

## Tailings dams technology: learning from failure (Part 3)

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In his third article on tailings storage facilities, Adriaan Meintjes looks at how technology can address the challenges.

In my previous two articles for Mining Mirror on tailings storage facilities (TSFs), I focused firstly on water security and then on safety. This article will look more closely at how technology has evolved with regard to both understanding and addressing the challenges of tailings dams. I will argue that we are in store for exciting times, as advances in technology promise to pave the way to safer and more environmentally sound tailings storage practices.

Certainly, ever-increasing computing power — harnessed by continuously evolving software — has allowed great strides in the field of modelling in soil mechanics, rock mechanics and, by extension, tailings engineering. This will deserve more detail in a moment. However, technology also includes the scientific and engineering methods that must underpin the process of discovery in any discipline. These methods, and how they have recently developed in regard to tailings management, are worth some discussion first. They form the foundation for how we as consultants — along with our fellow-professionals in this discipline — frame the problems we encounter and the solutions we recommend.

In the scientific method, we usually investigate and quantify the laws of nature in a theoretical or applied manner. Considering aspects of a material's strength, for instance, would draw on theory such as the laws of gravity, as well as on applied mechanics — such as the motion of pendulums and centrifugal forces.

The engineering method — which can include the scientific method — usually starts from the 'boundaries' of applied mechanics. Here, there are three major approaches: firstly, for situations where closed-form

mathematical solutions can be developed; secondly, where reasonable mathematical solutions can be developed; and thirdly, where empirical methods are used to evaluate behaviour. In geotechnical engineering, all three approaches are followed — which is perhaps why certain aspects of the discipline are referred to as a science and other aspects as an art.

## Finding the answers

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This leads us on to consider the value and the role of numerical analysis in finding answers to our questions. Numerical analyses are based on a mathematical model which is used to represent (in other words, to model) some form of physical problem. To do this, we make certain assumptions about how the material we are looking at will behave under different conditions.

The first methods developed for slope stability assessment were limit equilibrium slope stability methods; for some of these, closed-form mathematical solutions could be developed, and many problems could be solved without significant computing power. However, they assume that the failure surface will develop at the same time in all materials through which the failure surface passes. For geotechnical materials with different stiffnesses and failure paths, this assumption would not apply.

With the growth of computer power available to practitioners and researchers, the development of finite element theories became practically possible. These evolved from linear elasticity and non-linear elasticity, to simple elastoplastic models and later to more sophisticated elastoplastic models which included critical state theory models. More recently, even more sophisticated models emerged, considering strain hardening and softening.

Each of these have made a contribution to the way we have approached TSFs, although there are weaknesses. With linear elasticity, for example, there are two reasons that constrain its application. In the first place, most natural geotechnical materials do not have a linear elastic stress strain curve, so a linear elastic model can only approximate the behaviour of natural materials at certain parts of the stress strain curve. Secondly, it cannot model the actual failure, as some form of plasticity behaviour (that is, limiting stresses) is required to model failure conditions.

## Critical state soil mechanics

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Hard data from the field have also contributed to our understanding of TSFs — by informing our technology-driven modelling. In the 1960s, the inventory of field and laboratory test results were used in developing the theory of critical state soil mechanics. Over the next 20 years, the theory of critical state soil mechanics gained general acceptance, forming the basis of our understanding of clay soil behaviour. This theory was in turn applied to the behaviour of sandy soil. These theories were extended in the past 20 or so years to develop even more sophisticated elastoplastic models that include strain hardening and softening models.

As computing power and models developed in the 1970s, they were put to good use addressing practical problems in soil mechanics such as seismic behaviour, static liquefaction, and progressive failure. The results improved in each decade as the models improved. Almost realistic seismic behaviour modelling of dams using elastoplastic models began in the 1970s, and the software gradually evolved to be able to model tailings dams as well.

In the past 10 years or so, specialised firms including consulting companies have developed enough experience to model seismic behaviour of clayey and sandy soils. Recording of earthquake records has also improved, helping provide a proper engineering basis to the exciting work that can now be done.

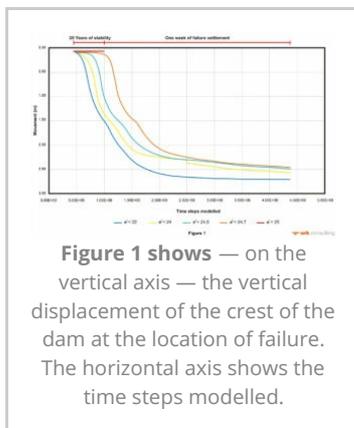
Importantly, this improved technological capacity is also giving us a better understanding of static liquefaction and progressive failure in tailings dams. While dynamic liquefaction of a soil structure takes place as a result of a sufficiently high seismic perturbation or disturbance, static liquefaction occurs due only to a small perturbation. There are several factors which could lead to static liquefaction; modern computers and software — leveraging the results of laboratory and field testing — are now capable of modelling the behaviour of tailings dams for these static liquefaction triggers.

