ISSMGE - TC221 TAILINGS AND MINE WASTE

The International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) Technical Committee TC221 on ***Tailings and Mine Waste*** organized an online debate/discussion on November 7th, 2022. This webinar about the evaluation of the undrained strength of tailings has been motivated by the results of the previous webinar on geotechnical aspects controlling the stability analysis of tailing dams. A pragmatic view of this issue is that there is a group of professionals working on tailings dams who believe that the evaluation of the undrained strength can be done through laboratory tests (eg, triaxial, simple shear, direct shear) in combination with field tests (eg, SCPTu, SPT, Vane Shear, Vs). On the other hand, there is a view that this topic is highly complex due to the high stratification, unsaturated conditions, granulometric differences, aging and variation in the void ratio, among other factors, that real tailings deposits present, so more research would be needed to develop more effective methodologies to take into account the complex reality of tailings. These two technical visions were presented during the webinar.

Question: What is an appropriate method for evaluating Undrained strengths in existing tailings dams?

Speakers

Prof. Adrian Russell, Australia
Prof. Takashi Kiyota, Japan
Dr. Ramon Verdugo, Chile
Prof. Scott M. Olson, USA
Prof. Sarat Das, India
Prof. Antonio Viana, Portugal
Prof. Roberto Cudmani, Germany
Dr. Mike Jefferies, Canada

Moderator: Dr. Felipe Ochoa

Professor Adrian Russell, UNSW Sydney

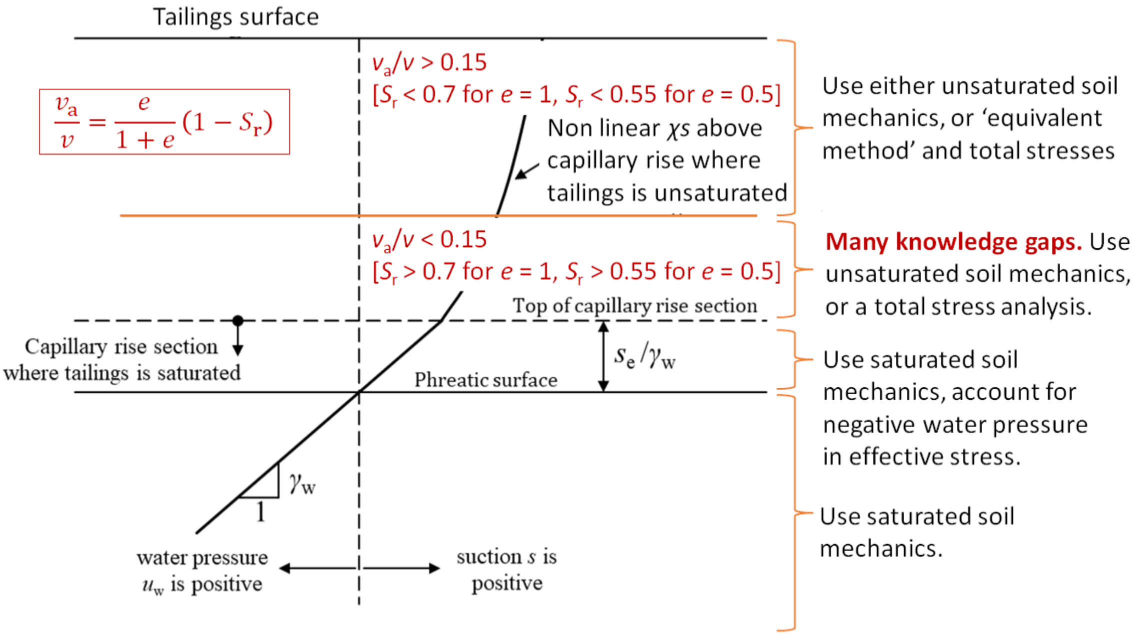
Strengths during fast loading are important, in saturated and unsaturated silty tailings. They control resistances to cone penetrations during CPTs. They also feature in stability assessments of tailings dams for post-liquefaction scenarios. A fast loading condition may be viewed as an undrained constant-volume condition when silty tailings is saturated. The same may not true when unsaturated as the presence of air, which is compressible, permits volume change. This volume change, along with suction due to capillary action, must be accounted for in CPT interpretations and stability assessments when unsaturated silty tailings are involved.

This talk summarises how partial saturation influences CPT results and static liquefaction of silty tailings'. It will address:

1. the latest advances on how to interpret CPTs in unsaturated silty tailings, and how to determine the state parameter in a future state when the tailings becomes saturated;

2. how the degree of saturation and in situ stress states influence the instability lines and post-liquefaction strengths;

3. and, in response to the main question, what strengths should be used for fast and slow loading scenarios when unsaturated silty tailings are present, especially around and above phreatic surfaces, noting that a pseudo-drained condition prevails when 15%+ of the tailings' volume comprises air.



