Rainfall Induced Transient Pressure Wave Mechanisms in Tailings Dams

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Abstract

The failure of tailings dams are most frequently attributed to liquefaction, erosion and overtopping. The purpose of this study is to investigate alternative physical/hydrological processes resulting from high rainfall intensities causing slope instability. In particular, the advancing wetting front may cause transient air pressure waves to rapidly increase the phreatic surface and change pore water suction status. Some research has been conducted on this phenomenon in natural hillslopes but have not been considered in the case of tailings dams. In order to quantify these physical processes, specific experiments have been conducted. Laboratory work included a large leak-proof column filled up to 2.65 m with silica fines material with similar hydraulic characteristics as platinum tailings at *in-situ* dry bulk density. The column was instrumented with seven data ports, each consisting of a time domain reflectometry probe to measure volumetric water content, a mini tensiometer to sense pore water pressure and a pore air pressure probe. The experimental setup allowed for the application of artificial rainfall at different intensities and controlled boundary conditions, during automatic logging of the hydraulic state variables. Recorded observations showed that after the application of water to the soil surface, pore air pressure ahead of the wetting front increased rapidly, causing air pressure wave propagation to mobilise pre-event water and reduce pore water suction. This led to the conclusion that high intensity rainfall events are likely to contribute to the generation of transient pressure waves in tailings porous medium, thereby inducing the rapid transmission of pressure head to a potential failure plane, where changes to effective stress may contribute to slope instability.

Keywords: Pore Air Propagation, Groundwater Mobilisation

Introduction

Previous research studies, conducted on natural hillslopes, found that high rainfall intensity events lead to excessive infiltration while rainfall frequency impacts on antecedent moisture conditions and the generation of pre-event water (Guo *et al*. 2008) (Rahardjo *et al*. 2001). Both these event characteristics (intensity and frequency) could contribute to tension saturated or near saturated conditions and have an impact on physical and hydrological processes that regulate the structural integrity of engineered slopes and earth embankments. According to Rahardjo *et al*. (2004) surface infiltration during and after a rainfall event cause slope instability by increasing pore water pressure, which leads to a decrease in the shear strength of residual soils. Zang *et al*. (2019) argue that water infiltrating the soil profile, combined with pre-event water contained in the capillary cringe, provides ideal conditions for the rapid mobilisation of groundwater and eventual slope failure. The contribution of pre-event water to stormflow could be attributed to a range of hydrological processes, including transmissivity feedback, non-Darcian pressure waves, and preferential flows. Cloke *et al*. (2006) argue that the fine nature of tailings media allows for a greater propensity for capillary fringe rise, thereby reducing the probability of Darcian flux occurring. This paper builds on research previously presented by Waswa and Lorentz (2015) that found transient pressure waves in natural hillslopes to be responsible for the rapid release and mobilisation of previously antecedent moisture through the mechanisms of Groundwater Ridging (GWR) and the Lisse Effect (LE).

Mechanisms contributing to the rapid mobilisation of groundwater

Several studies describe GWR as the rapid response and disproportionate rise in the water table after a rainfall event in shallow groundwater systems (Zang *et al.* 2019; Meyboom 1967). According to Zang *et al.* (2019) GWR ridging only occurs if the capillary fringe extends from the water table to the natural ground surface. Gillham (1984) argues that the 'capillary fringe effect' causes a transient influence on the position of the water table and that the magnitude of rapid water table response is enhanced by fine-grained geologic materials. Under such conditions, the near-saturated porous medium in the capillary zone provides a continuous pore water phase that is entirely dominated by tension. The addition of a small amount of water relieves this tension, thereby releasing pre-event water to combine with the phreatic surface, resulting in a magnitude of GWR much greater than the amount of surface infiltration. This argument is supported by Cloke *et al.* (2006) who state that even a small amount of infiltrated water can rapidly convert the negative capillary pressure head in the capillary fringe to a positive pressure head, thereby changing the water table gradient and forcing pre-event water out. In contrast, the energy hypothesis was proposed by Waswa and Lorentz (2015), finding that the intensity of a rainfall event provides additional energy required to convert water in the unsaturated zone to water below the phreatic surface. Similar to previous studies, Waswa and Lorentz (2015) found that the extension of the capillary fringe is necessary to enable GWR by providing contact between the kinetic-energy-carrying intense raindrops and the potential-energy-deficient pore water. They further postulated that the only difference between the capillary fringe and phreatic zone would therefore be the energy content (Waswa and Lorentz 2016).