The same applies to the problem of progressive failure in soil mechanics, which is the phenomenon behind some of the case histories of TSF failures involving failed foundations.

Progressive failure usually starts off very slowly but, with time, the rate of deformation increases rapidly. In several case histories, the failure starts as an effective stress site condition; then, when the rate of deformation is high enough, the mode of failure changes from effective stress to undrained or total stress behaviour. Once again, computer technology's ability to use past data can be employed to model the behaviour of tailings dams for these progressive failure triggers.

## The face of displacement

One back-analysed model is represented in **Figure 1**. This shows the overall picture of displacement in a return water dam, with time steps modelled. This dam showed no signs of distress for more than 20 years and then failed dramatically within one week, with more than 2.5m of displacement at the crest of the water dam.



Note the following:

- The change in the time increment related to the time steps modelled when the effective stress behaviour was changed to undrained behaviour;
- The effective stress properties changed when the inception of failure commenced and the rate of failure was about to accelerate; and
- When the rate of failure was increasing, the stiffness of the clay soils was changed from a Poisson ratio of 0.2 to a Poisson value of 0.45 (close to 0.5).

The key point to be understood is this: The time increment related to the time steps for the effective stress portion of the graph is much longer than for the time increments related to the time steps for undrained behaviour modelling. This means that the horizontal axis for the time period before failure commences for the 24.7-degree case should be 20 years, and the time from inception of failure to the end of failure should be 10 days.

If a set of shear strength properties are selected, such as an average effective stress friction angle of 25 degrees, then the model cannot be made to fail — even after a long time of modelling. If an average effective stress friction angle of 24.7 degrees is selected, it can be seen that — for a long time — the model behaves in a meta-stable manner; when sufficient loss of effective stress strength occurs, the failure develops very quickly, as was observed on site. This is the class A prediction of the actual behaviour of this strain softening clay material from site. If, however, the actual average shear strength of the clay is taken as an effective stress angle of 22 degrees, it can be observed that the modelled failure occurs a short while after the end of construction, which does not correspond with the observed site conditions where it took 20 years for the failure to be initiated. The other two examples modelled, as shown on Figure 1, are located between the limits of 22 degrees and 24.7 degrees and show the impact of friction angle (shear strength) on the inception and manner of progressive failure.

## Evolution of technology

Another important contribution to the TSF modelling and design tools at our disposal today come from other technologies. Satellite-type technologies, for example, can be used to measure three-dimensional displacement profiles. In one case, satellite imagery has been used to measure the extent to which sinkholes below a tailings dam were allowing settlement of the TSF over a few years.

Technological developments in milling will also have an impact on how we design TSFs going forward — in particular the implications of finer grind. While 45% of tailings before 1980 was finer than 75 microns, this had risen to 90% by 2010. In new mining projects, the expectation is that 80% of material will be finer than 53 microns.

The significance of this cannot be overstated. This will mark the first time that rock-flour tailings from hard rock mines will become too fine to be self-supporting for normal rates of rise of about one metre a year. The change in the permeability of tailings will require new tailings deposition techniques and TSF designs. This might include solutions such as impoundment walls and suitably sized buttresses of various materials. Mines will soon be considering the use of waste rock, filtration layers, and filtered tailings as conventional construction material in their TSF strategies.

The good news is that computer technology and continuous software improvements have given the sector valuable tools with which to leverage our considerable experience in TSF management. That said, innovation is not always quick or easy; but the work has begun and needs continued commitment from all who are affected.



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## About SRK

SRK Consulting — a global network of engineers and scientists — earned much of its early reputation from its work on tailings storage facilities, working closely with mining companies to develop science-based innovations to make tailings dams safer and more environmentally sound. Today, SRK is a multidisciplinary operation with a depth of expertise relevant to mining, infrastructure, environment, energy, and water.

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Adriaan Meintjes, principal civil geotechnical engineer SRK Consulting South Africa. Image credit: SRK Consulting

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## About the author

Adriaan Meintjes has been involved in civil and geotechnical engineering for over three decades and has worked for SRK Consulting SA since 1992. His speciality areas include soil and rock mechanics, numerical modelling, foundation design, water and tailings dams, and risk assessment. Through his extensive experience serving the mining industry, he has developed wide-ranging expertise in the geotechnical behaviour of tailings dams, dams, and fills, among other fields.

Adriaan has worked on projects across South Africa, southern Africa, and other regions of Africa, as well as South America, publishing and presenting over a dozen papers at professional and scientific forums. His qualifications were earned at Stellenbosch University and London University, and he is a registered professional engineer and member of the South African Institution of Civil Engineering (SAICE).

*The article is the first in a series of three on "Tailings dam technology: learning from failure".*