This work forms part of TAILLIQ (Tailings Liquefaction), which is an Australian Research Council (ARC) Linkage Project (LP160101561) supported by financial and in-kind contributions from Anglo American, BHP, Freeport-McMoran, Newmont, Rio Tinto and Teck. TAILLIQ is being carried out at The University of New South Wales, The University of South Australia, The University of Western Australia (lead organisation) and The University of Wollongong. We acknowledge the support and contributions of project personnel at each of the supporting organisations. The work also forms part of an ARC Future Fellowship (FT200100820) held by Russell. Key contributors to the talk contents include Yanzhi Wang, Thanh Vo, Juan Ayala, David Reid, Andy Fourie.

Links (open access):
Paper: Cone penetration test in saturated and unsaturated silty tailings: doi/10.1680/jgeot.21.00261
Youtube: Partial saturation influences on silty tailings: youtube.com/watch?v=d_0A2p2f5uk
TAILLIQ website (including publication list): tailliq.com

Dr. Takashi Kiyota, IIS University of Tokyo, Japan

The most basic and essential means of assessing in-situ undrained strength is laboratory testing using in-situ samples. This is because undrained strength is a parameter that is strongly dependent on the soil type and its condition. However, except for freezing sampling methods, which are very expensive and difficult to apply in practice, it is almost impossible to obtain high-quality samples of the loose sandy and silty soils that make up tailings dams using common undisturbed sampling methods: it is almost impossible to take samples and set them in a testing apparatus without disturbing the density and soil particle structure (fabric) of the soil. Therefore, laboratory tests with common undisturbed specimens probably should not be done, because the actual strength may be underestimated or overestimated and correlated incorrectly, e.g. with CPT results.

Meanwhile, our team has been investigating various factors affecting the undrained cyclic strength (CRR) of various soils using triaxial tests. In particular, we have assumed that the undrained strength of a given sandy or silty soil under a given stress condition is determined only by soil density and soil fabric, and have conducted undrained cyclic triaxial tests with samples in which the shear wave velocity Vs and shear moduli G0, parameters reflecting soil fabric, were varied by initial stress history under given density conditions. The results in Fig. 1 show that in sandy and non-plastic silty soils without cementation effects, the change in CRR due to soil fabric has a good correlation with the change in shear wave velocity Vs, as long as the soil density is the same for each tested sample.

Using the above findings, we propose a new method of evaluating in-situ CRR based on in-situ PS logging and RI logging, as well as laboratory testing (Fig. 2). The first step in this method is to collect the sample from the target soil layer at the investigation site, even if it is a disturbed sample obtained via SPT. Then, measure its shear wave velocity, Vs, via PS logging, and density via RI logging. Second, prepare a remolded specimen in any manner, but the specimen density should not differ from that of the in-situ condition; then, obtain the shear wave velocity, Vs*, and cyclic resistance ratio, CRR*, under the in-situ stress condition at the depth of the target soil. Finally, determine the in-situ CRR by the equation, which was derived from Fig. 1.

By applying this method, it is probably possible to evaluate the in-situ CRR reflecting the in-situ soil density and soil fabric which includes aging effects without the use of undisturbed samples of uncertain quality from common sampling methods. We also applied this method to the assessment of liquefaction for past earthquakes. As a result, the liquefaction safety factors based on the in-situ CRRs evaluated with this method was generally consistent with the trend of occurrence or non-occurrence of liquefaction confirmed after the past earthquakes.

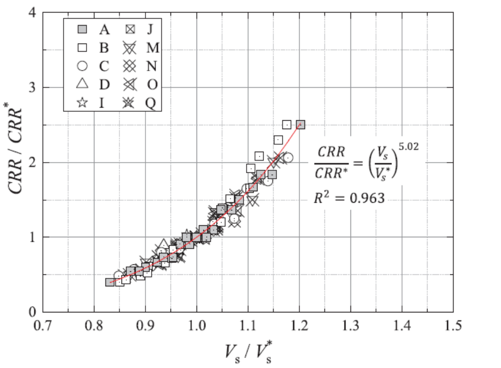


Fig. 1 . Relationship between the V_s/V_s^* and CRR/CRR^* of samples without cementation and plasticity effects (CRR^* and V_s^* definition includes all cases of CRR and V_s).

