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Instrumented column testing of settling, consolidation and desiccation of coal tailings slurry under ambient weather conditions

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ABSTRACT: Understanding the time required for coal tailings deposited as a slurry to desiccate, the depth of desiccation and the amount of settlement that occurs on desiccation are important to ensure the safety and efficiency of a tailings storage facility (TSF) as it rises. An instrumented column test was designed and monitor these key factors. The column was instrumented with moisture, suction, salinity and temperature sensors, designed, developed and manufactured at The University of Queensland (UQ). The settlement and cracking of the tailings were recorded by a camera capturing the tailings surface. The column was filled with coal tailings slurry, and installed on a building roof at UQ, alongside a weather station, and was subjected to the ambient weather conditions, while the sensor readings were instantaneously sent to the internet for visualisation and analysis. This paper reports on the instrumented column set-up and the early results obtained from the test.

1 INTRODUCTION

Conventional sub-aerial tailings deposition involves pumping slurry tailings at low solids concentration to a TSF, where the tailings undergo settling, self-weight consolidation, and desiccation under natural weather conditions. The optimisation of tailings deposition aims to maximise the settled solids concentration and dry density, and lower the phreatic surface, while the permeability of the tailings will reduce dramatically. Optimisation generally involves cycling the deposition of tailings in relatively thin layers and leaving time between layers to achieve settling, consolidation and desiccation, before the next layer is poured. The tailings are best deposited from the perimeter of the facility. This allows maximum utilisation of the storage volume available for the tailings, and increases the geotechnical stability of the facility.

The optimisation of tailings deposition requires a thorough understanding of the behaviour of the tailings under ambient weather conditions; in particular, the time required for desiccation, the depth of desiccation, and the settlement induced by desiccation. Conventional testing methods test separately the settling, consolidation and desiccation of tailings slurry. There is a need to test all three processes in the one apparatus, from a slurry state, and preferably under ambient weather conditions, to best replicate field conditions.

A column, instrumented with moisture, suction, temperature and salinity sensors, plus a camera and a weather station, was designed to test all three processes. The instrumented column test was carried out on coal tailings slurry exposed to ambient weather conditions.

2 EXPERIMENTAL DESIGN

2.1 *Column design*

A schematic of the instrumented column is shown in Figure 1. The height of the column was selected as 1.2 m, since the depth of desiccation was expected to be far less than this depth (Zhang et. al. 2014). The diameter of the column was selected as 0.2 m, since the wall effect is found to be trivial for coal tailings (Shokouhi et al., 2017), and pipes of this diameter are readily and cheaply available commercially. The bottom of the column was sealed, while the top of the column was open to allow the deposition of the tailings and allow tailings surface to be exposed to sun and air after filling. The column was manufactured in two sections of 0.6 m height, connected by a sealed flange, for ease of installing and removing sensors and placing and removing the tailings, before and after the experiment. The sensors were installed through the wall of the column at increasing depth intervals down its height, with each set of sensors located at quarter points around the circumference of the column (Figure 2a and 2b).

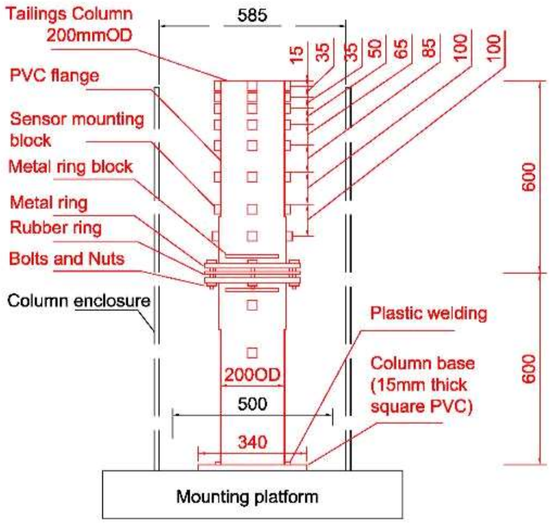

Figure 1. Schematic diagram of instrumented column for settling, consolidation and desiccation test.

