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Reflections on Recent Tailings Dam Failures and How the Application of Burland's Soil Mechanics Triangle Concept May Avert Future Failures.

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ABSTRACT: In his Nash Lecture in 1989, Burland presented the concept of what he referred to as the Soil Mechanics Triangle. The three apexes of the triangle were identified as Ground Profile, Soil Behaviour and Applied Mechanics, and embedded within the triangle and linked to all three apexes the notion of empiricism and well-winnowed experience. Burland used this concept to emphasise the critical and interlinked nature of the three triangle apexes when teaching Soil Mechanics to undergraduate students. This paper applies the triangle to the current state of practice regarding tailings dam management, highlighting how lack of attention to the concepts embedded in Burland's approach have resulted in sometimes catastrophic consequences. Using the published forensic reports on two recent, major tailings dam failures around the world, the paper illustrates how they may have been avoided if a proper appreciation of the three pillars of good practice suggested by Burland had been adhered to. It also argues for more rigorous training in geotechnical engineering and engineering geology of practitioners working in the field of tailings engineering.

KEYWORDS: Teaching soil mechanics**,** Tailings dam, Failures, Soil mechanics triangle

1. INTRODUCTION

Tailings storage facilities (TSFs) are some of the largest man-made structures in the world. Current mining operations include mines that produce in excess of 200 million tonnes of tailings per day. The most common practice at present is to transport the tailings hydraulically to the TSF, where they are deposited into impoundments, many of which comprise rudimentary retaining embankments (with many notable exceptions of course) constructed using tailings that has been excavated from previously deposited material. There is therefore no structural shell, unlike concrete dams or even conventional earthfill dams, which usually include a zone of highly competent rockfill to ensure adequate geotechnical stability.

Another significant difference between TSFs and water retaining dams (be these concrete or earthfill), is that TSFs are almost always raised incrementally, i.e. there is not construction to completion of a retaining embankment prior to placement of tailings but rather, as noted above, ongoing use of the tailings itself to raise the facility. Techniques for 'wall raising' include what are referred to as upstream, centreline and downstream construction. An illustration of the key differences are given in Figure 1 and Vick (1990) discusses these three primary procedures, as well as other less well-used procedures in some detail.

Water is also usually stored on top of TSFs, although current leading practice is to minimise such storage, keeping the 'decant' pond as small as possible. The stored water is derived from two sources, the water used to transport the tailings hydraulically to the TSF, and precipitation. Recent years have seen increased implementation of high-density, thickened tailings, but such operations are still small in number. The hazards associated with storage of water at elevation, on the surface of a facility that has not been constructed according to conventional engineering specifications, is evident from the large number of catastrophic failures that have occurred in the past, and unfortunately appear to be continuing to occur. As an example, there were six reported failures in 2019 alone (Wise-Uranium, 2020).

2. FREQUENCY OF FAILURES OF TAILINGS STORAGE FACILITIES (TSFS)

Table 1 provides an overview of some of the truly catastrophic failures that have occurred over the past three decades or so. For every one of the tabulated failures, there are many times more failures that have occurred. The tabulated data are thus a snapshot.

From Table 1 it is clear that TSF failures resulting in catastrophic consequences have occurred regularly over a long period of time, and do not seem to be getting any less frequent. Perhaps the contrary. Aside from fatalities, TSF failures have other, serious consequences including large scale environmental damage, inability of people to continue to make a living (e.g. farmers) and liquidation of companies, resulting in many related impacts such as loss of employment.

