore pressures causing a small leachate discharge (consolidation driven flow, however, cannot be modelled by Vadose/W). For days 125 to 160, a period of elevated rainfall led to an extremely small rate of drip flow from the outflow pipe, although this was very difficult to measure accurately. For days 180 to 230, the model predicts some small discharge due to elevated rainfall around this time despite no field evidence for this.

An alternate model was run assuming a saturated initial ash profile, however, this led to significantly greater leachate discharge than that observed. The model run adopted is based on field-measured initial moisture contents.

The 14 month period of the field trials was a time of below average rainfall, a problem exacerbated by the excess potential evaporation over rainfall as well as above average temperatures throughout most of this time.

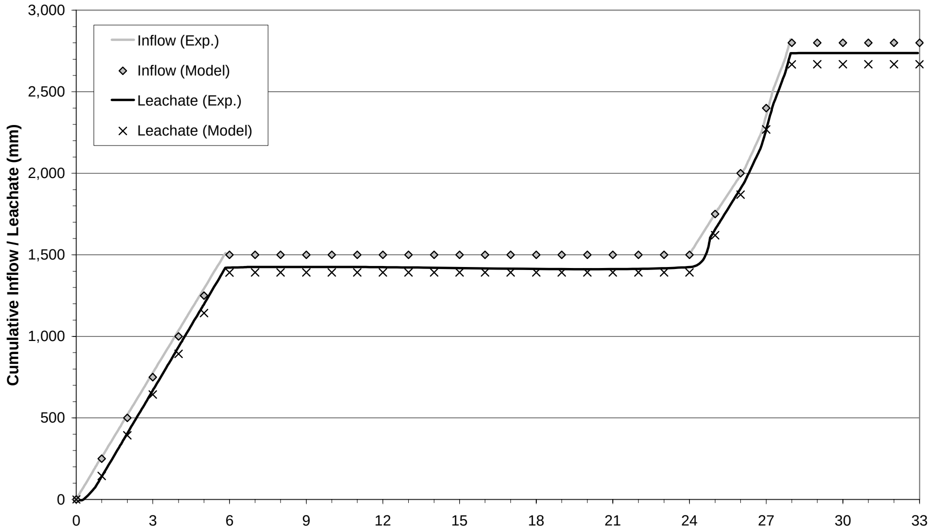

Figure 3. Small Column – Cumulative Inflow / Leachate Fluxes (mm) Over Time (days)

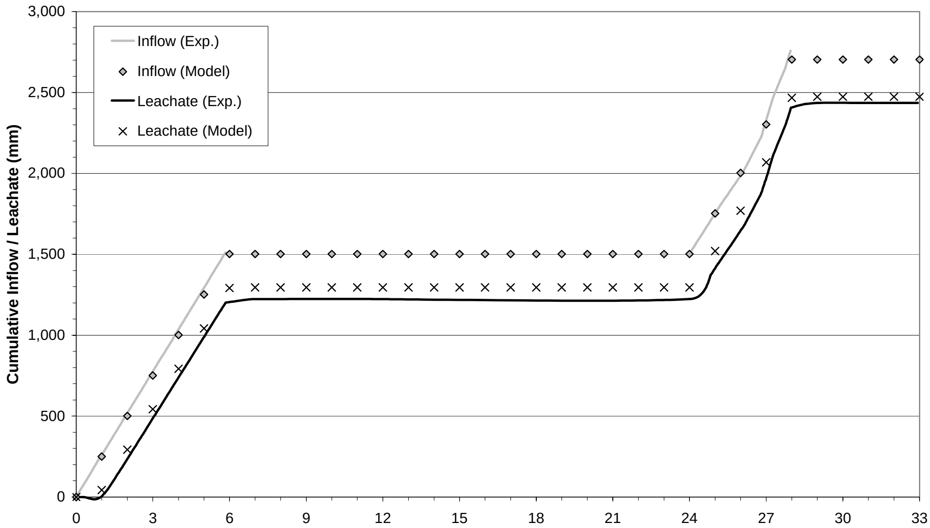

Figure 4. Medium Column – Cumulative Inflow / Leachate Fluxes (mm) Over Time (days)

4. Discussion

Overall, it is considered that Vadose/W has successfully modelled the complex processes of unsaturated moisture flow and actual soil evaporation in both a laboratory and field context. The laboratory columns represent the simplest case whereby temperature and relative humidity are constant with controlled, predictable inflows. The Dry Cell represents a more realistic situation of an expected ash disposal cell within an overburden dump at Loy Yang.

