Rainfall-induced groundwater ridging and the Lisse effect on tailings storage facilities: A literature review

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Synopsis

The failure of tailings storage facilities (TSFs) results in the discharge of significant quantities of hazardous waste material into the natural environment. Research studies relating to slope instability have identified physical mechanisms such as rainfall-induced erosion, liquefaction, and shear failure as the main triggers. The generation of transient pressure waves and the mobilization of pre-event water in the unsaturated zone have been found to trigger shallow landslides in natural hillslopes. In this paper we review these physical mechanisms, known as groundwater ridging (GWR) and the Lisse effect (LE), from other studies. Previous researchers have explained both these phenomena through field and laboratory observations, numerical modelling, as well as conceptual discussions. These case studies demonstrate the impact of rainfall characteristics on the generation of transient pressure waves that rapidly increase the phreatic surface and change pore water suction. Reference is also made to the influence and behaviour of physical porous medium characteristics on the establishment of a continuous water phase that facilitates the transmission of an induced pressure head. However, previous studies fail to recognize the possibility that the pressure increase in pre-event water through pore air propagation could cause slope instability in tailings dams. The authors suggest that the physical properties and hydraulic behaviour of unsaturated porous tailings media make it susceptible to GWR and the LE, resulting in the creation of a potential failure plane.

Keywords

transient pressure wave mechanisms, groundwater ridging, Lisse effect.

Introduction

The global mining industry has suffered several severe tailings storage facility (TSF) failures in the last few decades, which have resulted in extensive damage, catastrophic environmental impacts, loss of life, and severe socioeconomic disruptions. According to Azam and Li (2010), trends indicate a steep increase in these failures, particularly since the 1960s. The current authors note that this timeframe coincides with a marked increase in CO_2 emissions and global temperatures, resulting in higher intensity rainfall events under the force of climate change (Schulze *et al*., 2011). The location and timeline of TSF failures are illustrated in Figures 1 and 2. Gariano and Guzzetti (2016) argue that variations in rainfall parameters could make certain areas in southern Africa especially vulnerable to the possibility of slope instability and landslides. This paper will consider alternative causes of such failures by examining the generation of groundwater ridging (GWR) and the Lisse effect (LE) in natural hillslopes and extrapolating it to TSFs.

Rainfall-induced slope instability

Lyu *et al*. (2019) found that an overwhelming majority of tailings dam failures (approx. 90%) occur with the upstream method of construction. Even though dam type, therefore, seems to contribute to the risk of failure, research results recognize rainfall-induced slope instability as the main trigger. This includes findings by *e.g*. Blight, Robinson, and Diering (1981) and Jennings (1979), who identified seepage, overtopping, shear failure, piping, and erosion as some of the most important factors causing slope failure. Blight and Fourie (2003) reported that pore water pressure and a high phreatic surface contribute to the generation of flow failure in mine waste dumps, tailings dams, and municipal solid waste landfills. This notion is supported by Yaya, Tikou, and Lizhen, (2017), who found that insufficient control of water

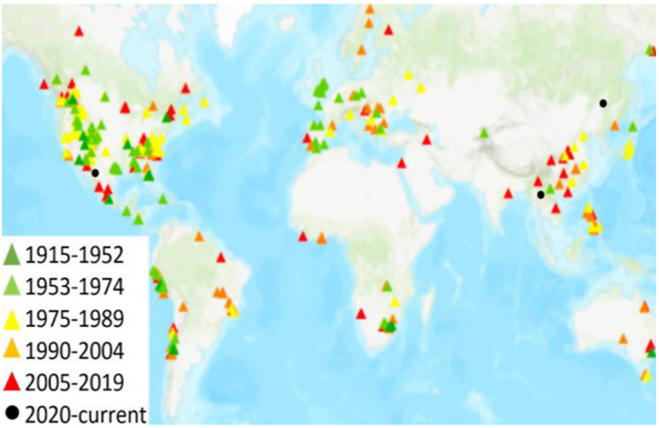

Figure 1—Tailings dam failures: location and time of occurrence (adapted from Cheng *et al.*, 2021)

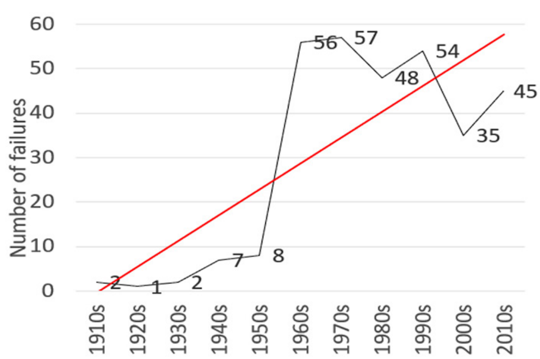

Figure 2—CO_2 emissions, temperature increases, and global TSF failures over time (**adapted from Lyu** ***et al.***, **2019; Azam and Li, 2010**

pressure can result in structural inadequacy and subsidence failure. Muñoz (2019) points out that although the increase in pore water pressure is a significant factor, the decrease in soil suction brought about by the wetting front also contributes to changes in the phreatic surface and a probable reduction in slope stability. This perception is supported by Robertson *et al.* (2019), who concluded that loss of suction in tailings was a contributing factor to the Brumadinho disaster in 2019.