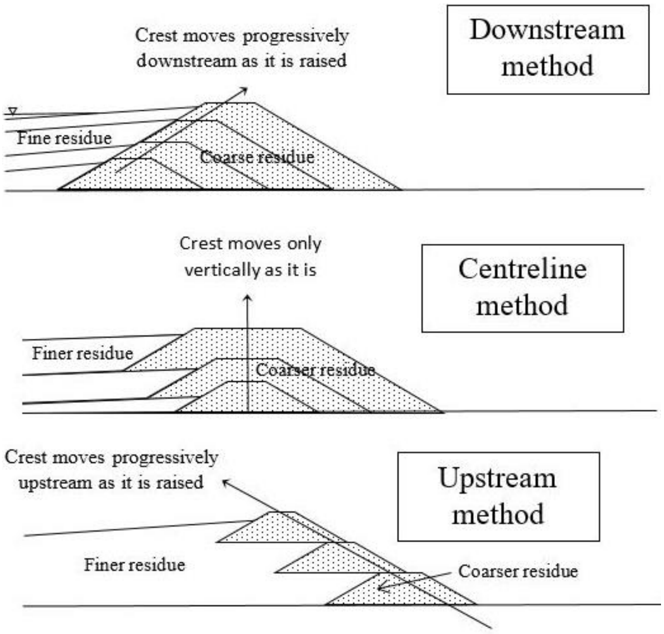

Figure 1 Illustration of the difference between downstream, centreline and upstream construction of tailings storage facilities

Regulation of TSFs varies from country to country, with countries such as Canada, the USA and Australia relatively well regulated, but many emerging countries suffer from little to no regulation. Despite this disparity in extent of regulation, Table 1 demonstrates that many TSF failures have occurred within jurisdictions which likely qualify as 'well-regulated'. What then explains the continued, unacceptably high rate of failures of TSFs, even within well-regulated mining regions?

3. ENSURING GEOTECHNICAL STABILITY

The primary causes of failure of TSFs have been many and varied, with typically common mechanisms including overtopping, piping, foundation failure, overall slope failure, or seismically-induced liquefaction. Although the mechanism of static liquefaction has recently been identified as the cause of a number of failures, the realisation that this is a possible failure mechanism is recent, despite evidence in the literature that it caused failures many years ago (e.g. Smith 1969). Furthermore, it is potentially highly dangerous because it is very difficult to obtain early warning of a potential failure with this mechanism, as discussed later.

Table 1 Reported incidents of TSF failures resulting in fatalities over the past three decades

Year	Facility name	Country	Method of construction	No. of reported fatalities
1993	Marsa	Peru	Upstream	6
1994	Merriespruit	South Africa	Upstream	17
1994	Longjiaoshan	China	Upstream	31
1995	Surigao	Philippines	Upstream	12
1996	Sgurigrad	Bulgaria	Upstream	107
2000	Nandan	China	Upstream	28
2001	Sebastião das Águas Claras	Brazil	Unknown	2
2006	Zhen'an County Gold Mining	China	Unknown	17
2008	Taoshi	China	Unknown	277
2009	Karamken	Russia	Unknown	1
2010	Ajka	Hungary	Downstream	10
2014	Herculano	Brazil	Unknown	2
2015	Fundão	Brazil	Upstream	19
2017	Tonglvshan	China	Unknown	2
2018	Cieneguita	Mexico	Unknown	3
2019	Feijão	Brazil	Upstream	259

Unfortunately, there is a tendency in the literature to assign a single, unique mode of failure to each TSF that is reported on. However, as with many other engineering structure failures, there may be a sequence of events that lead to a failure. An example is the Merriespruit failure that occurred in South Africa in 1994, which resulted in 17 fatalities. This failure is usually reported as an overtopping failure. However, there had been many previous instances of TSFs in South Africa overtopping, but not resulting in a catastrophic failure such as occurred at Merriespruit. What seems to have been different at Merriespruit is that the overtopping event eroded the slightly densified outer shell of the TSF, exposing extremely loose, contractive tailings that liquefied once lateral confinement was removed. To call the Merriespruit failure either an ‘overtopping’ failure or a ‘static liquefaction’ failure alone is thus not strictly correct.

The spate of recent, high-profile TSF failures, such as the two in Brazil (2015 and 2019) has generated a surge in activity that includes an emphasis on improving governance and stewardship standards of TSFs as a way to minimise the likelihood of similar failures in the future. While improved governance is a pre-requisite to improving TSF design, construction and operational standards, it is not sufficient. There is the danger of over-reliance on systems and procedures as the necessary protective measures to ensure TSF safety. This paper argues that excellent governance and stewardship relies, and depends on, equally excellent geotechnical engineering design, monitoring and evaluation.