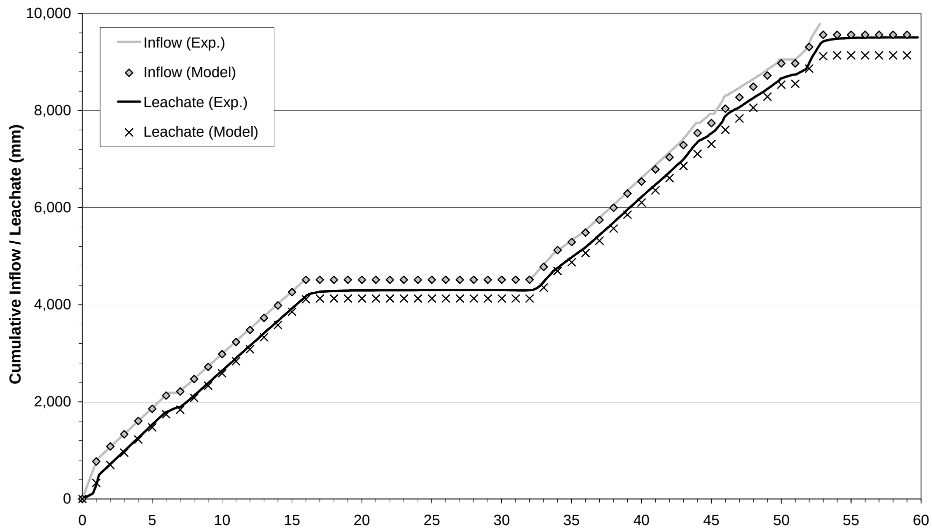

Figure 5. Large Column – Cumulative Inflow / Leachate Fluxes (mm) Over Time (days)

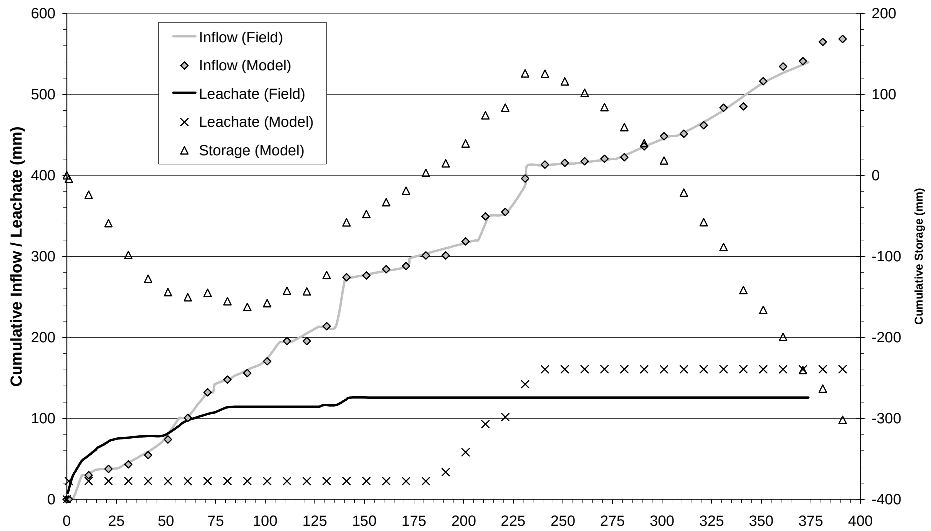

Figure 6. Dry Cell – Cumulative Inflow / Leachate Fluxes (mm) Over Time (days)

The models of the three columns, calibrated through visual fit, show a very close correlation. The model of the Dry Cell, however, shows some difference in modelled discharges. As the ash, in general, is not pozzolanic (see companion paper, (Mudd *et al.*, 2005), this is expected to be due to the initial ash behaviour during self-weight consolidation generating very minor leachate discharges.