Rainfall intensity and pre-event water in stream storm flow hydrograph

According to Rahardjo, Leong, and Rezaur (2008), high-intensity rainfall events cause shallow landslides in slopes with residual soils. This is believed to occur after excessive rainfall infiltration increases pore water pressure and reduces shear strength. In the case of the LE, Meyboom (1967) and Guo, Jiao, and Weeks (2008) contend that the advancing wetting front produced by a high-intensity rainfall event creates an impermeable 'lid' restricting the outflow of air. Fredlund and Stianson (2011) explain that low infiltration capacities result in ponding, which creates an additional load and higher compression values in the unsaturated zone, thereby exacerbating the magnitude of the LE. The authors of this paper argue that this would also occur if high rainfall intensities exceed infiltration capacity, regardless of soil type. In the case of GWR, Abdul and Gillham (1984) and Gilham (1984) proposed that the rapid conversion of water held in the capillary zone occurs due to the fill-meniscus hypothesis, whereby the addition of small amounts of rainwater brings about a change in suction, relieving tension in the tension-saturated capillary zone. In contrast, Waswa and Lorentz (2015) introduced the energy hypothesis whereby the intensity of a rainfall event provides additional energy, enabling the conversion of pre-event water held in the capillary fringe (CF) to water in the phreatic zone.

Guo, Jiao, and Weeks (2008) and Rahardjo *et al.* (2001) suggest that rainfall frequency impacts antecedent moisture conditions and the generation of pre-event water. Antecedent water is generated through the infiltration and percolation of precipitation and, through hydrograph separation studies, the presence of base flow water in the stream storm flow hydrograph is recognized (Kim *et al.*, 2017). Other researchers, *e.g.* Blight *et al.* (2012), Cloke *et al.* (2005), and Meyboom (1967), argue that, in the case of TSFs, this source is supplemented by vast quantities of slurry that are discarded and stored together with tailings. It is also suggested that pre-event water exists permanently in the subsurface profile, thereby establishing a tension-saturated continuous pore water phase. Cloke *et al.* (2005) found that this is caused by the uninterrupted supplementation of water sources such as rising consolidation water. The authors of this paper also suggest that, in contrast to similar studies conducted on natural hillslopes, the absence of phreatophytes exacerbates higher water content levels. Not only does this mean less moisture being removed from the soil profile, but engineered embankments would also be more prone to erosion, while the soil structure would not have the stability provided by a root system. Even though the authors of this paper postulate that GWR and the LE are significant contributors to slope instability, it is recognized that insufficient drainage causes low consolidation speeds and increases the weight of the dam, thereby reducing the shear strength and effective stress.

The significance of pre-event water in slope stability is supported by a study conducted by Rahardjo *et al.* (2001) into the causes of 20 shallow landslides on the Nanyang Technological University campus in Singapore. An investigation into similar critical rainfall events, not leading to landslides, showed similar characteristics. However, the triggering rainfall event during which slope failure occurred was found to be preceded by several non-critical rainfall events resulting in elevated levels of antecedent moisture. The notion that pre-event water, and not infiltrated water, contributes to rapid and transient increases in pore water pressure, is supported by Premchitt, Brand, and Phillipson (1986). They reported that soils in which landslides occurred in Hong Kong had an infiltration time of between 14 hours to three days. Immediate slope failure could therefore not have been attributed to infiltration, but rather to pre-event water already contained in the soil profile. Zang *et al.* (2017) also report that pre-event water contained above the phreatic surface in the CF plays an integral part in the rapid mobilization of groundwater.

Transient pressure wave mechanisms

Waswa and Lorentz (2015) state that transient pressure waves are responsible for the rapid release, mobilization, or pressure perturbation of previously stagnant antecedent moisture through the mechanisms of GWR and the LE. This enables groundwater levels, during storm events, to rise disproportionately with the amount of water infiltrating the soil profile (Waswa, 2013). Various researchers, *e.g.* Lins, Schanz, and Fredlund (2009), Rahardjo, Choon, and Tami (2004), Salas-García *et al.* (2017), and Waswa (2013), have investigated pore air propagation and transient pressure wave generation in unsaturated porous media through the use of automated columns. Waswa (2013) observed different responses depending on the depths of the water table (WT) by recognizing that GWR occurs at a shallow WT and the LE at deep WTs. Rassam and Williams (2000) conducted soil column experiments for the prediction of soil water characteristics curves (SWCC) in tailings. The set-up consisted of two tensiometers and one time-domain reflectometer (TDR). This study did not report on GWR or the LE but was able to analyse the drainage cycle and predict the behaviour of tailings in the establishment of an extended CF. Further soil column studies were presented by Yang *et al*. (2004). Similar to the above studies, the column was equipped with TDRs and tensiometer sensors placed at specific depths to measure water content and pore water pressure. Even though this study focused on water content and suction data, transient pressure waves were observed. All the abovementioned studies were able to demonstrate exaggerated WT responses after the application of a small amount of surface recharge. In agreement with Iverson (2000) and Waswa (2013), the authors hypothesise that after the application of surface recharge, rainfall-induced pore pressure rapidly propagates downward in the soil profile.