It is only if a TSF is designed by a highly competent geotechnical practitioner (often in collaboration with other, relevant experts such as hydrologists, water engineers, landform designers, to suggest but a few) and construction and operation of said TSF is similarly overseen by competent geotechnical engineers, that mistakes such as those that have led to some of the reported failures can be avoided. Only by truly understanding geotechnical engineering principles can the synergistic interactions between multiple possible failure mechanisms be accounted for, and the likelihood of such events be ruled out through suitable design approaches.

4. REVISITING BURLAND’S SOIL MECHANICS TRIANGLE

Burland (1989) presented a conceptual approach to undertaking geotechnical projects that integrated a number of separate, but related activities. A schematic is reproduced in Figure 2.

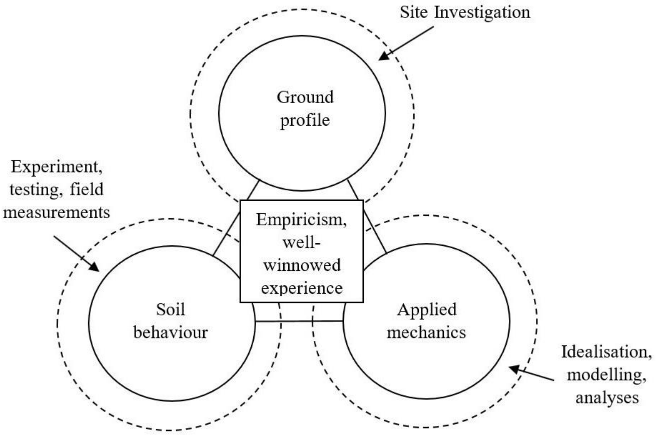

Figure 2 Burland’s soil mechanics triangle

A key aspect of the approach summarised in Figure 2 is the need for appropriate input from geologists and particularly engineering geologists when planning and designing a geotechnical structure. Recent times have seen the closing of many University departments of Engineering Geology, presumably because these courses attract relatively small student numbers. However, the value added by engineering geologists and the insights they often provide should be sufficient grounds for ensuring these skills are not lost entirely.

Perhaps it is because of Burland’s undergraduate training in South Africa, and his exposure to the work of a number of practitioners and academics, such as Jennings, who considered engineering geology a cornerstone of geotechnical engineering practice, that it was emphasised so strongly in much of his work. As discussed in following sections, taking cognisance of the geological history of a site and the potential for this history to dictate key geotechnical considerations, may have prevented some of the major TSF failures that have occurred in the past.

5. RECENT FAILURES OF TAILINGS STORAGE FACILITIES

Some of the recent failures that have occurred have seen the appointment of an Expert Panel to investigate and report on the most likely reason(s) for the failure. These panels and associated investigations have tended to focus on geotechnical issues, which is entirely logical given the nature of the failures. The reports of these various panels have generally been very detailed, and often contain a wealth of information such as in-situ and laboratory test data, stability analyses undertaken during the life of operation, and monitoring data accumulated prior to the failure. The discussions below draw on these reports.

5.1 Cadia

The Northern Tailings Storage Facility (NTSF) at Newcrest's Cadia Valley Operations experienced a major slump on March 9th, 2018. The consequences were by no means catastrophic, although production was halted until an alternative deposition area could be established and made operational. The panel report (Jefferies et al. 2019) undertook significant post-failure work, including extensive geological investigations that included drilling and sampling to characterise the site, laboratory tests that included advanced laboratory testing, and numerical simulations of both deformation behaviour and ultimate failure states.

5.1.1 Observations prior to the failure

The failure was reported at around 18:45 to 19:00 on 9th March 2018. On the morning of the failure, prominent cracks were first noticed at about 8 am. These cracks developed and expanded throughout the day and at around 16;.00, ground heave at the toe of the slope was noticed. As a precaution, personnel were evacuated, particularly as there was excavation work going on at the toe of the slope that failed.

The failed mass moved up to about 170 m laterally, and the width of the failure was some 300 m, with approximately 1.3 million m^3 of material eventually being involved in the slump. There was no loss of containment of tailings, unlike many of the failures reported in the literature (including most of those in Table 1). A tailings run-out did not occur, primarily because the decant pond was so far from the perimeter of the TSF; maintaining a decant pond as small as possible is a key objective in tailings management, but unfortunately it is often violated. The Cadia slump is an excellent example of the benefits of this practice.