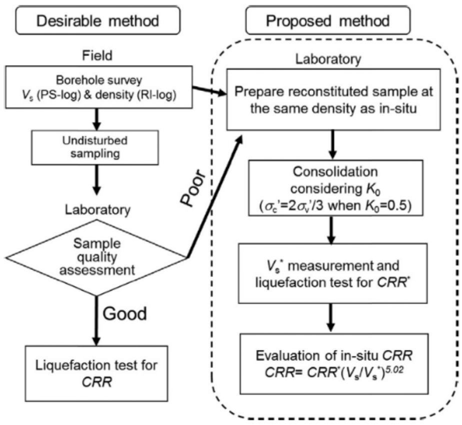


Fig. 2 . Proposed in-situ CRR evaluation method.

Links (open access): Kiyota et al., ”Using in-situ and laboratory-measured shear wave velocities to evaluate the influence of soil fabric on in-situ liquefaction resistance”, Soil Dynamics and earthquake Engineering, No. 117, pp. 164-173. https://doi.org/10.1016/j.soildyn.2018.11.016

Dr. Ramón Verdugo, CMGI - Chile

The actual behavior of sandy and low plasticity silty soils is more complex than is normally described and modelled considering the critical state or steady state of deformation as a theoretical framework. The undrained strength of granular materials that have a mechanical response that can be identified as sand-like behavior, is basically a function of the void ratio. Depending on the combination of void ratio and confining pressure, the response can be contractive or dilatative. The common understanding is that in the e- p´ plane, the contractive response occurs when the initial states are above the SSL, while the dilatative response occurs for those initial states below the SSL. However, experimental results show that there is a region in the e - p´ plane, below the SSL, where initial states first develop a quite contractive response, with a drop in strength to a minimum value, followed by a strong dilation that mobilizes an ultimate strength (or steady state strength), which is significantly higher than the transient minimum value. An example of this peculiar behavior is shown in Fig. 1a, where after a contraction, the dilation phase is such that the ultimate condition, or steady state, is to the right of the initial state. The Initial Dividing Line indicated in Fig. 1b separates those initial state with and without drop in strength, being interesting to observe that this line is located between the SSL and QSSL in a wide range of pressures. Therefore, although the initial state is below the SSL, the soil response is initially so contractive that a momentary loss of strength occurs, which undoubtedly influences the overall response of the soil mass. The quasi steady state condition depends on the fabric and the initial confining pressure, which makes the estimation of the minimum strength mobilized in-situ somewhat more complicated.