2.2 *Sensors*

Five different types of sensors were installed in the column (Williams & Zhang, 2017):

- Ten in-house dielectric moisture sensors to measure the volumetric water content indirectly via the dielectric permittivity of the tailings compared to that of water (80 to 90, depending on salinity and temperature), which is much higher than that of dry tailings (10 to 15, depending on mineralogy and temperature). Although the readings from dielectric permittivity-based moisture sensors are affected by salinity and temperature, these impacts can be corrected by acquiring salinity and temperature at the same location using other related sensors. Moisture sensors based on dielectric permittivity were found to be much more reliable in saline tailings than sensors based on time domain reflectometry, which transmit high frequency waves in the tailings and measure their reflections. The incoming wave may be attenuated immediately by hypersaline water, resulting in the sensors being dysfunctional.
- Ten in-house thermal suction sensors to measure the suction of the tailings indirectly via their thermal conductivity, as well as measuring the ambient temperature. The advantage of applying this sensor in tailings is that the sensors are not influenced by salinity, which varies significantly in tailings.
- Two DECAGON$^{\text{TM}}$ GS3 sensors to measure the bulk salinity of the tailings indirectly via electrical conductivity (EC), covering the range from 0 to 20 dS/m. The bulk salinity can be correlated to pore water salinity via the measured water content and suction at the same location.
- Five in-house humidity-based salinity sensors to indirectly measure bulk salinity via the relatively humidity of the air adjacent to tailings. This is based on the principle that the solvent in the pore water would disrupt the exchange of water ions be-tween liquid and gas phases. As a result, the air humidity near the hypersaline pore water becomes less than fully saturated. This sensor is particularly sensitive when tailings salinity becomes higher than seawater (from seawater salinity of 35 part per thousand [ppt] to the solubility limit of 265 ppt).
- Two in-house pore water pressure sensors to measure the location of the water table within the column. Previous columns employed load cells underneath the column to measure the change in weight due to evaporation/rainfall. However, due to significant fluctuation of temperature and wind, the monitored weight was found to fluctuate too much to enable the water balance in the column to be reliably calculated.

In addition to the sensors, a weather station was installed next to the column to monitor in real time weather conditions, which can be correlated to the potential evaporation. A high-resolution camera was mounted above the column facing the surface, to monitor the settlement and cracking of the surface, and salt precipitation at the surface.

All sensors were connected to an in-house data logger (Figure 2f), which is powered by solar and sends monitored data instantaneously to the internet for visualisation and analysis.

2.3 *Column test preparation*

Calibrated sensors were mounted in the two column sections. The flange between the columns was then connected, with grease applied to the rubber O-ring seal to avoid leakage (Figure 2b). To allow for the settling of the last layer of tailings slurry placed to the level of the top of the column, an additional 0.1 m high section was added and sealed with silicone, to later be removed. The column was tested for water-proofness by filling with water, covering the top of the column and checking that the water level had not dropped after 10 days.

The supplied coal tailings were first oven dried, with the oven temperature restricted to 60°C to avoid combustion of any coal content. The oven-dried tailings were crushed to powder, and coal process water added to achieve 25% solids concentration by mass (void ratio of 3.0 and dry density of 0.470 t/m^3, given the specific gravity of the coal tailings of 1.949; Figure 2c). The coal tailings slurry was carefully poured into the instrumented column in a series of layers about 200 mm thick, which settled to about 100 mm over 1 day before the supernatant water was removed and the next layer was poured. Coal tailings slurry was added until the settled tailings reached the top of the column, and the short column section was removed. The filled column was then enclosed by four PVC panels to prevent the column being tipped over by strong winds and to isolate the sides of the column from sun and wind to the extent possible (Figure 2d). The coal tailings were then allowed to desiccate under ambient weather conditions.

Figure 2. Images of column assembly processes: (a) assembled column with sensors installed, (b) top view of sensor layout before deposition of tailings, (c) prepared coal tailings slurry at 25% solids, (d) view of solar panels and electrical enclosure, (e) rear view of column protected by a PVC enclosure, and (f) electrical enclosure.

3 EXPERIMENTAL RESULTS

The column test commenced in late March 2018 and had run for 7 months to mid-October 2018 up to the time of reporting. Figure 3 shows the weather station data. The weather data show that rainfall occurred in March, April and October, with little rainfall in May, June, July, August and September. In general, the solar intensity and temperature were higher in the wetter and hooter periods. The average temperature and humidity during the monitoring period were 20°C and 40%, respectively, representing typical sub-tropical weather.

