Appendix No 3

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Third Party Planning Appeal of the decision by Meath County Council to grant planning permission for development Planning Reference Number: 22331 Meath CoCo.

Planning Application Reference: 22331 Meath County Council
Development Address: Randalstown, Simonstown and Sillogue, Navan, Co Meath
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Editorial

Geotechnical Engineering

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Editorial: Tailing dams – slow responses to risks long known

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Every year mining operations worldwide generate a large amount of mineral residue in the form of particles that are disposed of in large structures known as tailings dams. Repeated tailings dam failures during the last decade (Mount Polley, Fundao, Cadia, Brumadinho) have been a shocking reminder of the need to improve design and operation of those structures. The aftershocks of those incidents have been felt throughout the mining industry, leading to important changes in tailings management procedures and design regulations at international level (ICMM, 2020; 2021; ICOLD 2022). Within this context, this themed issue wanted to offer a space to contributions that would advance the geotechnical understanding of tailing dams. There was an excellent response to the call for papers, with potential contributions arriving from four continents. After peer review, nine papers were finally selected for the themed issue.

The paper by Cambridge (2022) offers a different perspective from most other contributions. The author underplays the role of enhanced geomechanical knowledge in the problem, identifying instead as primary causes of historical failures 'poor design and operation practice, together with a lack of competent inspection and monitoring'. The remedy will be 'a more detailed consideration of the design, construction and operation risks'. How to achieve this detailed consideration, he argues, is something that might be found, for instance, in recently published European standards (BS EN 16907–7 (BSI, 2021)).

That perspective, however, glosses over the fact that what constitutes 'good design' and 'competent inspection and monitoring' might not always be so clear cut. Consider, for instance, monitoring: it is difficult on reading BS EN 16907–7 (BSI, 2021) to identify what kind of competent monitoring was missing in Brumadinho, an inactive dam that failed almost three years after closure. Indeed most, if not all, of the items that the standard recommends were present and gave no actionable warning of the observed failure (Arroyo and Gens, 2021; Robertson *et al.*, 2019), as also pointed out by Jefferies (2022), discussed further below. This is particularly important when liquefiable material is present in the facility, a situation inescapable in many existing dams. The above-mentioned European regulation states the following:

> The prediction of soil liquefaction, especially in the case of fine-grained extractive waste, remains the subject of advanced soil mechanics research. For this reason, application of empirical methods based on field testing and theoretical constitutive models developed for naturally deposited soils and extractive wastes shall be validated by expert geotechnical engineers and adopted with caution. (BSI, 2021; D.2.3.5)

Wise words, certainly, but unlikely to be of immediate assistance to designers, inspectors and/or regulators facing the problem. Fortunately, many of the contributions in this special issue try to fill that gap.

To evaluate a risk, the relevant hazard needs first to be understood. Overtopping was the proximate cause of the 1994 tailing dam failure at Merriespruit in South Africa. However, overtopping incidents in South African tailings dams were not unheard of. Wagener *et al.* (1998) report that the operator of the failed facility at Merriespruit had 90 years of experience in similar dams in which overtopping had led to well defined erosion gulleys, of limited extent, which did not result in the destructive flowslide that characterised Merriespruit. The difference, it seems, was that the tailings deposited in Merriespruit were very contractive and prone to liquefaction. The paper by Mánica *et al.* (2022) presents a critical-state based numerical analysis of this case, concluding that the amount of overtopping-induced erosion required to trigger liquefaction failure in this case was fairly small.

The engineers at Merriespruit did not fully appreciate the vulnerability of their dam to static liquefaction nor the consequences that were likely to follow from relatively minor incidents. The paper by Jefferies (2022) argues – with characteristic forcefulness – that this is still very much the case today for a large part of the tailing engineering profession. He identifies basic misconceptions around static liquefaction deriving from lack of appropriate grounding on critical state theory (CST). Understanding and familiarity with CST should

become a core competence of engineers designing and inspecting tailings dams.