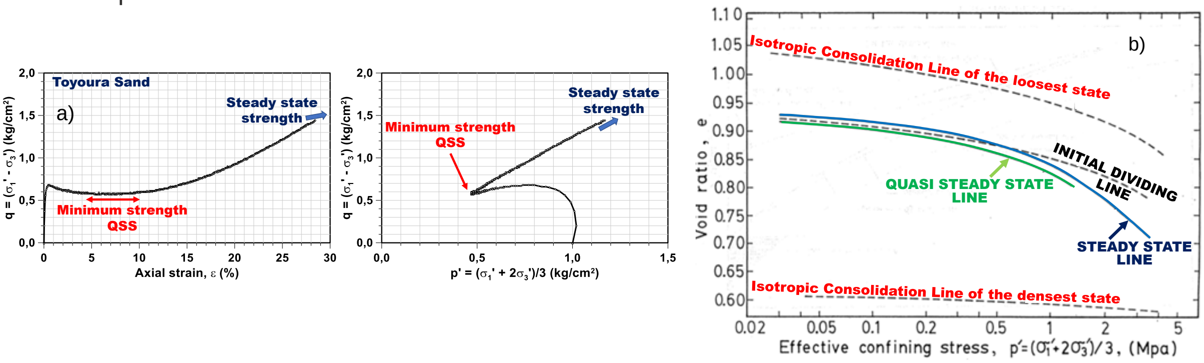


Fig. 1.- Minimum strength or Quasi Steady State Strength

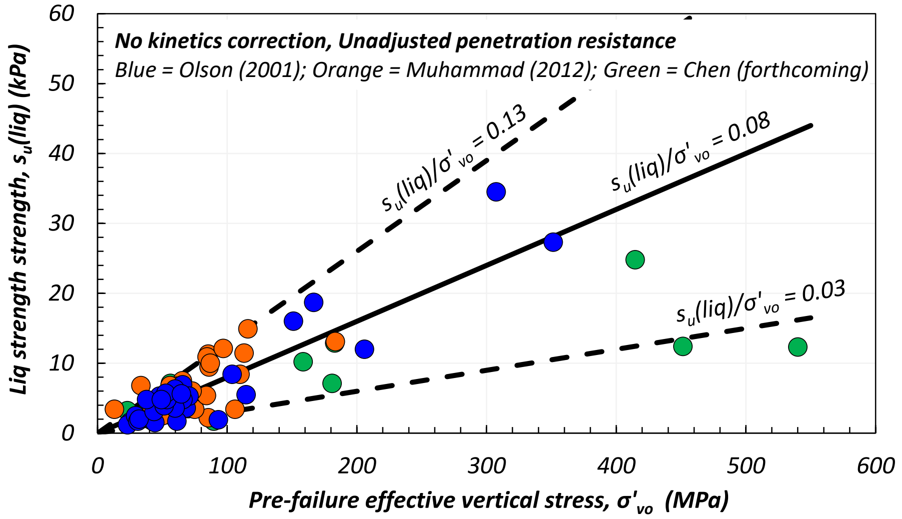
On the other hand, it is well known that the undrained response of soils is affected by the applied stress-paths. For a given state, the experimental evidence shows that the undrained strength (at the steady state or quasi steady state) is highest in triaxial compression, lower in simple shear and even lower in triaxial extension. If this fact were really accepted, it would not be possible to refer to a specific value of undrained shear strength, but rather it would depend on the specific stress path that is developed in each sector of the analyzed soil mass. Nevertheless, from a practical point of view it seems appropriate the use of the shear strength established from simple shear tests. In any case, this situation raises the question of what would be the undrained shear strength obtained from field tests such as CPT (tip or sleeve resistance) or Vane Shear. This uncertainty increases if it is considered that in sandy tailings these tests could be associated with a condition of partial drainage. It is also necessary to keep in mind the highly stratified structure of any tailings mass, which also affects the measurements and the decision on the representative value of strength. Additionally, the undrained strength of clayey soils depends on the applied strain rate, so in the case of fine-grained tailings, the evaluation of its undrained strength requires taking this variable into consideration. Accordingly, it is possible to point out that for practical purposes it is necessary to carry out laboratory tests (triaxial in compression and simple shear) and field tests (CPTu and Vane Shear) and, depending on the results, establish the minimum undrained strength that the mass of tailings can mobilize in the different sectors involved in its stability. Thus, the question is correct, but the factors that control the minimum strength must be properly included, which may imply that the considered undrained strength is not a unique value in any analysis.

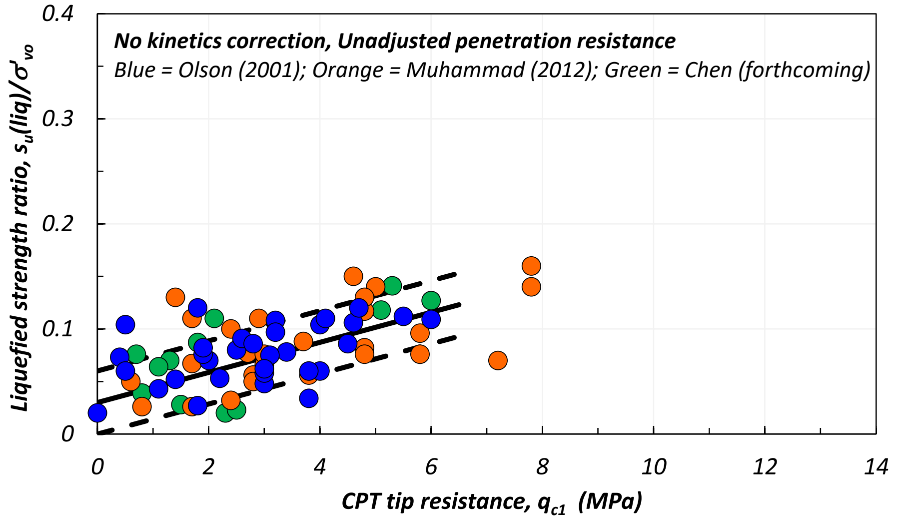
Link: K. Ishihara. Liquefaction and flow failure during earthquakes. Géotechnique, Vol. 43, 3, 1993. https://doi.org/10.1680/geot.1993.43.3.351. R. Verdugo : Static Liquefaction in the Context of Steady State/Critical State and Its Application in the Stability of Tailings Dams. Proc. 4th Int. Conf. Performance Based Design in Earthquake Geo. Eng. Beijing 2022. DOI: https://doi.org/10.1007/978-3-031-11898-2.

Prof. Scott Olson

Flow failure field case histories play critical role in understanding the liquefied shear strength of nonplastic to low plasticity soils (including tailings), validating semi-empirical and theoretical shear strength models, and calibrating constitutive models. Despite their importance to quantifying the stability of many tailings storage facilities (TSFs), there have been relatively few efforts to rigorously and consistently evaluate these flow failure case histories, and even fewer efforts to systematically expand the flow failure case history database. Recent efforts (Olson 2001; Muhammad 2012; and Chen forthcoming) have expanded the case history database to 72 flow failures.

