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The influence of standpipe piezometer lag time on the stability of Tailings Storage Facilities

L'influence du temps de latence du piézomètre de la colonne montante sur la stabilité des installations de stockage des résidus

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ABSTRACT: With the number of inactive Tailings Storage Facilities (TSFs) in South Africa and with the advances in technology making old ore deposits commercially viable, it is likely that many of these TSFs may be recommissioned in the future. This recommissioning will result in a change in pore pressure regime within the TSF which will influence the stability. A common method to measure this change in pressure regime is the use of standpipe piezometers. However, a limitation of these piezometers is the delayed response time due to the volume of pore water require to infiltrate into the piezometer. The influence of this time delay was investigated by means of numerical modelling of a wetting front caused by recommissioning of a hypothetical TSF and stability analyses at selected time intervals. At each time interval, a Factor of Safety (FoS) was calculated using the true pore pressure regime. Other FoS values were then calculated for various piezometer response times and the results were compared. It was found that the calculated FoS reduced from 1.5 at the time of dormancy to 1.0 in a period of 300 days after the simulated recommissioning. This highlights the need to consider the delayed response time of standpipe piezometers when a change in pore pressure regime is expected.

RÉSUMÉ: Avec le nombre d'installations de stockage de résidus (TSF) inactives en Afrique du Sud et avec les progrès technologiques rendant les anciens gisements de minerai commercialement viables, il est probable que bon nombre de ces TSF puissent être remis en service à l'avenir. Cette remise en service entraînera un changement de régime de pression interstitielle au sein de la TSF qui influencera la stabilité. Une méthode courante pour mesurer ce changement de régime de pression est l'utilisation de piézomètres à colonne montante. Cependant, une limitation de ces piézomètres est le temps de réponse retardé dû au volume d'eau interstitielle nécessaire pour s'infiltrer dans le piézomètre. L'influence de ce délai a été étudiée au moyen d'une modélisation numérique d'un front de mouillage provoqué par la remise en service d'une TSF hypothétique et d'analyses de stabilité à des intervalles de temps sélectionnés. À chaque intervalle de temps, un coefficient de sécurité (FoS) a été calculé en utilisant le régime de pression interstitielle réel. D'autres valeurs de FoS ont ensuite été calculées pour différents temps de réponse du piézomètre et les résultats ont été comparés. Il a été constaté que la FoS calculée est passée de 1.5 au moment de la dormance à 1.0 dans une période de 300 jours après la remise en service simulée. Cela met en évidence la nécessité de prendre en compte le temps de réponse retardé des piézomètres à colonne montante lorsqu'un changement de régime de pression interstitielle est attendu.

KEYWORDS: *Tailings dams, standpipe piezometers, seepage modelling, slope stability.*

1 INTRODUCTION

Tailings Storage Facilities (TSFs) are used to store mine waste. These are typically large structures and have long operating lives, often spanning over many decades. Unlike conventional water dams, tailings dams are continuously being constructed and their geometry is constantly changing. Further to this, the deposited material is often used to construct the embankment and is hydraulically deposited in a loose state. As part of the design and safety evaluation of these structures, it is important to be able to quantify the tailings material properties. These include physical properties such as grain size, strength properties such as a friction angle and hydraulic properties such as permeability. The properties of the tailings material being stored are generally related to the parent rock from which it is being mined as well as the process method used to extract the minerals.

The material properties will typically vary spatially within the TSF due to natural segregation during deposition (e.g. Papageorgiou 2004) and due to different operational and management procedures. This will also result in varying degrees of anisotropy within the deposited slurry. A change in the deposition rate and position of the deposition stations will also cause spatial variation in material properties due to the associated change in drying time between deposition cycles.

Hydraulic deposition of tailings is the primary deposition method used, not only in South Africa, but also worldwide. The residue is deposited in slurry form and, as it settles and consolidates, excess water is returned though decanting structures to the plant to be re-used. To further dewater the facility a network of drains can be implemented to collect some of the interstitial water. The expulsion of interstitial water due to consolidation, and the associated flow to the drains or decant structure, results in a pore pressure distribution within the TSF that may vary spatially. This can be illustrated by a flownet in which the pore pressure gradient is not hydrostatic as shown in Figure 1.