Groundwater ridging

The GWR hypothesis is described by Abdul and Gillham (1984) as a process occurring in the subsurface near the stream (and in this case near the tailings pond) that allows for the rapid rise of the WT to the surface. Figure 3 illustrates the mechanism of GWR, recognized by the rapid uneven rise in the phreatic surface after a high-intensity rainfall event. Abdul and Gilham (1984) support this view and propose that ridging is probable under high rainfall intensities under certain slope and soil conditions. In contrast, Bonell *et al*. (1998) and Elsenbeer *et al*. (1985) dismiss the notion that high-intensity rainfall events contribute to GWR and believe that event water is dominant in such environments.

According to Waswa and Lorentz (2016), a high-intensity rainfall event does not necessarily result in slope instability. Instead, a rainfall event of specific intensity and duration combined with particular antecedent moisture conditions is needed for critical conditions leading to failure. According to Cloke *et al*. (2005), rainfall intensity controls initial ridge development as well as the amount of pre-event water being discharged into the stream. It was established that low rainfall intensities (0.036 mm/h) resulted in low zones of pre-event water proportions (PEZ), while high rainfall intensities (360 mm/h) also showed low PEZ values due to event water becoming overland flow and dominating discharge. A medium-intensity rainfall event of 3.6 mm/h was found to allow ridge development and cause a significant proportion of discharge. Cloke *et al*. (2005) argue that rainfall intensity is relevant only when the CF does not extend to the ground surface and saturated hydraulic conductivity (Ks) is high enough to have rainfall-limited infiltration. Similarly, Zandarín *et al*. (2009) found that a high-intensity rainfall event is not necessarily detrimental to dam safety, but rather lower intensity events that have a longer duration (resulting in more infiltration) and which are preceded by antecedent rainfall events. Furthermore, events that have a higher intensity towards the end than at the start have a far more destabilizing effect than events with constant intensity. Rainfall events associated with shallow landslides have been found to trigger these failures after a spike in intensity during the middle or towards the end (Waswa and Lorentz, 2016).

Waswa and Lorentz (2005) argue that the extension of the CF to the ground surface is a prerequisite for GWR to occur. This notion is supported by Zang *et al*. (2017), who found that antecedent water contained above the phreatic surface plays an integral part in the GWR mechanism. Cloke *et al*. (2005) challenge this view and suggest that the role of the CF concerning the process of GWR may have been overemphasised. The hydrological model applied by Cloke *et al*. (2005) enabled the evaluation of the GWR hypothesis in different riparian environments. The study made use of a laboratory experiment from Abdul and Gillham (1984), as well as a conceptual model solving the Richards equation for matrix flow. A discrete CF was then modelled with the use of the Brooks-Corey soil moisture algorithm. These two attributes disregard any non-Darcian processes responsible for pre-event water discharge and/or pressure ridge development. It was concluded that WT height and saturated hydraulic conductivity (K_s) have the largest influence on GWR. Even though the CF regulates pressure ridge development, Cloke *et al*. (2005) suggest that it has little control over the discharge of pre-event water. They propose that the height of the WT and the CF may become significant in GWR only when combined with controlling factors such as soil hydraulic properties. This includes assumptions, *e.g*. that the fine nature of tailings would contribute to extended CF levels, establishing a continuous pore water phase and enhancing conditions facilitating the rapid mobilization of pre-event water to lower horizons (Waswa, 2013). Waswa and Lorentz (2016) report the rate of change in pressure potential to vary between soils of different grain sizes. This is illustrated by the pressure potential in fine soils measuring 15 cm-H_2O less than in coarse soils within 10 minutes after application of a simulated rainfall event. The response in pressure potential also seems to be delayed in fine soils, such as porous tailings media, which appears to be linked to the height of the CF (Waswa and Lorentz, 2016).

Waswa and Lorentz (2016) explain that the rapid rise in the phreatic surface is due to the conversion of capillary water held