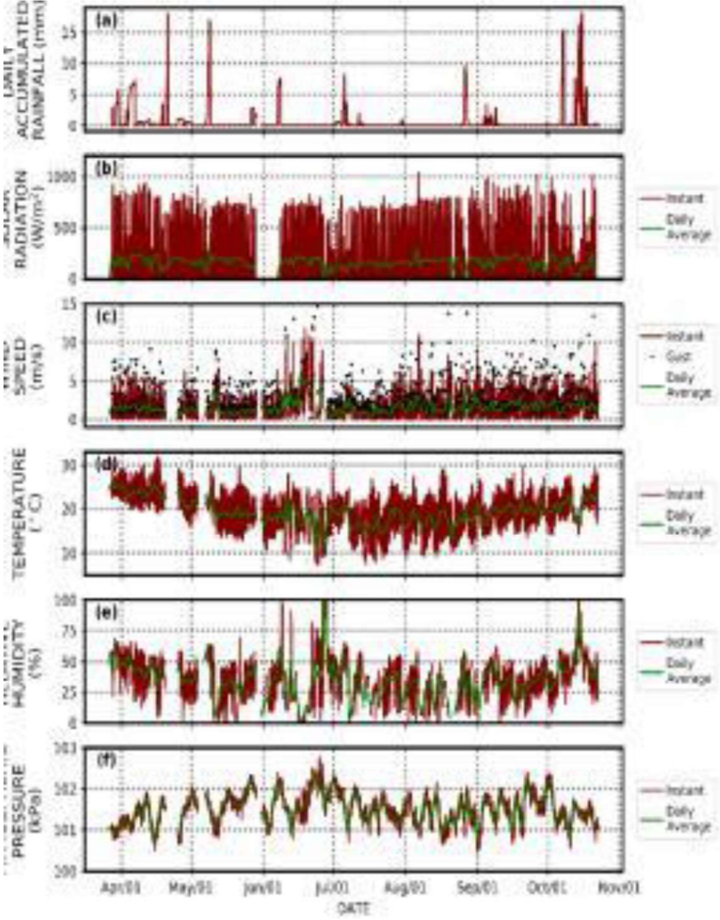

Figure 3. Monitored data from weather station, including: (a) daily accumulated rainfall, (b) solar radiation, (c) wind speed, (d) temperature, (e) relative humidity, and (f) atmospheric pressure. Brown lines are measured data and green lines are daily averages.

The gain in moisture (from rainfall) and loss (from evaporation) and other data monitored in the column during the monitoring period are shown in Figure 4, with images of the surface at different stages of the test shown in Figure 5. Based on the change in volumetric moisture content (Figure 4e), and the comparison between the potential evaporation and actual evaporation (Figure 4b), the monitoring period can be divided into two desiccation phases. The first desiccation phase lasted for 40 days, starting from the beginning of the test to 8 May, when 28 mm of rainfall occurred over two consecutive days, re-saturating the column. The second desiccation phase started on 8 May and lasted for 150 days until the intensive rainfall events in October, totalling 52 mm, again re-saturating the column.

The weather in the early stage of the first desiccation phase was characterised by intermittent rainy and sunny days. Under such repeated wetting and drying cycles, the tailings did not become unsaturated, although about 30 mm of settlement occurred (Figure 4g).

After the wetting and drying cycles, dry weather predominated for 2 weeks, leading to the desiccation of the upper 12 cm of tailings (Figure 6a). The unsaturated surface tailings also caused the deviation of actual evaporation from potential evaporation (Figure 4b), and this deviation increased as the tailings surface became drier. During the first desiccation phase, the bulk tailings EC on the surface fluctuated more than that at 60 cm. However, the EC of the tailings overall remained below 2 dS/m during the entire monitoring period, indicating that the salinity of the tailings remained low, despite desiccation.