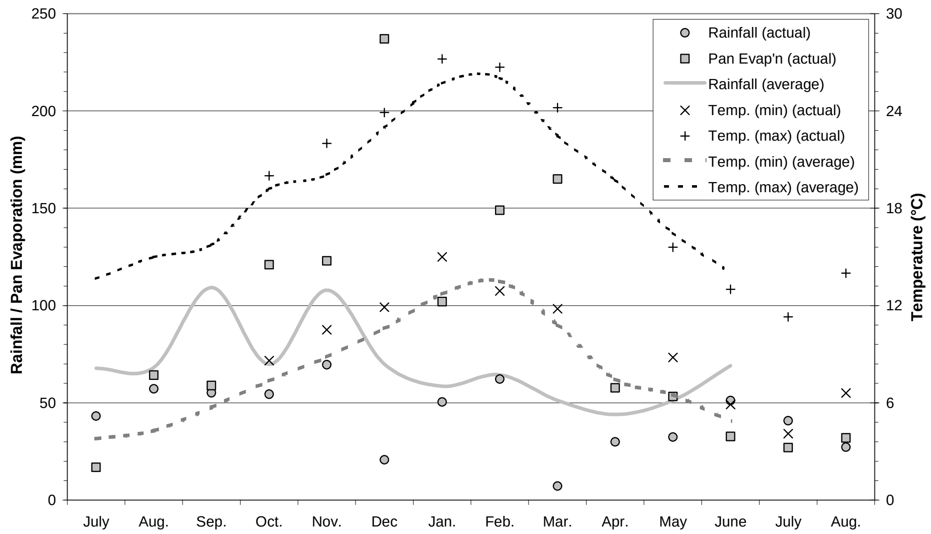

Figure 7. Dry Cell Climate Date – Average and Actual, July 1997 to August 1998

Although altering the initial moisture content was found to have an effect on the extent of discharge, the overall impact of this is essentially small since the rates of leachate discharge are minor (~100 mm) in comparison to the overall influx generated by rainfall (~600 mm). This is evidenced by the fact that there was no measured discharge from day 150 to 400.

The modelled cumulative storage is also important in understanding the potential for leachate discharge. In the early period of operation (days 0 to 100) the minor leachate discharge is considered to be due to self-weight consolidation while overall storage continues to decline due to evaporative losses. Between days 100 to 240, however, the model shows an overall increasing trend in storage, reaching a value of +100 mm (ie. increase) before declining to –300 mm around day 390 (ie. decrease). In comparison, the pore volume of the Dry Cell is approximately 2,250 mm, suggesting that the changes in storage are relatively small. This also implies that a considerable and sustained inflow flux is required to overcome climatic conditions and the high storage capacity of the ash and generate any significant volume of leachate discharge from the base of a potential disposal site. This observation is also re-inforced by the field data.

5. Conclusions

The accurate prediction and modelling of coal ash disposal requires a thorough understanding of the controlling processes, especially the behaviour of moisture within a potential disposal site. This paper has presented the results of using the relatively new Vadose/W coupled atmospheric-unsaturated flow model to laboratory and field leaching studies of Latrobe Valley ash as a basis for engineering design and assessment of disposal sites. The unsaturated hydraulic properties of the ash were calibrated using the flow data of the column experiments and then used to model the Dry Cell field test. In general, the columns showed very good calibration while the initial conditions of the

Dry Cell led to some variability in the predicted leachate outflow by the model. The model was shown to be a most useful tool in the assessment (and therefore design) of potential ash disposal sites. Importantly, the modelling has reinforced the desirable storage capacity and hydraulic characteristics of aged ash as a cover material.

Acknowledgements

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