The first figure below the 72 flow failures in liquefied shear strength [$s_u(liq)$] – pre-failure effective vertical stress [σ'_{vo}] space. These data exhibit a range of liquefied shear strength ratio [$s_u(liq)/\sigma'_{vo}$] from approximately 0.03 to 0.13, with an average of approximately 0.08. These values are consistent with the original range proposed by Olson (2001) and Olson and Stark (2002). The second figure below presents these flow failure cases in liquefied shear strength ratio – effective stress normalized CPT tip resistance (q_{T1}) space. As illustrated in the figure, the original correlations proposed by Olson (2001) and Olson and Stark (2002) still reasonably characterize the case histories. However, the relationships presented in the second figure do not continue indefinitely, but rather are limited by flow liquefaction susceptibility considerations. These considerations and minimum shear strength concepts (also related to liquefaction susceptibility) will be discussed during the webinar.

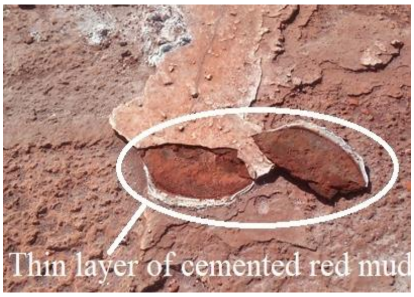


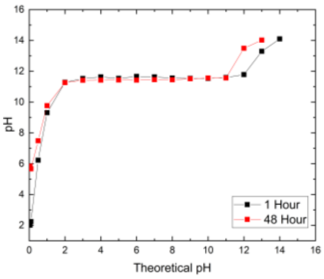


Key reference: Olson, S.M. and Stark, T.D. (2002). Liquefied strength ratio from liquefaction case histories. Canadian Geotechnical Journal, 39, 629-647

Prof. Sarat Das, Indian Institute of Technology, Dhanbad, India

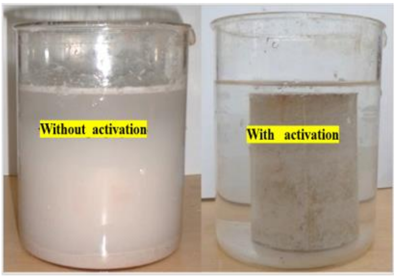
The processed tailings are from the industries and consist of mainly coal ash from thermal power plant, bauxite residue and steel slags with chemical changes. The unprocessed tailings of metallic mines and mine overburden from the coal mines derived are due to mechanical processes such as excavation, blasting, grinding etc. The disposal systems: slurry or dry disposal makes the stratifications. In the bauxite residue a white layer at intervals even in the dry disposal system is a testimony to this statement. The chemical composition of the industrial wastes also governs the short term and long-term strength of these tailings. The bauxite residues get cemented as shown in Figure 1, for which suitable in-situ investigation to be used to determine these thin layers. The strength information of these layers may come as outliers in the CPT and MASW. As these materials are also dispersive in nature, in long term this cementation may dissolve and there may be underground cavities as evident from rain cut furrow on the surfaces. As per the triaxial tests, the cementation breaks at 1-2% of strain. Higher yield strength of the bauxite residue in comparison to its particles size is due to the presence of chemicals like sodalite. Fortunately, bauxite residue is having a wide range of buffer value in the acidic environment.



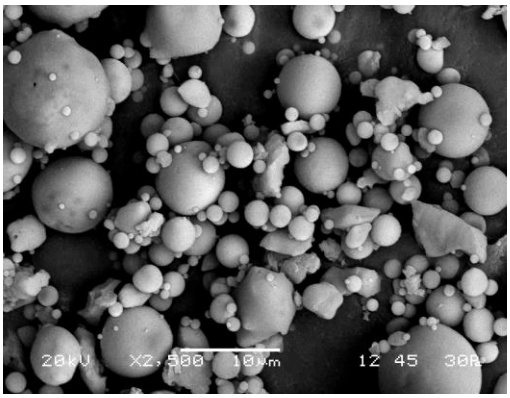


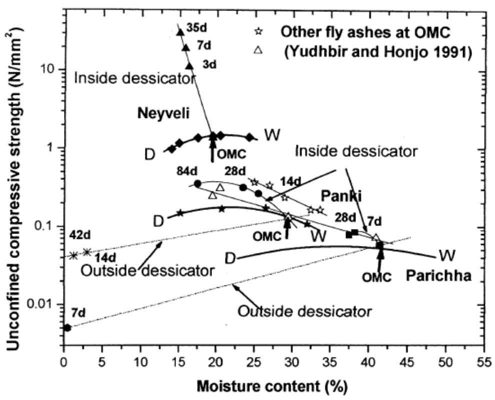
Buffer zone tests for the Bauxite residue

The iron ore tailings also contain dispersive materials as shown in Figure below. Piping and consequence local slope failure on open pit iron ore mine is evident of this. Hence, finding a strength behaviour with laboratory testing for such cases may not be sufficient.