A number of earlier studies have recognised the exaggerated response of the water table after surface recharge and infiltration (Meyboom 1967). Guo *et al.* (2008) described this occurrence as the LE and found it to develop after the build-up of air pressure between the wetting front and the phreatic surface. Zang (2019) describes the process of conversion as being due to the increasing pore air pressure that increases pore water pressure below the advancing wetting front, converting negative pore water pressure to positive pore water pressure. During a rainfall event, surface infiltration produces a downward moving wetting front, forming a restriction to the outflow of air (Meyboom 1967) (Guo *et al.*, 2008). Weeks (2005) explains that the encroaching wetting front causes rapid pressure transmission to the top of the capillary fringe and continues to build up until entrapped air pressure is higher than the pressure head of the infiltration profile. According to Cloke *et al.* (2005) this increase in pore air pressure is accompanied by the induction of transient pressure waves. The corresponding increase in pore water pressure creates a continuous water phase in the capillary fringe, which allows for the rapid transmission of antecedent water. Even though some air will escape, the temporary rise in saturated zone pressure may be enough to induce slope instabilities. The LE, similar to GWR, is particularly dependent on the intensity of a rainfall event. High rainfall intensity events often lead to infiltration that fills the entire soil pore space but it is also possible that rainfall intensity during a critical event may exceed the infiltration capacity of surface soil, resulting in ponding (Fredlund and Stianson 2011). Simulation results compiled by Guo *et al.* (2008) indicate an increase in ponding depths to contribute to a substantial rise in the water level of the observation well. Meyboom (1967) states that ponding would inhibit the escape of air from the soil which contributes to higher compression values in the unsaturated zone, thereby intensifying the magnitude of the LE. It is therefore recognised that high intensity rainfall events, would be more prone to generating conditions required for both GWR and the LE to occur.

Methods

The experimental design involved infiltration experiments under controlled boundary conditions while monitoring the physical response of hydraulic state variables to simulated rainfall events. Laboratory work included a large 2.85 m high leak-proof column (600 mm ID) filled up to 2.65 m with tailings replica at *in-situ* dry bulk density. Similar to the procedure described by Waswa (2013), the PVC pipe was packed in 300 mm layers and administered the same number of blows after each deposit to ensure uniform bulk density. The complex nature of physical and hydrological processes in the vadose zone required sensing devices and automated data acquisition techniques to accurately determine hydraulic properties of a homogeneous tailings medium and simulate the generation of transient pressure waves. For this reason, the PVC column was instrumented with seven data ports, spaced vertically down the column. Each port was comprised of three custom made instruments including a time domain reflectometry (TDR) to measure volumetric water content, a 1 bar mini tensiometer (MT) to measure soil pore water pressure and a pore air pressure probe (PAPP). Ports were installed at 500, 600, 700, 800, 1100, 1400 and 1700 mm from the bottom of the pipe while automatic logging of the hydraulic state variables ensured accurate uninterrupted data of phreatic surface dynamics, the soil moisture profile and pore water/air pressure responses. Schematic details of the column apparatus and test setup (Figure 1) follow a similar design as the soil columns used by Waswa (2013) and Salas-García *et al.* (2017). The PAPP was connected