5.1.2 Details of the Cadia TSF

The Cadia NTSF was originally designed and operated as a modified centreline facility. As was common practice at the time, there were no drains installed on the downstream toe of the embankment. Such drains are very common in upstream construction, but until recently not widely utilised in downstream or modified centreline construction. As often occurs, the life of the Cadia operations was extended beyond the initial design life, in turn requiring additional tailings storage space. A decision was made to transition the NTSF from a modified centreline construction approach to an upstream construction approach, with the transition occurring when the embankment was about 68 m high.

5.1.3 Findings from the forensic investigation

The forensic investigation found there had been horizontal movements of up to 100 mm in the five years preceding the slump, and retrospective investigations using InSAR (Interferometric Synthetic Aperture Radar) monitoring indicated there were accelerated movements prior to the slump occurring. However, neither of these data sets, whether considered individually or together, would have predicted the slump. This is because there was no model of what constituted a threshold displacement rate (i.e. a 'trigger') above which some form of intervention or response plan could be implemented. To provide meaningful trigger values for displacements invariably requires the use of some form of advanced numerical model, or what is increasingly fashionably being referred to as a 'digital twin'. Once such a model has been calibrated (e.g. against high quality laboratory data) and implemented for a particular TSF, all future observations may be compared against the predictions of the model. Although there are a small number of facilities around the world where this is current practice, it is currently certainly not widespread.

Burland (1989) highlighted the importance of numerical modelling when discussing the 'soil mechanics triangle', and additionally focussed on an issue that remains largely unappreciated to this day, i.e. the importance of strain. Many numerical models focus on stress, e.g. plotting of stress contours, and relating predicted stresses to potential instabilities by comparison of respective stress states. However, as discussed in some detail by Burland (1989), predicting and monitoring strains (or, more correctly displacements) is equally important. He observed that:

- Deformation and strain are observable realities and it is only by their measurement that stress is usually inferred.
- Deformation and strain have a profound influence on the properties of soils and rocks both in relation to their geological history and during loading from their initial in situ states.

Referring to the first bullet point, to enable stresses to be predicted from measured displacements requires development, calibration and implementation of a suitable numerical model. As an example, displacements may induce the mobilisation of peak shear strengths and, if the material is brittle, the onset of post-peak strain softening behaviour. Indeed, as Jefferies et al (2019) point out, the timing of the slump at Cadia was controlled by accumulated deformations and they strongly recommended that movements within the foundation soils below the TSF embankment be monitored in the future. Implementation of this measure still requires a model of predicted (and acceptable) behaviour and draws on Burland's triangle apex that motivates for more advanced experimental testing. In the case of Cadia that would include testing of both the foundation soils and the tailings material.

The investigation by Jefferies et al. (2019) argued convincingly that the instability was controlled by a very localised zone of high void ratio residual soil. The horizon in question was identified as the Forest Reef Volcanics Unit A (FRVA), which was found to be a very localised zone of high void ratio residual soil bounded by two thrust faults. Burland (1989) notes that there are countless examples where minor structural features, such as thin planes of weakness, have dominated behaviour. This suggestion is particularly germane to the Cadia slump but was also highlighted in the forensic investigations of the Los Frailes failure in Spain in 1998, as discussed at length by Alonso and Gens (2006). Perhaps more comprehensive adoption of the philosophy outlined by Burland (1989), of understanding, 'what is there' and 'how it got there' could have identified the existence of the FRVA horizon. It is certainly expected to underlie the approach to designing potential future expansions to the TSFs at Cadia.

5.2 Fundão TSF failure

On the afternoon of 5th November, 2015, the Fundão TSF in Brazil collapsed. The resulting flowslide of 32 million m^3 of tailings flowed for some 660 km downstream (after entering a river), engulfing the town of Bento Rodrigues and resulting in 19 known fatalities. It was probably the worst industrial accident in Brazil until that time; unfortunately, it was eclipsed in 2019 by the failure of the Córrego de Feijão TSF in Brazil.