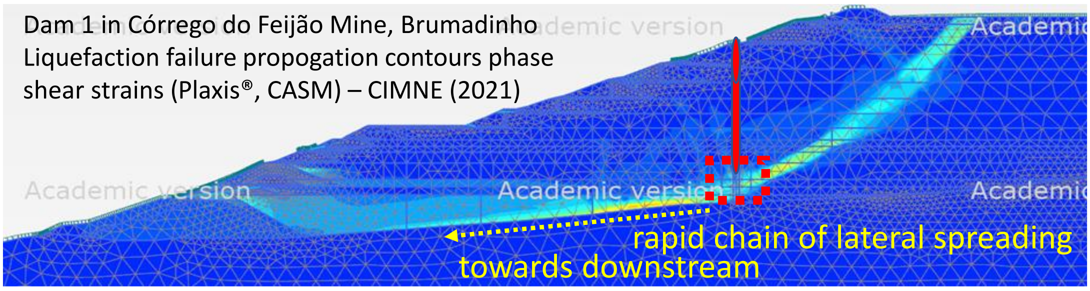


The fly ash is non-plastic due to its spherical shape and strength of fly ash tailing pond depends upon the saturation level.

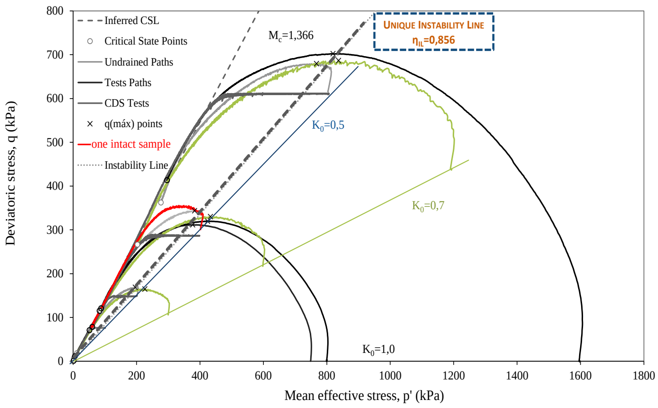


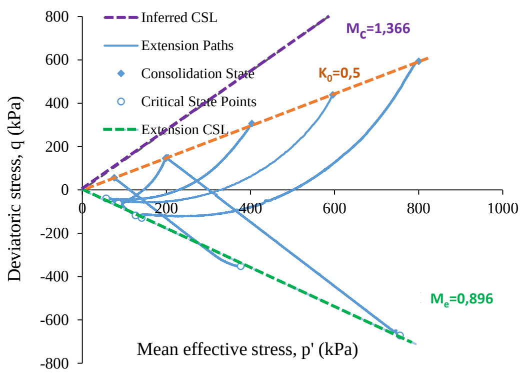


Prof. António Viana da Fonseca



Recent dam failures have highlighted the brittleness of the materials deposited in Tailings Storage Facilities (TSF), special dams, emphasizing the importance of studying this peculiar materials in order to understand their hidro-mechanical behavior and designing safer. The tailinsg Dam I at the Córrego do Feijão iron mine complex (Brumadinho, MG, Brazil) collapsed in Jan 2019 due to liquefaction. To define constitutive parameters for numerical simulation of the failure using a computational model (CASM), an extensive laboratory testing campaign included a large number of triaxial tests, on remolded samples of 4 types (clusters) of deposited tailings (differentiated by the percentage of iron elements). Diverse initial state conditions (loose and dense), consolidation paths (isotropic and anisotropic) and shear paths (drained and undrained; compression and extension under strain and stress control (Viana da Fonseca et al. 2022 a and b). The tests results embraced the evaluation of physical, hydraulic and mechanical properties necessary for the calibration of constitutive models that can reproduce the undrained softening underlying the flow liquefaction phenomenon that caused the dam failure. Specific characteristics of undrained anisotropic behavior of these heavy iron ore tailings were observed: (1) loose specimens at low stress levels undrained sheared have a strong strain-softening behavior, followed by a loss of stability, rapid increase in shear strains and pore pressure development that would lead to uncontrollable failure; (ii) the peak strength points for these samples allowed the definition of the instability line in the invariant *q–p'* space (S_p ratio). After the peak undrained strength is mobilized, the stress-path drops down to the CSL for low values of *q* (post-liquefaction strength or residual undrained strength, $q_{res} \approx s_{ures}$); normalized strength ratio depends on the consolidation path, with much larger values of S_p for anisotropic consolidation; the axial strain required to reach peak strength was much smaller for anisotropic test (0.06%) than for isotropic tests (0.90%).