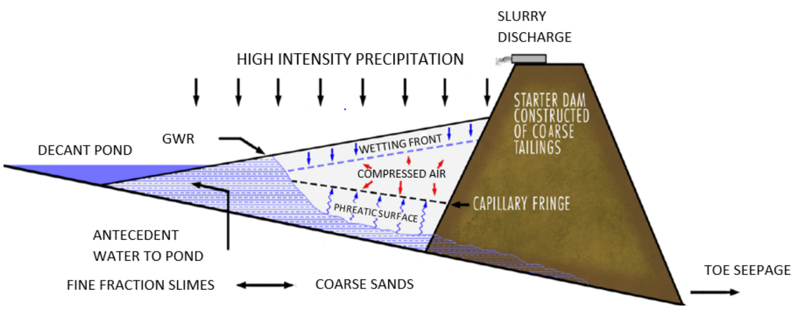

Figure 3—Schematic depiction of GWR (modified from Pacheco, 2019; Zang *et al.* 2017)

in the unsaturated zone to phreatic water in the saturated zone. Gilham (1984) and Abdul and Gillham (1984) argue that this happens according to the fill-meniscus hypothesis whereby the addition of small amounts of rainwater brings about a change in matric suction. This change relieves tension in the saturated capillary zone, resulting in vadose water converting to phreatic water with a subsequent rise in the WT. Waswa and Lorentz (2015) reject this argument and propose the energy hypothesis, whereby the intensity of a rainfall event provides additional energy that transforms kinetic energy to potential energy, enabling mobilization of pre-event water. These authors further suggest that the only difference between the CF and phreatic zone is the energy content (Waswa and Lorentz, 2019). The extension of the CF provides the contact between the kinetic energy-carrying intense raindrops and the potential energy-deficient pore water. Moisture profiles involved in the process of GWR are illustrated in Figure 4.

According to Zang *et al.* (2017), the rise in the WT is not entirely dependent on the amount of rainwater infiltrating the soil during the high-intensity event, but also on the amount of pre-event water already held in the capillary zone. The rise in the WT is therefore disproportionate to the amount of infiltrated water. According to Waswa and Lorentz (2015), seeing that a small amount of rainfall is required to fill the capillary menisci, it would result in an almost immediate and excessive rise in the WT during an event. During this process, the steep hydraulic gradient is directed towards the stream and leads to the discharge of antecedent water into the stream (Zang, 2019). This argument is supported by Cloke *et al.* (2005), who state that even a small amount of infiltrated water can rapidly convert the negative capillary pressure head in the CF to a positive pressure head, thereby changing the WT gradient and forcing the pre-event water out. GWR studies conducted on beaches support this concept and found the rapid and exaggerated WT rise to be attributed to the upper extent of the CF (sand surface). Several soil column studies confirmed that a small amount of surface recharge could result in an instant disproportionate rise of the WT, simulating GWR responses (Abdul and Gillham, 1984; Turner and Nielsen, 1997). Khaled *et al.* (2011) carried out comparable tests on Toyoura sand and Chiba LiC soils that were packed homogenously into two acrylic columns with 50 cm length and 7.5 cm ID. After the

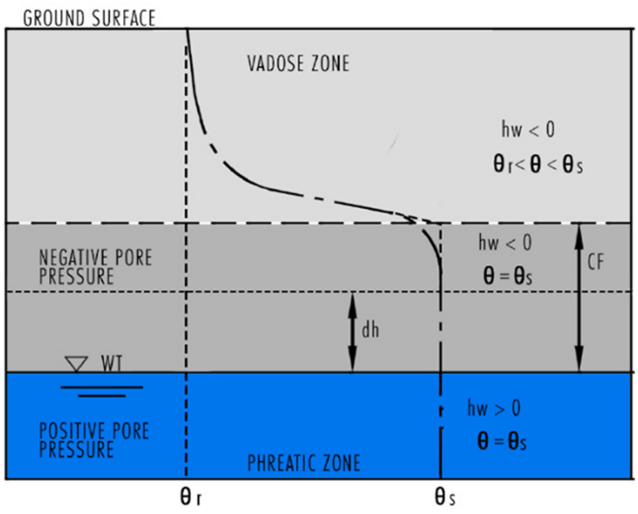

Figure 4—Moisture profiles under GWR: h_w - pore water pressure, θ_r - residual soil water content, θ_s – saturated soil water content (modified from Miyazaki, Ibrahimi, and Nishimura, 2012; Waswa, 2013)

addition of only 1 mm of surface recharge, an instant fluctuation in the phreatic surface occurred, resulting in a 50 mm rise within 10 seconds. A total rise of 120 mm was observed. This upsurge is attributed to the rapid conversion of the pressure head in the vadose zone. A similar field experiment, conducted by Gillham (1984), found a significant rise of 300 mm in a shallow WT, resulting from the addition of 30 mm of water.

Zang *et al.* (20179) report that as rain intensity decreases, so does pore air pressure in the vadose zone with a subsequent reduction in induced air flow and GWR. Another study by Abdul and Gilham (1984) suggests that CF GWR will not be responsible for pre-event water discharge in all environments. Cloke *et al.* (2005) also found a complex interrelationship between riparian characteristics and GWR. From their findings, it became evident that in the case of low capillary rise and low WTs, no ridge development occurred. The initial WT before the rainfall event is therefore a strong indication of the zone of pre-event water proportions reached. Rainfall intensity was found to control initial ridge development, especially if the CF did not reach the ground surface and hydraulic conductivity was high enough to allow for rainfall-limited infiltration. The magnitude of GWR would also depend on rainfall intensity, but it was further found that for rapid GWR to occur through antecedent moisture contribution from the capillary zone, a continuous water phase extending from the natural ground surface to the phreatic surface is required (Waswa and Lorentz, 2019). This agrees with observations from field studies conducted by Marui *et al.* (1993), confirming that pressure transmission through pore spaces occupied a continuous water phase enables the rapid response of pore water pressure in the deep soil profiles.