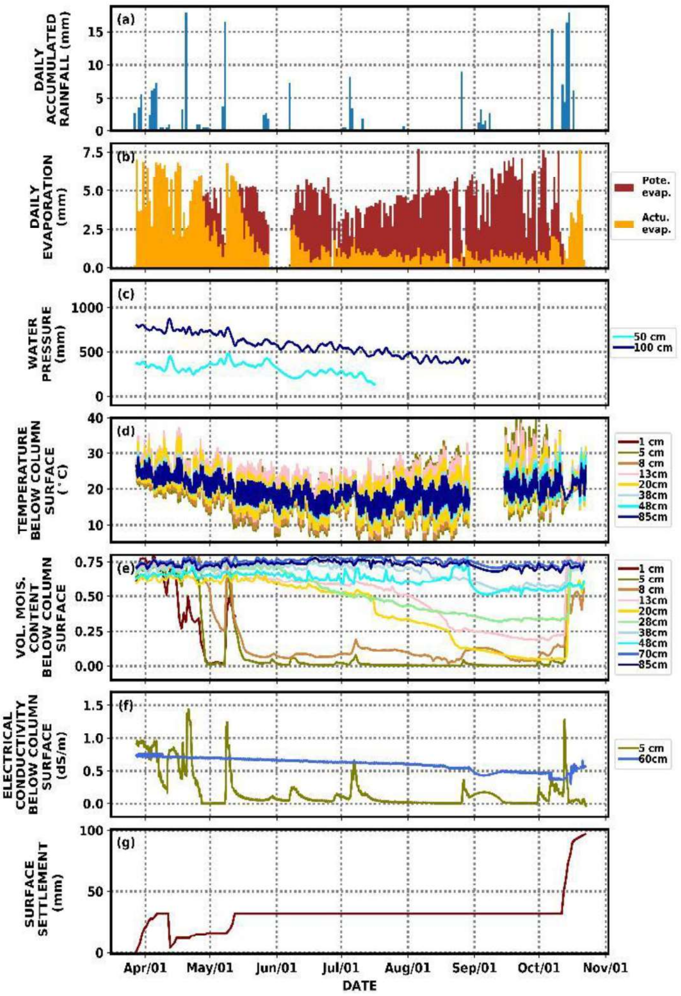

Figure 4. Monitored data including: (a) rainfall, (b) potential and actual evaporation derived from weather station data using Penman-Monteith equation, (c) water pressure, (d) temperature, (e) volumetric water content, (f) EC, and (g) surface settlement.

The second desiccation phase resulted in a rapid 20 mm of settlement, with no further settlement as desiccation continued. Although occasional rainfall occurred during the second desiccation phase, its impact on saturation of the tailings was almost negligible. Similar to the first desiccation phase, the surface tailings changed from fully water-saturated to completely dry during the first 3 weeks, and the saturation profiles with depth achieved after the first 3 weeks for the two desiccation phases were almost identical (Figure 6).

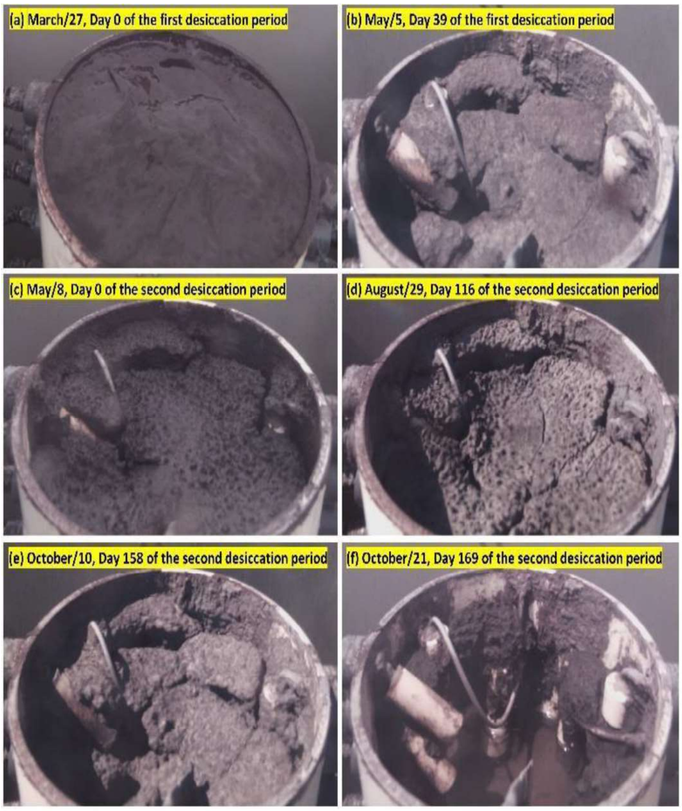

Figure 5. Images of column surface at different stages of test.

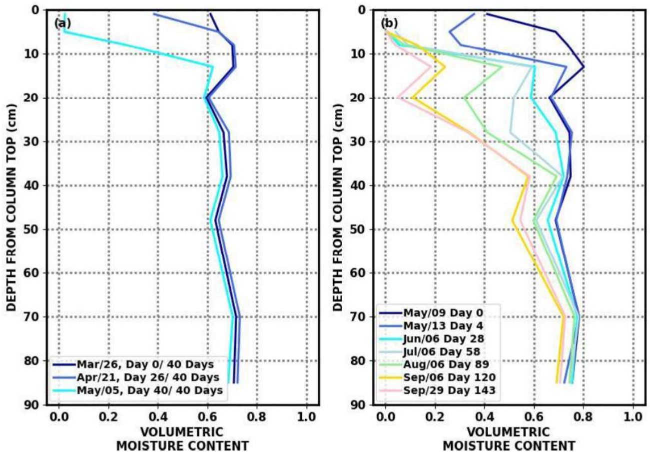

Figure 6. Monitored saturation profiles during: (a) first, and (b) and second desiccation phases.