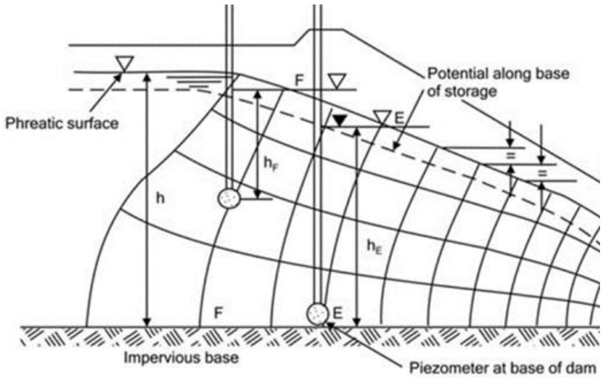

Figure 1: Flownet with non-hydrostatic conditions (Blight 2010)

It has long been known that the material properties, TSF geometry, as well as the pore pressure distribution within a TSF, control the stability of the TSF (Vick 1983). Over a short time period, it is the pore pressure regime that is most likely to vary and since the strength of soil is influenced by its effective stress, any change in pore pressure will affect a change in the calculated Factor of Safety (FoS) against failure. Although it is known that the pore pressure regime will change due to a change in operating conditions, it is practically impossible to measure this change over the entire facility accurately and timeously. A particular case where there would be a relatively rapid change in the pore pressure within a TSF is when the TSF is recommissioned. This is when a facility that has not been operated for a long period of time (i.e. dormant) is brought back into operation.

With the number of inactive TSFs in South Africa and with the advances in technology making old ore deposits commercially viable, this scenario is becoming increasingly likely. A rapid change in the pore pressure regime cannot be accurately recorded due to the inherent lag time in conventional standpipe piezometers. This paper aims to highlight the influence that this time lag can have on the FoS, calculated from standpipe piezometer results, compared to when the FoS is calculated using the true pore pressures in such a situation. This difference in calculated FoS can be attributed, in addition to the non-hydrostatic pore pressure conditions (Geldenhuys et al. 2019), to a delayed representation of the true pore pressures in a standpipe piezometer due to the permeability of the tailings and the design of the standpipe piezometer. The scope is limited to an idealised gold TSF in which the material properties are homogeneous with an assumed anisotropy.

It must be reiterated that this is a simplistic representation of a hypothetic TSF in which effective stress parameters are used. The authors are well aware of the move within the industry to conduct undrained stability analyses, however, it was found sufficient for achieving the aim of this paper to limit the scope of this paper to effective stress parameters.

2 PORE PRESSURES WITHIN A TSF

A fundamental understanding of the pore pressure regime in a slope is required before analysis is conducted using water levels from standpipe piezometers. This understanding should include acknowledgement of both the temporal and spatial limitations to determining pore pressure from standpipe piezometers. The effect of the spatial variation has been illustrated by others (e.g. Wagener et al. 1998, Geldenhuys et al. 2019) and this paper aims to illustrate the effect of the temporal variation.

The spatial and temporal variation is influenced by deposition cycles, pool control, rainfall, decanting procedures, drainage conditions, facility height, base geometry, consolidation, etc. The flow conditions are three-dimensional, temporally variable and are near impossible to predict. The pore pressures can be determined by conducting Cone Penetration Testing with pore pressure measurements (CPTu) probing, also referred to as piezocone probing.

Although CPTu probing provides an accurate representation of the pore pressure in the TSF (Wagener et al., 1998), the results are only representative for the time (therefore also the dam geometry) and location at which probing was done. As CPTu probing is expensive and typically only conducted annually at best, alternative solutions are required to measure pore pressures at shorter intervals.

A standard approach to monitor pore pressures in a TSF, between the periods when piezocone testing is conducted, is the installation of permanent fixture devices. There are several instruments available to perform this function such as observation wells and open standpipe, hydraulic, pneumatic, vibrating wire and electrical resistance piezometers (Dunnicliff 1993). Each of these instruments have their own advantages and limitations. In South Africa, pore pressures are traditionally measured using single open-end standpipe piezometers and more recently vibrating wire piezometers. Both measure the pore water pressure at a specific depth below the surface. To effectively use the measured data, the reference elevation of these depths needs to be known.