Further studies on the effect of compressed pore air on groundwater fluxes using soil columns were conducted by Marui *et al.* (1993). This study found that groundwater fluxes commence as soon as compressed pore air pressure in the unsaturated zone increases. Even though pore water pressure was monitored by tensiometers, volumetric water content and the influence of the CF were ignored. Waswa (2013) also researched the effect of compressed pore air ahead of a wetting front on the rate of infiltration using laboratory column experiments. The column was instrumented with pore air pressure probes, pore water pressure probes, volumetric water content sensors, a groundwater outflow tube, and a piezometer. It was determined that a GWR transient pressure wave mechanism arises in cases where the CF extends to the ground surface. The results also indicated that high-intensity rainfall events release tension forces in the CF, thereby discharging pre-event water. This finding supports the notion that the magnitude of GWR is proportional to the intensity of the event. Results confirmed by Waswa (2013) indicated a significant increase in pressure potential at the initial WT brought on by the advancing wetting front. It was further established that the rate of increase was directly related to the thickness of the CF and therefore proportional to, but less than, the magnitude of compressed pore air pressure.

According to Fredlund, Rahardjo, and Fredlund. (2012), transient or steady-state pore pressure changes are coupled with infiltration, particularly during heavy rainfall events. Such events cause a change in negative pore water pressures, which contributes to slope failures. The same authors state that the primary factor contributing to the unusual behaviour of residual soils is negative pore water pressure, which is related to pore air pressure. Analytical studies and laboratory experiments found that even a minor reduction in pore air pressure results in an exponential increase in slope stability (Ba-Te, 2005). Figure 5 illustrates the relationship between pore water pressure at different depths of the WT, while Figure 6 shows the relationship between pore water pressure and pore air pressures. The difference between the last two mentioned parameters also indicates matric suction.

Lisse effect

Miyazaki (2011) describes another mechanism of similar magnitude to GWR, but of different origin, that leads to the mobilization of pre-event water (a comparative summary is listed in Table I). The LE occurs due to the build-up of air pressure between the wetting front and the phreatic surface (Guo, Jiao, and Weeks, 2008). This effect is likely to occur if pore air is present in the upper boundary of the CF and the phreatic surface is located at sufficient depth. Waswa (2013) states that similar to GWR, the CF plays a pivotal role in WT response. According to Kutílek, Nielsen, and Reichardt (2007), soil that is wetted quickly, as in the case of a high-intensity rainfall event, will contain approximately 3–8% entrapped air. Fredlund, Rahardjo, and Fredlund (2012) argue that soil air content could be as much as 15% by volume. The rainfall event produces a downward moving wetting front, effectively acting as a low-permeability lid that restricts the outflow of air (Meyboom, 1967; Guo, Jiao, and Weeks., 2008). According to Li and Horne (2006), the relationship between the air and water phases is described by the Brooks and Corey relative permeability model that considers capillary pressure as a power function of the wetting phase. It is recognized that in the case of low-permeability soil, this relationship causes the two phases to undergo a phase transformation and mass transfer as pressure changes.

Weeks (2002) explained that at this point, pressure is transmitted rapidly to the top of the CF and continues to build up until the entrapped air pressure is higher than the pressure head of the infiltration profile above. Meyboom (1967) suggests that the increase in pore air pressure is accompanied by the initiation of transient pressure waves. In response, the increase in pore water pressure establishes a continuous water phase in the CF, enabling the rapid transmission of antecedent water. Meyboom (1967) found that the water level rise in the well commences before actual recharge due to rainwater percolation. Instead, the water level increase may be driven by air flow induced by an advancing wetting front at approximately 0.6-1.0 m below ground surface.

A review by Fayer and Hillel (1986) found that some entrapped air will escape vertically upward, indicating that the magnitude of the LE is governed by the air entry pressure (Guo, Jiao, and Weeks, 2008). Some entrapped air will remain in the soil profile

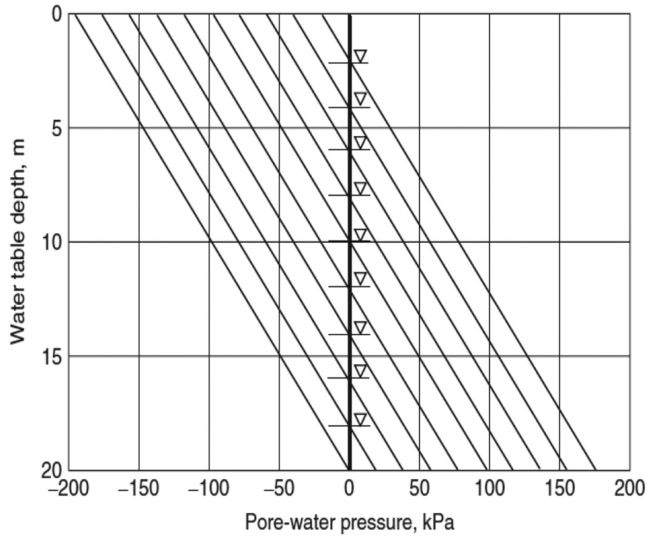

Figure 5—Equilibrium hydrostatic pore water pressures for various depths of water table (Fredlund, Rahardjo, and Fredlund, 2012)