This has to be considered relevant in the context of stability computations such as those addressing flow liquefaction. The effect of induced anisotropy in compression and extension stress-path, reveals that the instability region where inversion (rotation) of the principal stresses is imposed is much narrower when compared with the conventional one compressional path test.
Undrained shear strength is not an intrinsic value of a soils at stress in repos and can be transient.

Links (open access): Mechanics of iron tailings Dam1 Bruma (doi: 10.28927/SR.2022.001122)
The Tenth James K. Mitchell Lecture: https://youtu.be/CBygpI7i8AM

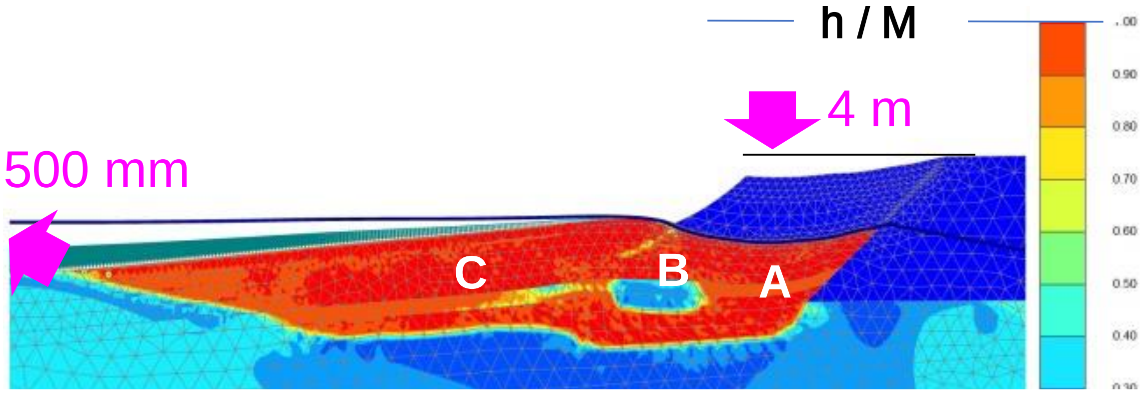
Prof. Roberto Cudmani, Technical Univ. of Munich, Germany

In spite of the huge effort of researchers and experts to understand and describe the mechanical behaviour of loose granular soils, particularly tailing materials under static and cyclic shearing, catastrophic tailing dam failures continue to occur worldwide. While these failures can be triggered by different mechanisms and are in general multicausal, the mechanical response of tailings to undrained monotonic and cyclic shearing, especially their susceptibility to partially or completely lose their strength (soil liquefaction) is recognized as one of the most essential and controversial issues to ensure the stability of tailing dams. Usually, two methods of analyses are applied in practice to assess the stability of tailing dams: The Limite Equilibrium Analysis (LEA) and the Effective Stress Analysis (ESA) via numerical methods, e.g. Finite Element Analysis (FEA) and Finite Different Analysis (FDA). In the LEA, the behaviour of the material is assumed to be rigid-plastic, i.e. the material does not experience any deformation until the yield conditions is achieved. Usually, the Mohr-Coulomb yield condition and the von Mises yield condition (alternatively the Tresca yield condition) are respectively assumed to describe the drained and undrained failure of the material. While loose granular materials are expected to show a strain-hardening behaviour during shearing and shear parameters describing the drained resistance can be unequivocally determined in the laboratory, the undrained shear behaviour of tailings is much more complex and the undrained shear strength ambiguous, as the existing, in some cases contradictory experimental evidence shows. Moreover, from the soil mechanical point of view, there are major concerns about the representability of the undrained shear strength determined in the laboratory and in-situ for the analysis of the stability of tailing dams.

In the ESA, tailing dams are deformable structures, whose mechanical response is governed by the mechanical (coupled) behaviour of the tailings, a set of initial and boundary conditions as well as the construction history. In principle, the ESA is much versatile and powerful than the LEA, and there are plenty of open source and commercial programmes available nowadays, which ease its application in practice. Nevertheless, the predictive ability of ESA, especially its capability to realistically predict the onset of failure, strongly depends on the constitutive model used to simulate the mechanical behaviour of the tailing materials. Several constitutive models, which are in principle able to capture the complex behaviour of tailing materials under monotonic shearing, have been proposed in the literature. These high nonlinear models are mathematically complex and require a large number of parameters. Generally, only specialists, sometimes solely the developers of the models, are in the position to calibrate the models and deeply judge their abilities and limitations. Mainly for these reasons, there are a great deal of scepticism among designers and consultants responsible for the stability of TSF about the capacity of advanced numerical modelling to predict the onset of failure of tailing dams. Moreover, many engineers consider ESA as “black-box analyses” which instead of helping to more realistically predict the undrained shear strength of loose tailing materials makes the problem cumbersome and the actually value of the undrained shear resistance uncontrollable for the user.