The open-end standpipe piezometer is commonly used in South Africa due to the low cost of procurement and installation as well as ease of use. These piezometers typically consist of a filter at the end of a small diameter polyvinyl chloride (PVC) pipe that is extended to the surface. The piezometer will normally be installed in the centre of a drill hole, the end filled with wet sand (adjacent to the porous filter) and the remainder of the gap around the pipe (above the porous filter) will be grouted closed. In some cases, standpipe piezometers are merely pushed into the tailings without sand surrounding the tip. Because of this installation technique, the water level in the standpipe only responds to the water pressure at the bottom of the standpipe and is isolated from other pore pressures along the length of the standpipe. The water level in the standpipe is therefore a measure of the equipotential at the tip and, as such, the water level in a standpipe will rise to the potential at the bottom of the standpipe.

This is an important point as the water column elevation within the standpipe piezometer will only coincide with the elevation of the phreatic surface under very specific hydraulic flow conditions within the TSF. In general, due to the drainage systems installed in TSFs, there is some downward component of flow and the pore pressure build-up with depth below the phreatic surface is non-hydrostatic (e.g. Wagener et al. 1998). This means that there will be an elevation difference between the water column in the standpipe piezometer and the phreatic surface within the TSF. The influence of this elevation difference has been investigated and it was found that it can have a meaningful impact on the calculated FoS depending on the slope geometry, material properties and hydraulic conditions (e.g. Geldenhuys et al. 2019).

The rate at which the water column within a standpipe responds to a change in pressure at the tip is dependent on the permeability of the surrounding material and the geometry of the piezometer. Unlike a vibrating wire piezometer, a standpipe piezometer requires a relatively large volume of water to equalise the pressure at the tip of the standpipe to the surrounding pore water pressure. Standpipe piezometers therefore have a lagged response, particularly to rapid changes in pore pressure under transient conditions (e.g. Hvorslev 1951; Hanschke & Baird 2001; Simeoni 2012).

An additional challenge with standpipe piezometers is that the elevation of the water column within the piezometer is typically only measured once a month. This results in discrete measurement points once every 30 days and any fluctuation between readings is not captured. To improve on this, recent developments in sensor technology and data capture have allowed for these standpipes to be retrofitted with pore pressure transducers and connected to data loggers. The height of the water column in the standpipe can therefore be recorded and relayed at very short intervals.

It should be noted, however, that this "real-time" measurement of pore pressure is in fact still only a measure of the pressure in the standpipe as a result of the water column within the standpipe itself. Therefore, instrumented standpipes, although popular, suffer from the same disadvantages as conventional standpipes when it comes to the response time to changes in pore pressure.

3 METHOD AND ANALYSIS

3.1 *Scope*

The scope of this paper is limited to the comparison of the FoS calculated with phreatic levels inferred from standpipe piezometers (assuming various lag times in the response of the standpipe piezometers to the change in pore pressure) and the FoS calculated with pore pressures from a transient seepage analysis for stability analysis on a TSF. A FoS was calculated using pore pressures at various time steps in the seepage analysis. This FoS was then compared to the FoS calculated with pore pressures determined from the transient seepage analysis for various lag times in the response of the standpipe piezometers to the change in pore pressure in the slope. The analysis was conducted using the SLOPE/W and SEEP/W components of the GEOSLOPE 2021 geotechnical software (SEEP/W 2001; SLOPE/W 2001).

A transient finite element analysis consisting of 1761 nodes and 1683 quad and triangular elements was conducted to model the evolution of the pore pressures with time due to a change in hydraulic boundary conditions. The FoS values were calculated using limit equilibrium slope stability analysis (method of slices according to Morgenstern & Price 1965). The material parameters used in the analysis are summarised in Table 1 and are based on typical parameters of gold tailings in South Africa (e.g. Vermeulen 2001; Papageorgiou 2004; Chang 2009). The focus of this paper was on effective stress analysis and therefore only drained strength parameters were considered.

The model geometry considered is shown in Figure 2 and is based on an upstream constructed TSF, typical for South Africa. To simplify the model, no internal drainage system was considered. Figure 3 shows the pore pressure conditions at the start of the analysis period (i.e. prior to recommissioning of the inactive facility). Figure 4 shows the pore pressure conditions at end of the analysis (i.e. once the pore pressures had stabilised after the change in the imposed boundary condition).