Since the tailings surface was almost dry (Figures 5d and 5e), the capillary connection between the deeper tailings and the surface tailings was disrupted, and evaporation was reduced to a very slow rate. As shown in Figure 4b and 4d, the difference between the potential and actual evaporation rates was significant (i.e., less latent heat consumption), while the temperature fluctuations became more significant (i.e., more sensible heat exchange). This limited further desiccation of the tailings at depth, with negligible desiccation below 40 cm depth, but increasing cracking at the surface (Figures 5d and 5e).

The intense rainfall following the second desiccation phase led to a collapse of the surface by about 60 mm and the ponding of water on the surface (Figure 5f). However, the tailings remained unsaturated at depth, resisting re-saturation and a recovery of the water table.

Figure 7 shows the water loss from the column de-rived from both the weather data and volumetric water content profiles with depth. In general, the loss of water during the two desiccation phases and the gain in water induced by rainfall calculated by both methods agreed well. However, discrepancies existed, for example:

- At the beginning of the monitoring period, the water loss calculated from the moisture profiles fluctuated around zero, while the weather data indicated rapid desaturation. This was probably because the initial desiccation was accompanied by shrinkage rather than de-saturation, which the moisture sensors are unable to show. In addition, overtopping of the column may have occurred during the early rainfall event.
- During all rainfall events, the total water gain calculated from the moisture profiles appeared to be more than the rainfall monitored by the weather station, although the latter would in general be more accurate. This may be induced by preferential infiltration into the tailings during rainfall events, which may have saturated the tailings around the sensors.
- The settlement of the tailings below the rim of the column would have limited wind-induced desiccation somewhat, and hence cause inaccuracy in the estimation of potential evaporation. This effect could be minimised in future column tests by adding detachable short extensions to the column.
- The calculation of actual evaporation from potential evaporation requires accurate measurement of volumetric water content at 1 cm below the surface, but the location of the tailings surface kept changing due to surface settlement.

4 CONCLUSIONS

This paper presents a novel and cost-effective testing method to monitor the settling, consolidation and desiccation of coal tailings slurry, involving an instrumented column exposed to ambient weather conditions. From the monitoring of coal tailings slurry over 7 months, the following conclusions may be drawn:

- The dry density of the coal tailings achieved 0.470 t/m^3 (void ratio of 3.0) on settling for 1 day, achieving an average dry density in the upper 20 cm of 0.520 t/m^3 (void ratio of 0.25) after 1 month of desiccation, and 0.627 t/m^3 in the upper 40 cm (void ratio of 0.21) after 5 months of desiccation.

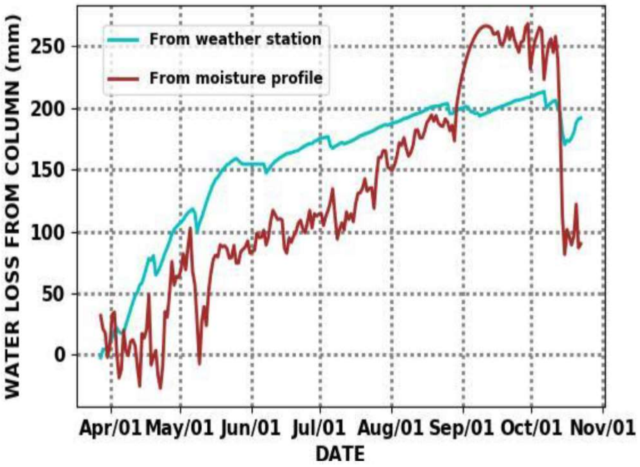

Figure 7. Water loss from the tailings column over time estimated by weather data and from moisture profiles.

- The tailings settled about 30 mm in the first desiccation phase and a further 70 mm to about 100 mm on flooding by rainfall after the second desiccation phase.
- Desiccation of the coal tailings by sun and wind was most effective during the first month of expo-sure, suggesting a cycle time for the coal tailings of 1 month and an optimal layer thickness of 40 cm.
- The unsaturated permeability of the desiccated coal tailings remains sufficiently high to allow partial re-saturation and recharging of the water table, although unsaturated zones remain.

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