5.2.1 Details of the Fundão TSF

The Fundão TSF was a cross-valley embankment, with the sides of the embankment abutting natural slopes on either end. The original plan was to deposit sandy tailings behind a compacted earthfill starter dam, thereafter, raising the height of the facility through a sequence of upstream raises. Deposition of sandy tailings from the embankment crest was to continue in concert with deposition of a separate tailings stream, which consisted of finer, clay-like tailings, often referred to as 'slimes'. The intention was to use the deposited sand tailings to retain the slimes, by maintaining a wide zone of free-draining sands adjacent to the embankment (the so-called 'beach' zone).

5.2.2 Findings from the forensic investigation

At the time of the failure there were several workers either on the slope of the embankment or on the embankment abutments. From the various eyewitness accounts, Morgenstern et al. (2016) reported the following sequence of events:

- On the afternoon of the failure, November 5th, 2015, a number of workers were on the facility and in a position to see along the length of the embankment crest. The first thing noticed by many workers was a cloud of dust rising from the left (looking downstream) abutment.

- A worker reported seeing waves developing in the central portion of the reservoir, accompanied by cracks forming on the left side and blocks of sand moving up and down on the left abutment setback.
- Another worker saw a crack open up along the crest of a step-back that been constructed adjacent to the left abutment, propagating in both directions.
- At another location, workers experienced an avalanche of mud-like tailings cascading down from the left abutment.
- Other observers reported seeing a sudden jet of dirty water “explode” out of an underdrain.
- A worker standing on the flat plateau (beach) reported the ground begin to move beneath him and crack around him, detaching from the set-back slope and moving downstream.

The report by Morgenstern et al. (2016) contains additional eyewitness accounts, providing an excellent timeline of events as they unfolded. Only the observations above, which were the first in a sequence of many, are included here in order to illustrate a specific point. This is to draw a comparison between the Fundão failure and the Cadia slump. The Cadia slump evolved noticeably over a number of hours (about 11 hours), and there was time to evacuate workers and anyone else potentially impacted by a failure. At Fundão it is clear the failure evolved over a few minutes. Some workers on the TSF managed to scramble to safety, but unfortunately, others did not.

Morgenstern et al. (2016) present an in-depth forensic evaluation of the Fundão failure, working through a number of hypothetical failure modes and steadily eliminating all but one based on the weight of evidence gathered. The failure was attributed to lateral extrusion of slimes at depth causing horizontal extension (and thus lateral unloading) of overlying, loosely placed sand tailings. Given these sand tailings were extremely brittle, the amount of strain required to initiate collapse due to static liquefaction was small. It appears these movements certainly did not manifest as cracks on the surface of the TSF or noticeable bulging at the toe of the TSF.

Comparison of the events immediately preceding the Cadia and Fundão incidents illustrates the clear difference between ductile and brittle failure initiation and propagation. In Figure 2 of his paper, Burland (1989) expands on the topic of one of his triangle apexes, i.e soil behaviour. He notes the importance of a number of inter-related topics, including contractant and dilative behaviour, undrained shear strength and the importance of a critical state framework. Presciently, he notes the pervasive use of isotropically consolidated triaxial testing and the key deficiency inherent to this approach. He shows work from Jardine (1985), i.e. 35 years ago, where reconstituted samples of both a low plasticity silt and London Clay were consolidated under K_0 conditions and then sheared under undrained compression. He notes that “at low overconsolidation ratios (OCR’s) the samples tested in compression show brittle behaviour with the peak strength corresponding to φ' values which are much less than the drained values (φ'_{cv})” . This is a key observation, but has remained largely unrecognised by many in the tailings industry. For example, investigations into likely causes of the Merriespruit failure in South Africa (Fourie et al. 2001) found that stability analyses carried out shortly before the failure occurred were based on effective stress stability analyses (using φ'_{cv}) and pore pressures obtained from standpipe piezometers. This completely misses the potential for shear induced pore pressures resulting in lower mobilised peak shear strengths than are predicted with the effective stress approach. Burland (1989) noted the importance of contractant behaviour, but perhaps the notion in tailings engineering persisted that ‘sands cannot fail undrained’.