Table 1. Material parameters used for the analysis

Material	Unit weight (kN/m^3)	Saturated K_x (m/s)	Phi' (°)	Cohesion (kPa)	K_y/ K_x
Tailings	15	1x10^{-6}	30	0	0.1
Foundation	18	1x10^{-9}	30	5	1

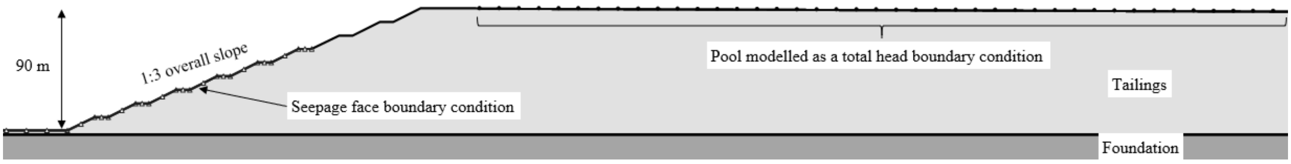

Figure 2: Model geometry, material zones and boundary conditions

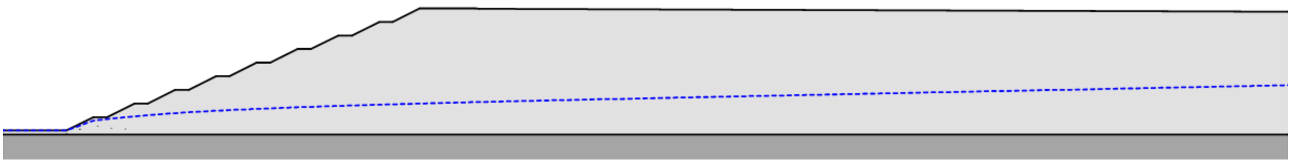
Figure 3: Steady state pore pressure conditions at t=0

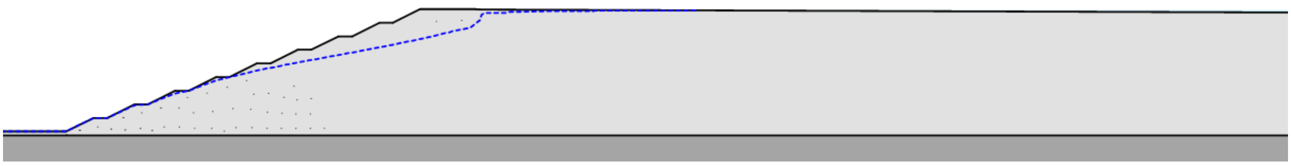
Figure 4: Pore pressure conditions at t=end

3.2 *Analysis matrix*

The seepage model considered a hypothetical case of a wetting front progressing through a TSF due to the introduction of a pool as a result of recommissioning of the facility. Due to the extent of the pool being conservative, operational boundary conditions such as a unit flux infiltration were not considered. The boundary conditions at the start (t=0) represent a case where there is no pool on the facility and the phreatic surface is low. This is shown in Figure 3. Thereafter, to simulate the wetting front, a pool ponding on the surface close to the outer embankment was introduced as a boundary condition. This is shown in Figure 2.

To develop the analysis matrix, the calculated lagged FoS was compared to the reference FoS. The reference FoS was calculated for various timesteps in the transient seepage model, starting at t=0 where the pore pressures in the seepage model were from the seepage model illustrated in Figure 3, up to t=end with the pore pressure conditions illustrated in Figure 4.

Once the set of reference FoSs was calculated, a set of FoSs was calculated for each assumed lag time. This was done by using the same pore pressures as were developed for the reference case, but applying a time lag. Thus, if a time lag of 10 days was assumed, the pore pressures used to calculate the FoS on day 100 were those used in the reference case for day 90. This methodology is presented in Table 2.

The analysis was therefore conducted with pore pressures entirely from the seepage analysis and not simulated from standpipe readings or piezometric lines. Only a lag in pore pressures was assumed and no consideration was given to the potential errors in standpipe readings due to non-hydrostatic flownets.

The critical FoS (i.e. the lowest FoS for the given slip mechanisms) was determined for what would be considered a major, or global, failure of the TSF embankment. For consistency of comparison, the entry-exit search method was used and the same search zone was applied to each analysis, as illustrated in Figure 5. In order to exclude near-surface slip mechanisms, and only account for global slip surfaces, the entry and exit ranges were restricted. It is possible that a lower FoS could have been calculated for a smaller slip surface in each case, had a wider range been used for the entry-exit zones.