There is no doubt that the broader outlines of CST are now clear enough to be taught, learned and applied. However, there are still many finer points that need clarification and research. Reid *et al.* (2022) focus on different stress state and stress history effects (K_0, intermediate stress values, principal stress rotation) on static liquefaction triggering analyses. They show how those often-neglected issues may have a significant impact on the triggering analysis outcomes and conclude by stressing the importance of dedicated experimental campaigns to reduce related uncertainties.

Critical state parameters – as all continuum model parameters for tailings – reflect underlying grain-scale properties. If clarified, the links between grain-scale properties and critical state properties will be most useful when characterising tailings. Research on this topic is very active, using both numerical simulation and experimental work. Pan *et al.* (2022) offer one example of the latter, when they investigate the differential effects of tailings particle size on crushing during triaxial isotropic compression and subsequent drained shear. Specimens formed with larger-sized particles crushed more and were more contractive.

The papers by Williams (2022) and Macedo *et al.* (2022) deal with seismic liquefaction design. Williams (2022) focuses on current standard methods. In those, the possibility of seismic liquefaction being triggered is first evaluated based on empirical relations between a cone penetration test (CPT)-based cyclic resistance ratio and cyclic stress ratio. If liquefaction is triggered other empirical relations are employed to evaluate undrained strength values that will be used in total stress stability analyses. The results of this process will be expressed by a factor of safety. She interrogates the meaning of this factor of safety in terms of probability of failure and points her finger at the important effect of model uncertainty of the CPT-based estimates. Those uncertainties strongly penalise cases in which a large proportion of the material in the dam is potentially liquefiable and the central estimate of residual strength is low. In those cases, a safety factor of 1.1 – a target in many standards – is still equivalent to a 44% probability of failure.

As Williams (2022) points out, uncertainty may be reduced by using more advanced testing methods. This is one of the aspects addressed in the work of Macedo *et al.* (2022), who present a very comprehensive suite of static and cyclic tests on tailings material. Other aspects addressed are the selection of input ground motion, the calibration of an advanced constitutive model and its numerical application on a nonlinear dynamic effective stress analysis. This is a very well documented case-study, illustrating the current state-of-the-art of seismic assessment for tailings dams, which will be surely useful in the future as a benchmark. The dam has not been built and the authors end with a note of caution, calling for further integration of static and cyclic liquefaction analyses once the properties of the as-deposited tailings become available. This is an interesting point as, despite being perhaps simpler as a concept, static liquefaction has not historically received as much attention as seismic-induced liquefaction. Translation of the concepts and methods applied in seismic liquefaction to the static liquefaction case might not be always immediate.

One aspect in which seismic design practice has led, which is easily transferable and clearly beneficial for other studies, is the attention given to small-strain stiffness and shear wave velocity measurements. Silva *et al.* (2022) present a very extensive laboratory campaign where shear wave velocity of iron tailings in different conditions has been measured with bender elements. They show clearly how the stress-effect on shear wave of these tailings is similar to that of sands. They also show how measured wave velocities are affected by the degree of compaction; a finding that may be useful for field monitoring – although the effects of partial saturation, not included in the paper, may be also present in compacted tailings in the field.

Partial saturation is the focus of the paper by Garino *et al.* (2022). However, they do not consider initially compacted tailings, but rather slurry deposition followed by atmospheric-induced desiccation. A carefully monitored laboratory experiment on slimes retrieved from a legacy facility is described. Shrinkage, cracking and salt deposition at the surface appear as complicating factors on evaporation that hinder the advance of desiccation within the tailings. The authors conclude that the phenomena observed may explain repeated observations of quasi-full saturation in dams exposed to arid conditions, even after very long times have passed after deposition.

We want to end by thanking all the authors and reviewers for their efforts in ensuring the best quality in all the contributions. We hope this themed issue will contribute towards the consolidation of this journal as a useful outlet for the ever-increasing geotechnical community in charge of tailings dams.

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