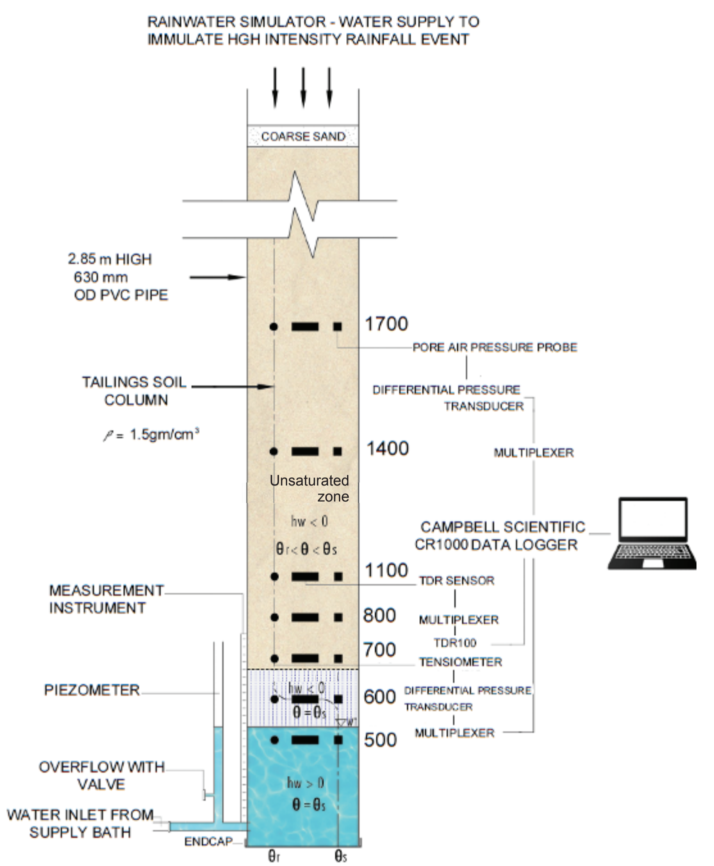

Figure 1 *Schematic diagram of the column test apparatus and setup. θr = residual soil water content, θs = saturated soil water content.*

to the 0.1 differential pressure sensor which was connected to the CR1000 data logger. The TDR probes were connected to the CR1000 data logger via the SDMX50 Multiplexer and Campbell Scientific TDR100 wave generator. The 1 bar pressure transducer connected the MTs to a data logger in order to obtain measurements. These sensors are connected to the CR1000 data logger via the multiplexer. After setup, the installation was allowed to settle. De-aired water was introduced from the bottom of the soil column, from the supply bath through an inlet valve positioned 200 mm from the base of the column, to prevent the capture of pore air and eliminate a disproportionate water table response (Waswa and Lorentz, 2016). Water was allowed to come to equilibrium, establishing a stable pre-simulation piezometric water level, positioned just below the lowest port at 450 mm from the base.

All sensors were monitored, by downloading data and plotting graphically, to ensure stability over at least four hours preceding the application of water at the surface boundary. Proceeding with the experiment, the coarse-grained topsoil surface was subjected to the artificial application of rainfall at three different ponding depths (event 3 not discussed), simulating surface recharge. These infiltration tests were conducted to investigate the effects of different boundary conditions and the advancement of the wetting front. The volume of each application was based on the depths of design rainfall events of particular return periods (1:200, 1:100 and 1:50 years) and calculated based on the inside area of the soil column. See Table 1. Design storms were obtained from station-specific data relevant to the area under study and applied in volumes calculated on the column's surface area. After each application the hydrostatic condition of the entire soil column was monitored by automated readings at 20 second intervals. This enabled the analysis of hydraulic properties and identification of transient profiles during the redistribution phase.

Laboratory results and experimental data analysis

After application of simulated rainfall events, there were several instant responses observed as soon as water was ponded onto the soil surface. Event 1 also showed some delayed responses. It should also be mentioned that in some instances it was impossible to define an accurate phreatic surface. Waswa (2013) owes this to the fact that the zero-pressure line may rise above the capillary fringe. It is also suggested that the particular fine nature of the soil medium allows for an undefined water table and extended capillary zone. The most significant responses will be discussed below.