This was done to represent the process that would typically be followed if the analysis were conducted for a piezometer-based stability assessment. Optimisation of the critical slip surfaces was not considered. All other boundary conditions were kept the same in the analysis.

As discussed earlier, the time lag is due to the volume of water required to infiltrate into the standpipe piezometer to equalise the pressure at the tip of the piezometer to the surrounding water pressure. This volume is directly related to the permeability of the surrounding tailings and the geometry of the standpipe. For this study, the time lags that were considered ranged from 10 to 300 days. A time lag of 300 days could be assumed excessive, however, it has been shown that lag times could range from a few hours up to 193 days (Hvorslev 1951).

Table 2. Analysis matrix

Time, t (days)	Time step used to determine pore pressure for stability analysis, t*			
	Base case	10 day lag	20 day lag	n day lag
t=0	t*=0	-	-	-
t=10	t*=10	t*=0	-	t*=10-n
t=m	t*=m	t*=m-10	t*=m-20	t*=m-n

Figure 5: Entry-exit range for the slip surface definition

4 RESULTS

The results showing the critical FoS calculated at the start, after 100 days and after 300 days are shown in Figures 6, 7 and 8, respectively. As was expected, there was a reduction in calculated FoS with time as the slope was saturated due to the presence of the pool. This degradation of FoS from a generally acceptable value of 1.5 initially to a marginal value of 1.0 after 300 days is illustrated in Figure 9. This curve was considered to be the base case (reference FoS) as the true pore pressures at the specified times were used.

The results of the comparable FoS values where the time lag associated with the deficiencies of standpipe piezometers is considered is shown in Figure 10. These FoS values were calculated for a sample range of lag times, using the method described in Section 3.2. For example, n-150 represents the calculated FoS for an assumed lag time of 150 days. The intent of this figure is to highlight the potential error in the calculated FoS value that could be made if the pore pressure regime is simply assumed as the water elevations noted in the standpipe piezometers. Consider the calculated FoS values at 250 days, as illustrated in Figure 11. The true calculated FoS value is 1.1. However, if there were a lag of 50 days, then the calculated FoS would be incorrectly assumed to be approximately 1.2. This error increases with an increase in lag time until a calculated FoS greater than 1.5 is obtained for a lag time of 250 days.

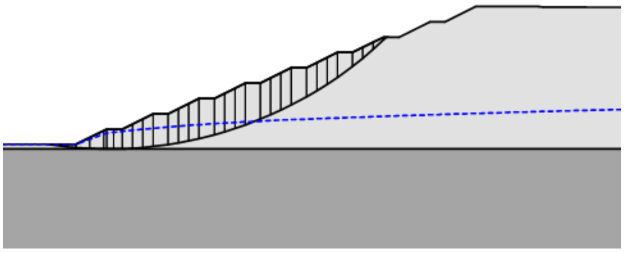

Figure 6: Critical slip surface at t = 0 days (FoS = 1.55)

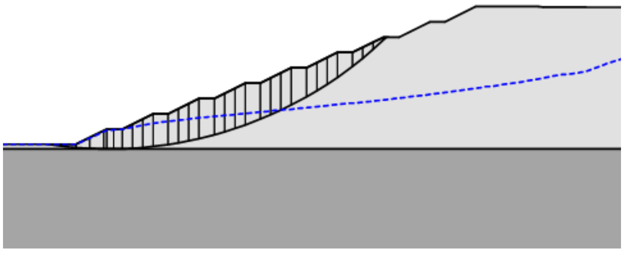

Figure 7: Critical slip surface at t = 100 days (FoS = 1.44)

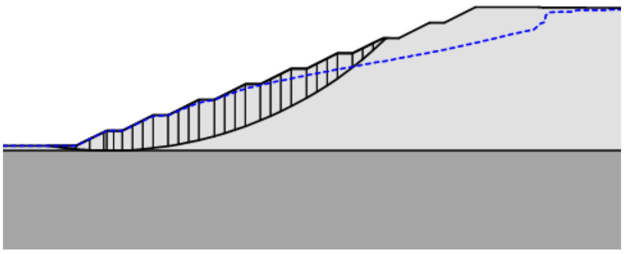

Figure 8: Critical slip surface at t = 300 days (FoS = 1.03)