Burland (1989) reproduces the figures from Jardine (1985) that show contours of axial strain on stress path plots of the data referred to in the previous paragraph. A critical outcome of this work is the extremely small strains at which peak shear strength is mobilised, being as low as 0.1%. Tests on isotropically consolidated samples fail at strain values substantially higher than this, i.e. more like 5% axial strain.

It is not only material such as London Clay that shows this behaviour. Fourie and Tshabalala (2005) show comparisons of anisotropically and isotropically consolidated specimens sheared in undrained compression. Similar to Jardine’s findings, peak strengths in anisotropically consolidated samples are mobilised at very low strains (also about 0.1% strain). Unless such behaviour is recognised and implemented in both conventional slope stability methods (where the possibility of both undrained and drained failure should be considered) and numerical modelling approaches, where realistic stress-strain behaviour must be accurately simulated, failures such as those discussed in this paper will continue to occur.

6. PREVENTING CATASTROPHIC FAILURES OF TSFS IN THE FUTURE

It is desirable to prevent all failures of TSFs in the future. However, it is more than desirable, it is an imperative that catastrophic failures that result in loss of human life be prevented. Rightly, the mining industry is under intense scrutiny at present in regard to their approach to ensuring stability of tailings facilities. The response has, in many cases, been sound. However, it is argued here that there is an over-reliance on the implementation of procedures that attempt to treat all facilities as similar. As an example, at some operations familiar to the author, particular instrumentation has been installed for no other apparent reason than it was used at a previous site. Very often, when selecting instrumentation, no thought is given to the most likely failure mechanism(s) for a particular TSF. For example, installing inclinometers to provide early warning of excessive displacement within a TSF will be effectively useless if the tailings were contractive and brittle, where very little displacement occurs prior to failure initiating.

Part of the current malaise may be that many people currently in senior management within the mining industry have a background where operations have a greater degree of similarity. Although in any industry there are of course differences from one site to another, tailings storage facilities are at the extreme end of the spectrum of inherent lack of similarity. A relevant characterisation of any TSF requires that not only the tailings themselves are adequately characterised, but also the foundation soils upon which the TSF is built. To add to the complexity, the way tailings are deposited, the way the free water pond is managed, how incremental construction is managed and recorded, all add to further entrenching key differences from one site to another.

Recent failures of TSFs have invariably led to a rush to run workshops on ‘lessons learned’. Although such workshops are often useful, it has also highlighted an inherent weakness in the profession, a weakness that consideration of Burland’s triangle could go a long way to alleviating. As an example, the failure of the Mount Polley TSF in Canada in 2014, was largely attributed to an apparent lack of recognition of the transition of the foundation soils from an overconsolidated state to a normally consolidated state as the tailings facility increased in height. Following this failure, and the inevitable ‘lessons learned’ workshops, there was a flurry of site investigation activity at many mining operations in Australia to ensure the same problem did not exist at these sites. If the key aspect of Burland’s triangle that emphasises the need to know ‘what is there’ and ‘how it got there’ had been followed, such retrospective investigations would have been unnecessary; the design engineers would already have known.

7. CONCLUSIONS

In his Nash lecture in 1989, Burland presented an evaluation of the inter-related aspects of geotechnical engineering that should be considered in order to ensure safe and sustainable projects are achieved. The three key aspects of ground profile, soil behaviour and applied mechanics were shown to be interlinked, with none of them taking precedence over another. Despite this paper being now more than 30 years old, many of the recommendations covered under these three headings remain unheeded, certainly when it comes to engineering design of tailings storage facilities.

Forensic investigations of two recent, significant TSF failures, one in Australia and one in Brazil, highlighted gaps in geotechnical engineering understanding of the facilities. Implementing the philosophy and approach outlined in Burland (1989) would go a long way to ensuring no further such catastrophic failures occur. Dedicated and detailed post-graduate training for engineers responsible for the design of tailings facilities is sparse, if even available. Although this is slowly changing, approval by senior University administrators of courses that do not attract very large numbers of students is difficult to obtain. While such courses are, hopefully, developed and made available in the future, practitioners would surely benefit from reading works such as Burland (1989) that provide lasting and durable guidance on fundamental issues relevant to ensuring geotechnical stability.

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