In this context, fundamental soil mechanics concepts regarding the undrained shear behaviour of loose granular materials will be qualitatively introduced and supported by experimental evidence and results of DEM simulations. The dependency of the undrained strength at the peak, quasi-steady state and critical state (steady state) on the state variables, the fabric and the strain/stress path will be discussed and conceptual difficulties to define a representative value of the undrained shear strength for stability analyses based on laboratory and field tests will demonstrated. In addition, the ability of advanced constitutive models to predict the undrained shear behaviour will be shortly analysed. It is concluded that the minimum undrained shear strength of loose granular materials, which is the shear strength at the quasi-steady state, only depends on the initial state, defined by the void ratio, the initial stress state and the fabric, but also on the stress history (e.g. monotonic, cyclic loading) and the stress / strain path (e.g. triaxial, biaxial, simple shear). Additionally, the quasi-steady state can be affected by the increase of the strain rate during softening and grain crushing. Therefore, considering that different regions of tailings can fail under different strain / strain paths, a unique, initial-state dependent undrained shear strength to be applied in LEA cannot be defined unambiguously based on laboratory and field tests. Consequently, the application of LEA in the case of liquefaction-susceptible soils will need an important portion of empiricism. Transferability of results and experience among different sites is therefore questionably. ESA is a promising alternative provided the constitutive models are able to capture the mechanical behaviour of tailings behaviour in the quasi-state and post-liquefaction. However, this is not possible yet with the majority of the models available in commercial codes. Therefore, developing and validating constitutive models by means of high quality laboratory tests and well-documented benchmarks as well as the implementation in commercial codes and training engineers to deal with these models is essential for a reliably application of ESA. Due to the well-known limitation of sampling techniques and the execution of laboratory tests for general stress / strain paths in the case of loose granular soils, numerical simulations with the DEM are becoming a valuable tools to better understand and quantify the undrained shear behaviour of tailing materials.

Dr. Michael Jefferies



Investigations of recent large tailings dam failures have required complete boundary value analyses (BVA; often using FLAC) incorporating critical state theory to understand how such failures developed. In itself, this immediately suggests limit equilibrium (LE) with undrained strengths is an inadequate design method for tailings dams. A feature of BVA is that soil properties are used 'as measured' and that soil state is assessed from CPT by formal inversion (as opposed to correlations). However, these recent failures were complicated, which limits assessment of BVA versus LE in general and with the possibility that LE might be adequate in simple circumstances. One case-history stands out as a validation case: the Tar Island liquefaction slumps. Tar Island is a 100m high upstream tailings dam, constructed over some 40 years. There were five liquefaction slumps into the pond in the early years as engineers developed the construction method for building out on loose tailings, and these provide the simplest possible validation case as the slumps were triggered by dead loading as a raise was constructed over existing loose tailings. And, there is much SCPT data, triaxial data, and even CPT calibration chamber tests.

Analysis of the largest Tar Island slump using PLAXIS/NorSand (large strain mode) produced the flowslide shown in the figure above and which developed from drained conditions. Using all data 'at face value', the reported large upstream propagation of the slump was matched while the crest settlement was near perfect at 4m. The zone shown in red on the figure has moved to its critical state, but because each part of the domain experienced a different stress-history during construction there is a wide range of critical state strengths: the strength ratios realised were s_r/σ'_{v0} = 0.101 at A (mid-point beneath cell), a slightly larger 0.143 at B (toe area, with most densification pre-collapse) and 0.042 at C (a reasonable characterisation of tailings still in the greenfield state). Collapse started from a 'rapid perturbation' tested against an instability criterion, not an undrained strength, with no excess pore pressure when failure started. Failure then propagates, undrained, as a 'plastic wave' with a velocity of about 50 m/s, essentially exactly as seen in the widely-available video of the Brumadinho collapse. The effect of stress-paths and soil compressibility are the essence of why BVA produced the simulation shown, and these aspects are absent from the LE method (undrained strength is a path-dependent behaviour, not a soil property).

Thus, this reply: it is the wrong question. The correct question is: are undrained strengths and LE analysis appropriate for assessing potential static liquefaction? I assert not, as the range of triggering conditions and their path dependence cannot easily be dealt with in LE while it is quite simple to do so using BVA and the critical state methodology.

Links (open access): Tar Island Liquefaction Validation… doi/abs/10.1680/jgere.21.00007
CPT procedures and soil state… doi/abs/10.1680/jgere.16.00008