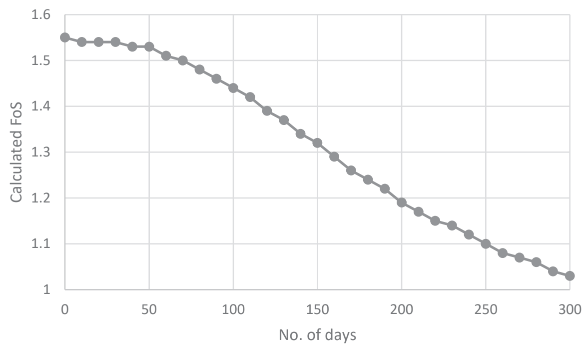

Figure 9: Calculated FoS for the hypothetic slope

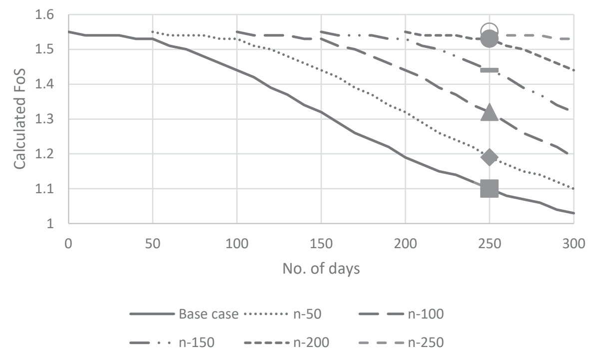

Figure 10: Calculated FoS for a range of assumed lag times

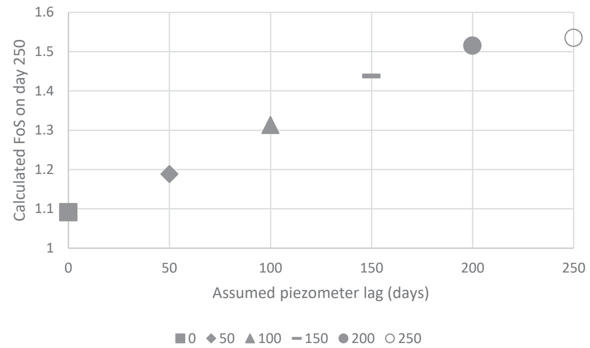

Figure 11: Calculated FoS on day 250 for various assumed lag times

5 DISCUSSION AND IMPLICATIONS OF RESULTS

A seepage and stability analysis were conducted for a hypothetic TSF as shown in Figure 2. For the geometry and seepage material parameters considered, the calculated FoS reduced from 1.5 to 1.0 in a period of 300 days as is shown in Figure 9. This is a significant difference and reason for great concern. A FoS of 1.5 is generally acceptable for long term stability, however a FoS of 1.0 implies the facility is on the verge of failure and emergency measures will likely need to be initiated. Although these findings are to a certain extent hypothetical there are two important points to be made.

- The first is that when the recommissioning of a facility is being considered, the development of the hydraulic conditions that are likely to result with the reintroduction of the operating pool must be taken into account.
- The second is that the progression of the wetting front will take time to develop and is generally a slow process which cannot easily be stopped. It is therefore important that the wetting front mechanism is understood prior to the recommissioning.

It is known that the progression of a wetting front through a TSF embankment will cause an increase in pore pressure which will lead to a reduction in the calculated FoS. The rate of the progression of the wetting front is, among other factors, dependent on the hydraulic properties of the tailings. The condition that drives the wetting front could include deposition after the facility has been inactive or it could include ponding on the basin after heavy rainfall. For this study, no reduction in soil permeability due to unsaturated conditions was considered, which could reduce the rate of progression of the wetting front.

When considering the lagged cases, there is an overestimation of up to 0.1 in the calculated FoS if there would be a 50 day lag in the pore pressure readings. As seen in Figure 10, for a 100 day lag, the overestimation of the FoS is up to 0.25 and for a 200 day lag the overestimation is up to 0.4.

Although the lag times of 100 or 200 days seems excessive, they are not unrealistic. Additionally, these results represent a case where the piezometer readings are taken daily. In practice, standpipe piezometer readings are typically only taken on a monthly basis and this can contribute to the time lag.