Before application, the piezometric water level was measured manually with the use of the piezometer, which indicated

Table 1 *Description of incremental addition of water to tall soil column. Rainfall depths based on station specific data (Smithers and Schulze, 2002)*

Event	Return period	Rainfall depth	Volume	Addition of water to tall soil column
1	1:200 year	84.1 mm/h	24 L/h	9 L/30 min, 14 L/15 min & 1 L/15 min
2	1:100 year	74.9 mm/h	21.2 L/h	8 L/15 min & 13.2 L/45 min

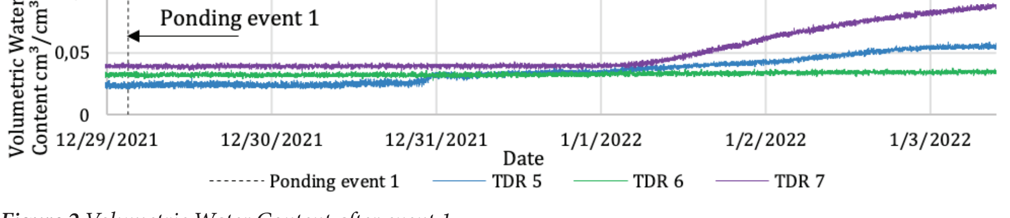

Figure 2 *Volumetric Water Content after event 1*

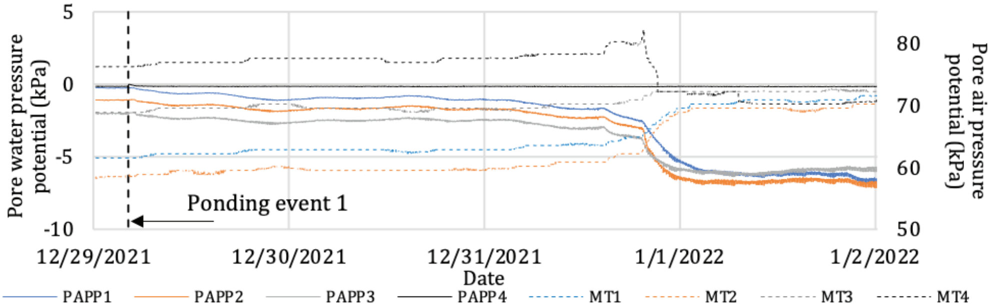

Figure 3 *Pore pressure response after the surface application of ponding event 1*

the location of the water level directly on Port 1. It is presumed that Port 2 was in the capillary fringe and since Ports 3 and 4 indicated unsaturated conditions, they were most likely located above the capillary fringe, together with the three shallow TDRs. Figure 2 illustrates the advancing wetting front that reached shallow TDRs (0.95 m below surface) after 50 hours.

The response in pore air pressure in the vicinity of the water table, to the advancing wetting front is shown in Figure 3. Compressed pore air pressure also brought about corresponding responses of pressure potential in the region of the capillary fringe. These results suggest that the magnitude of groundwater level responses is directly related to the magnitude of compressed pore air pressure. Waswa (2013) observed a similar simultaneous response in tensiometric pore water pressure at different soil depths, after a rainfall event of 67.8 mm, that also consisted of a high peak 1-minute intensity of 228 mm/h. There was found to be a clear relationship between the total change in pressure potential, in the vicinity of the water table, and the amount of compressed pore air pressure, imposed on the capillary fringe, after an extended time. Similar to Torres *et al.* (1998), Waswa (2013) assumed this to be the result of compressed pore air ahead of the wetting front. The proportional and corresponding change between pore air pressure and pore water pressure is therefore suggested to signal the presence of a pressure wave.

According to Koseki *et al.* (2010) a reduction in pore air pressure could be caused by the expansion of dense soil, possibly indicating mobilization along a failure plane. These conclusions were drawn while investigating the generation of negative pore air pressure in the filling of retaining walls during the simulation of earthquakes. However, even though soil saturation and an increase in porewater pressure reduces slope stability, it has been found that even a small reduction in pore-air pressure can significantly increase the factor of safety in slopes (Ba-Te, 2005, as cited in Fredlund *et al.*, 2012). Based on the principle of effective stress, it is suggested that the change in volumetric water content at the deep probes (not shown) is caused by the swelling or consolidation of soil due to the change in pore pressure above the air entry value. The small magnitude of the volumetric water content is attributed to the low compressibility of the soil matrix. It is therefore recognised that recorded changes in water content and pore water pressure are likely brought about by the rapid (downward) propagation of pore air pressure induced by rainfall.