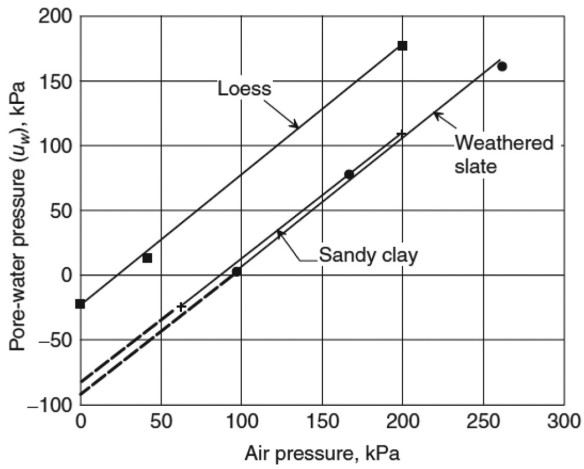

Figure 6—The relationship between pore water pressures and pore air pressures indicating matric suction (Fredlund, Rahardjo, and Fredlund, 2012)

and reduce saturation moisture content. However, the momentary increase in saturated zone pressure may be sufficient to induce slope instabilities. Figure 7 illustrates the LE whereby a rapid rise in water level in a well is observed during an event but holds little relationship to the water infiltrating the unsaturated soil profile (Bianchi and Haskell, 1966).

Table I

Comparison between the LE and GWR (Miyazaki, Ibrahimi, and Nishimura, 2012)

Lisse effect	Groundwater ridging
Energy is derived from compressed air pressure in the unsaturated zone ahead of a wetting front	Energy derived from the intensity of the rainfall event
Depth to CF is less than the depth to the WT	The CF extends from the WT almost to the natural ground surface
Rapid rise in the well but slow recession	Sharp rise in WT followed by a correspondingly sharp decline
High-intensity rainfall events	Rainfall events of fluctuating intensity
WT rises in response to pressure increase	WT frequently rises to ground level
Actual WT level not affected, but the rise in the penetrating well is significant	Affects both the WT level as well as the well tapping the phreatic surface

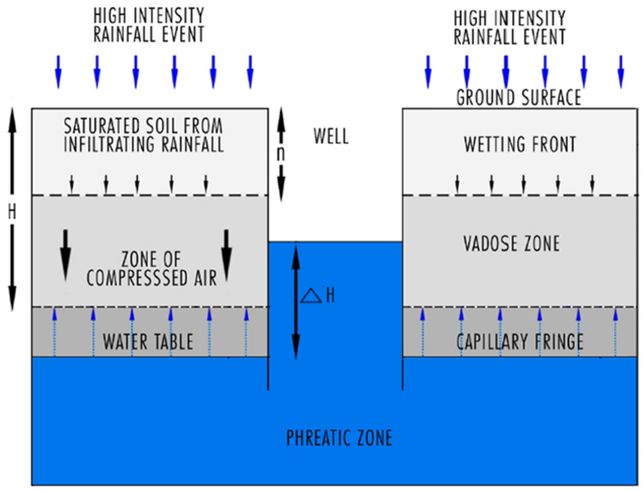

Figure 7—The conditions for LE occurrence. *n*: depth of infiltrated water following intense rain; Δ*H*: water level rise in the observation well resulting from the wetting front during intense rain trapping air and increasing soil air pressure; *H*: distance from the ground surface to the upper boundary of the CF (adapted from Meyboom, 1967; Miyazaki, Ibrahimi, M. K. and Nishimura., 2012; Weeks, 2002)

An analysis of recorded observations by Weeks (2002) indicates that if the depth of penetration of the wetting front is only a few millimetres, the water level in the well could rise by approximately 550 mm. Meyboom (1967) describes the ratio of rainfall to rise in the water level as being approximately 1:18. This value is confirmed by Hooghoudt (1947), who established a rainfall/rise ratio of 1:20 after solving for air pressure increase above the CF. Application of this calculation (Equation [1]) resulted in a rise in the observation well of 533.4 mm after a rainfall event of 25.5 mm, infiltrating the soil profile to a depth of 25.5 mm and the CF at 508 mm below ground surface.