It should be noted that the lag time in pore pressure response for piezometers on a slope would not be uniform for all piezometers on the slope. The lag time for individual piezometers would depend on the localised permeability (which could vary between fine and coarse zones within the embankment) as well as the depth to which the piezometers are installed.

6 CONCLUSIONS

With the number of inactive TSFs in South Africa and with the advances in technology making old ore deposits commercially viable, it is likely that many of these inactive TSFs may be recommissioned in the future. This recommissioning will result in a change in pore pressure regime within the TSF which will influence the stability. A common method to measure this change in pore pressure regime is the use of standpipe piezometers. However, there are several limitations with the use of standpipes piezometers, one of which is the delayed response time to a change in pore pressure due to the volume of pore water required to infiltrate into the piezometer. The influence of this time delay was investigated by means of numerical modelling of a wetting front caused by recommissioning of a facility and stability analyses at selected time intervals. At each time interval, a FoS was calculated using the true pore pressure regime (the reference FoS) and then several other FoS values were calculated for various assumed response times. These FoS values were then compared.

For the hypothetic TSF assessed, it was found that the calculated FoS reduced from 1.5 at the time of dormancy to 1.0 in a period of 300 days after the introduction of a saturating pool. This is a significant difference. A FoS of 1.5 is generally acceptable for long term stability, however a FoS of 1.0 implies the facility is on the verge of failure and emergency measures will likely need to be initiated. The monitoring of such a slope is therefore crucial. Real time estimation of the changing pore pressures would be critical in determining the FoS degradation on a TSF that has been dormant for a long time. Reversal of the situation through which the FoS has been reduced (i.e. by addressing the boundary condition that caused the wetting front progression) would not happen immediately.

The limitations of using standpipe piezometers for determining the FoS of a TSF is evident, particularly in the following cases:

- Poor installation
- Low permeability material
- Non-hydrostatic flownet conditions
- Rapid change in pore pressures

7 RECOMMENDATIONS

From the conclusions it is clear that a fundamental understanding of the pore pressure regime in a particular slope is required before analysis is conducted using water levels from standpipe piezometers. This understanding should include acknowledgement of both the temporal and spatial limitations to determining pore pressure from standpipe piezometers and the potential or flow conditions. The effect of the spatial variation has been illustrated by others (e.g. Geldenhuys et al. 2019; Wagener et al. 1998) and this paper aims to illustrate the effect of the temporal variation.

This analysis gives no consideration for the reversal of the wetting front and the time it would take for the FoS to improve. However, it is evident that the progression, and hence the reversal, of the wetting front is gradual and action needs to be taken early to address the boundary conditions that drive the reduction in the FoS. This highlights that, for any facility that is being recommissioned, real-time monitoring of the pore pressures is crucial. Apart from determining critical, or alert, levels for when the pore pressures reach a stage where the FoS would fall below acceptable, an additional safety concept should be implemented that takes into account the time lag in the pore pressure readings. Pore pressures should be monitored and stability concerns should be identified and predicted well in advance of the pore pressures reaching critical levels.

In summary, as is the case with most engineering instruments, standpipe piezometers should not be used in isolation. This is especially true when they are used for determining the stability of a TSF or any soil structure constructed using low permeability material. It is recommended that the standpipe piezometer information be supplemented by additional pore pressure data at regular time intervals. This could be done by installing and monitoring VWPs or by conducting CPTu probing. An understanding of the lag response in standpipe piezometers should be acknowledged and considered when conducting FoS checks on a TSF where a rapid change in pore pressure regime is expected.

It is recommended that the stability analysis is done in such a manner that the failure mechanism can be kinematically verified (i.e. finite element analysis using constitutive soil models). Site specific foundation conditions and tailings materials should also be considered as these might have a greater effect on the location and depth of the critical slip mechanism than the assumption made regarding the pore pressures.

In practice, there is debate around whether there are triggers that could initiate undrained shearing in tailings dams (i.e. whether the triggers exist and the likelihood of their occurrence). The consensus is that a well-designed and effectively operated facility should have fewer potential triggers. However, in the case of the recommissioning of a tailings dam, there will without a doubt be an increase in the phreatic surface which is a well-established trigger for undrained shearing. This aspect is outside the scope of this review but needs to be carefully considered in practice.

8 ACKNOWLEDGEMENTS

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