After application of ponding event 2, volumetric water content at the three shallow probes immediately recorded changes, while the four deep probes increased shortly after (although at far less magnitude). This is shown in Figure 4. These results are similar to the infiltration tests conducted by Salas-Garcia *et al.* (2017) whereby a sharp increase in water content at the top of the column, eight minutes after ponding, decreased shortly after ponded infiltration stopped. Comparable to the present study, water content measured by the deep instruments increased and decreased at a delayed time and at a slower rate as compared with those for the upper section. Similarly, Waswa (2013) observed

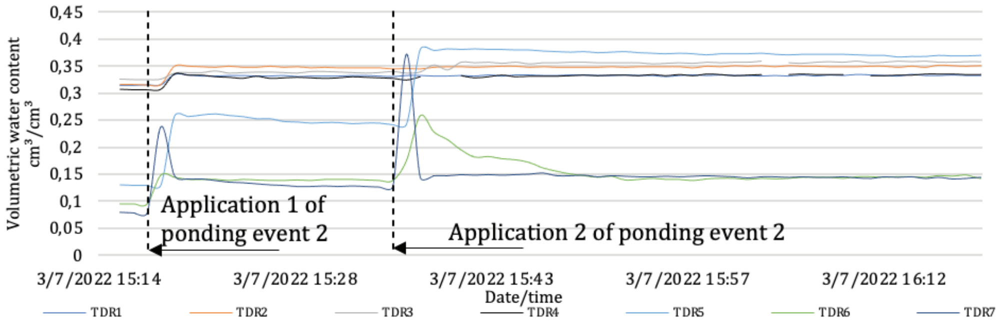

Figure 4 *VWC after the surface application of ponding event 2*

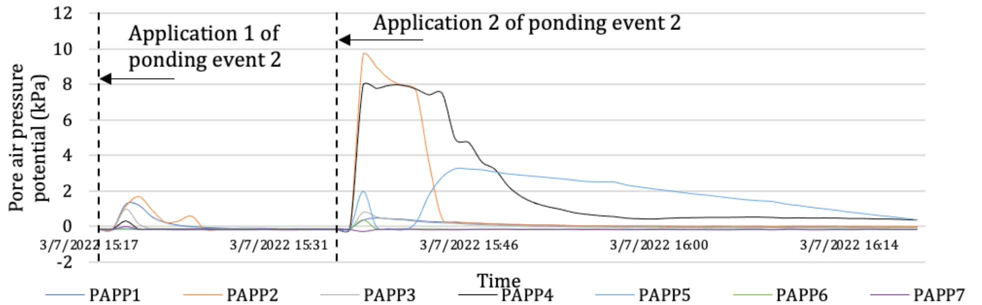

Figure 5 *Instant response in pressure potential proportional (ponding event 2)*

volumetric water content at the shallowest sensor to respond after 44 minutes from the start of the experiment, before arrival of the wetting front.

Ponding resulted in an instant response in pore air pressure potential. The magnitude of increase between application 1 and 2, shown in Figure 5, illustrates its sensitivity to ponding depth, which in turn is determined by rainfall intensity.

Discussion and Conclusions

Most pore air pressure sensors, tensiometric pore water pressure sensors, and water content sensors responded as soon as or shortly after water was applied to the soil surface. The significant response of deep MTs indicates that pore air pressure ahead of the wetting front caused the propagation of pressure waves that mobilised pre-event water and reduced pore water suction. These observations indicate that tensiometric pore water pressure responded to the compressed pore air pressure, before the arrival of the wetting front and supports salient literature on the hydrologic response of saturated soil confirming the unique relationship between pressure head and water content (Bear, 1972). It was also established that the rise of the phreatic surface is regulated by time-dependent flux boundary conditions and that the magnitude of water table response is regulated by the magnitude of compressed pore air pressure which in turn is determined by the intensity of a rainfall event. These pressure diffusion mechanisms cause an exacerbated increase in water content, independent of infiltration. It is therefore suggested that transient pressure wave mechanisms that are generated by high intensity rainfall events, originate in the unsaturated zone of tailings porous medium, thereby contributing to slope instability through changes in effective stress.

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