$$H_{\max} - H = \frac{n}{h-n} atm \qquad [1]$$

where ($H_{max} — H$) is the change in water level in the observation well, n is the depth of infiltrated water after a rainfall event, and h is the distance from the ground surface to the upper boundary of the CF. Other researchers, *e.g.* Guo, Bao, and Weeks (2008) and Weeks (2008), found that the maximum water level rise in the well would be less than the maximum air pressure induced by infiltration. Guo, Bao, and Weeks (2008) assert that the water level rise in the well is delayed relative to the rise in air pressure in the unsaturated zone. This phenomenon is described by Equation [2] (Weeks, 2008).

$$\Delta H = P_{WC}\left(\frac{m}{h-m}\right) \qquad [2]$$

where P_{WC} is the atmospheric pressure in the form of water column height, m is the depth of rain penetration and h is the distance from the natural ground level. Seeing as the entrapped air causes a decrease in the magnitude of the vertical hydraulic gradient, which restricts infiltration at the ground surface, it will also contribute to higher levels of runoff. This explains why light rainfall events often result in a disproportionate increase in runoff. Entrapped air may not only give the false impression of recharge, but may also reduce the amount of recharge that would be expected in its absence (Healy and Cook, 2002). Bear (1972) indicates that changes in volumetric water content could also occur due to swelling or consolidation of the soil profile, caused by a change in pore pressure above the air-entry value.

Guo, Bao, and Weeks (2008) suggest several variables, apart from rainfall intensity, that regulate the occurrence of the LE. For example, Fredlund and Stianson (2011) observed significant increases in the water level of the well, associated with increasing ponding depths. Simulation results compiled by Guo, Bao, and Weeks (2008) indicate an increase in ponding depth caused by the infiltration capacity of porous media being exceeded by a high-intensity rainfall event. Ponding inhibits the escape of air from the soil and, as it increases, it also results in higher compression values in the unsaturated zone, thereby intensifying the extent of the LE. Figure 8 demonstrates the effect of a 2 cm, 6 cm, and 10 cm ponding depth on the water level and air pressure (Guo, Bao, and Weeks, 2008). The characteristics of tailing material as a variable are discussed in the following section.

Tailings characteristics

Parametric studies predict how the WT will respond based on geotechnical properties such as pore size distribution (λ), permeability (k) and saturated hydraulic conductivity (K_s). These studies also enable the prediction of water retention capacities of the porous tailings medium, which becomes relevant in the establishment of a continuous pore water phase. Empirical functions, such as the van Genuchten parameters, normally present these characteristics.

Porous media conditions demonstrate intrinsic permeability parameters that play a pivotal role in generating both GWR and the LE. In keeping with Guo, Bao, and Weeks. (2008), it is believed that low-permeability formations inhibit the rate of infiltration, subsequently causing a delay in air pressure response. To our knowledge, this could result in ponding, which in fact would prohibit the escape of pore air, eventually leading to an increase in pore water pressure. This argument supports the observation of Rahardjo, Leong, and Ret (2008) that low-permeability soils, such as tailings, are more susceptible to high pore water pressures. Highly permeable soil conditions result in significant air pressure, but the response in the observation well will be diminished compared to a less permeable soil profile. For instance, soil permeability (k) of 1×10^{-12} m/s demonstrates a maximum water level rise of 0.16 m compared to only 0.08 m for soil with a permeability of 1×10^{-13} m/s (Guo, Bao, and Weeks, 2008). In contrast, higher levels of permeability do not guarantee maximum water levels in the observation well. This is due to adequate

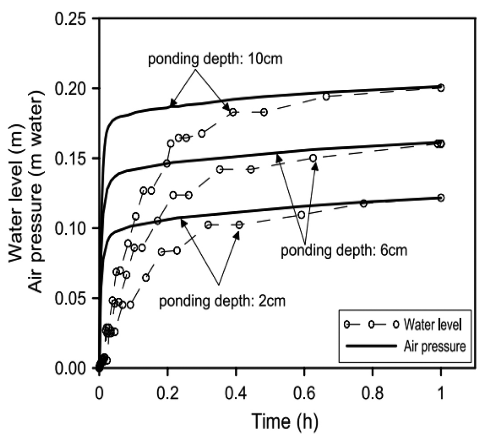

Figure 8—Effect of ponding depth of water level and air pressure (Guo, Bao, and Weeks, 2008)

hydraulic conductivity that does not allow for ponding, resulting in the release of air from the ground surface. Guo, Bao, and Weeks (2008) have shown that the magnitude of the LE is insignificant in highly permeable soils but increases as permeability decreases.

Another soil property impacting significantly on transient pressure waves is pore size distribution, which is directly related to soil uniformity. Since a high pore size distribution signifies a narrow range of particles and pore sizes, it would encourage higher levels of air pressure in the unsaturated zone and increasing water levels in the wells (Guo, Bao, and Weeks, 2008). According to Cloke *et al.* (2005), the development of a positive ridge is less dependent on the CF and relates more closely to soil type. To illustrate this belief, GWR results showed that, in the case of the CF intersecting the ground surface, a rise in the WT is enabled through the application of a small amount of water. However, if the WT is low and the CF does not intersect the ground surface, WT response is regulated by the saturated conductivity (K_s) of the porous medium. Cloke *et al.* (2005) further recognize that fine-grained soils encourage ridging by allowing for the extension of the capillary zone to the ground surface. while coarse-grained soils allow for increased infiltration capacities. The size of the CF is therefore inversely related to the K_s of the material.

The analysis of particle size distribution studies conducted by Dacosta (2017) and Blight *et al.* (2012) enabled the classification of tailings material from a platinum mine near Mokopane. Results obtained from Sample 1 (30 kg) and Sample 2 (3.9 kg) are illustrated in Figure 9 and show similar curves representing the characteristics of fine soil. Approximately 5–11% of the unconsolidated tailings sample falls within the finest clay fraction and 45– 59% in the fine to coarse silt fraction. The remaining 30–50 % was found in the finest sand fraction (Dacosta, 2017; Blight *et al.*, 2012). The fine nature of porous tailings media suggests that it is liable to retain pre-event water and establish a continuous water phase in the CF.

Discussion

This review found several studies that recognize the impact of GWR and the LE on the rapid mobilization of groundwater. Waswa and Lorentz (2016) have driven this concept further and established that critical rainfall events generating transient pressure waves contribute significantly to triggering landslides. Even though the results obtained from these studies were constrained to natural hillslopes, similar results will likely be obtained from the analysis of porous tailings media and provide insight into the cause of slope instability in tailings dams. Further research is required to determine the hydraulic mechanisms that control and transmit induced pore pressure through transient pressure waves during and after surface recharge. The authors of this paper suggest that both GWR and the LE would contribute to the failure of TSFs, and that a clear understanding of these mechanisms would facilitate better long-term design and maintenance of tailings dams, thereby reducing geohydrological risks.

We propose laboratory simulations similar to those carried out by Waswa (2013). This will be done by replicating the automated tall soil column and fitting it with seven data ports, each consisting of three probes including a time-domain reflectometry (TDR) instrument to measure volumetric water content, a 1 bar tensiometer to measure soil pore water pressure, and a 0.1 bar pore air pressure probe. The experimental design will involve infiltration experiments under controlled boundary conditions while monitoring the physical response of hydraulic state variables to simulated rainfall events. Observations and results will be used to determine phreatic surface dynamics, the soil moisture profile, pore water/air behaviour, and physical processes to facilitate the analysis of flow of water throughout saturated tailings based on short-term, one-dimensional laboratory column flow. The complexity of the physical processes occurring in the unsaturated zone necessitates automated data acquisition to accurately simulate infiltration and predict transient pressure-wave generation associated with unsaturated soil water flow. It is further intended to verify results through numerical modelling using HYDRUS software. This application simulates water flow in variably saturated soils under steady-state and transient water flow conditions. It also allows short-term, one-dimensional laboratory column flow studies, making it an invaluable resource for numerical modelling (Šimůnek, van Genuchten, and Šejna, 2012).

Summary

Both GWR and the LE have been recognized and explained by previous researchers who investigated these physical processes through conceptual discussion, numerical modelling, and field and laboratory observations. From these studies, the authors conclude that landslide responses to rainfall involve transient processes, and that these processes are linked to groundwater pressure heads that change in response to rainfall. It is further determined that critical rainfall events occurring on slope profiles containing pre-event water in the capillary zone, provide a continuous water

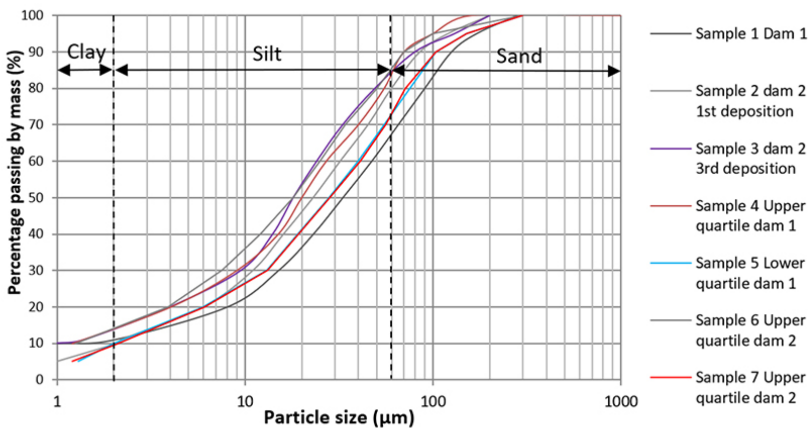

Figure 9—Particle size distribution of platinum tailings (Malvern analysis) (Dacosta, 2017; Blight *et al.*, 2012)

phase necessary for the transmission of an induced pressure head to a potential failure plane. These studies confirm that low-permeability soils are more prone to saturated conditions when combined with pre-event water, thereby enabling the formation of tension saturated or near-saturated conditions.

The authors propose that the design and operation of TSFs and the characteristics of tailings, combined with its high capacities for antecedent water, makes these engineered structures especially prone to slope instability mechanisms generated by GWR and the LE. This assumption will be addressed in future research.

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