GEOTECHNICAL ISSUES ASSOCIATED WITH THE STABILITY OF TAILINGS DAMS

SEPARATION OF THE ANSWERS ACCORDING TO TYPE OF RESPONSE TO PERFORM THE DEBATE

TC-221 – TAILINGS AND MINE WASTE

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(TC221 – TAILINGS AND MINE WASTE)

<u>Question 1</u>:

Is it possible to design upstream tailings dams where their stability can be guaranteed on a long term basis? If so, which are the basic requirements that an upstream tailings dam must meet?

<u>Who think that it is possible</u>

1.1.- Yes, when the seismic activity is low or negligible, it is possible. But there is a much higher need for quality checks. The deposition of material has to be followed very carefully in order to guarantee segregation and formation of a beach with coarse material. The void ratio (or degree of compaction or similar) of this "constructive zone" has to be checked regularly as well as the extension.It should be wide enough. Beach has to be well draining material in order to have a low ground water level. Dilative material (well compacted). Low rate of raising in order to prevent pore pressure build up. No watertight dams. These are some of the requirements.

1.2.- Yes. All the state of the art studies, important remark on the drainage of the tailings.

1.3.- There is a tacit implication in this question that we are dealing with something intrinsic to 'upstream construction'. In reality, many failures (Los Frailes, Mt Polley, Cadia extending to Ft Peck and Nerlerk if we include other loose-fill liquefactions) developed in the foundation. Whether the dam was upstream or centreline seems irrelevant if the errors were in assessing foundation behaviour. Most generally, if the foundation is adequate, loose sands are reasonably used as fill provided they remain partially saturated (= 'drained' is not enough). The issue of long-term stability thus comes down to engineered drainage to keep the phreatic surface in such a position that static liquefaction is no longer a concern; which is a similar issue as in conventional water retaining dams were engineered filters and drainage is the essence of a safe dam.

1.4.- There are examples of successful performance of upstream tailings dams' construction that consider some grain size segregation, leaving enough time to the deposited surfaces to dry out to apply some compaction and relatively flat downstream slopes of the order of 4:1 to 5:1 (H: V). This the case of some tailing's deposits in Australia, Canada, and South Africa. Usually suitable in flat areas, arid regions with moderate seismicity.

1.5.- Yes, it is possible to design upstream tailings dams, safe at closure. One of these two requirements must be met: i) the dams are located in an arid environment where they will dry out over time and the risk of water ingress and saturation is negligible; or ii) a buttress robust enough to provide for overal stability assuming a fully liquefied tailings body is provided before the dam is abandoned. In both cases, walk-away designs should be mandatory.

1.6.- Short answer I believe you can in low seismic regions. Instrumentation and robust monitoring plan is a basic requirement to have from the beginning and throughout the life of the facility. Is essential to have piezometers (piezoelectric and analogs for redundancy), survey points ideally using a fixed total station and topographic prisms. Construction QC/QA is essential with the corresponding As-Built records to keep in the mining unit in case, designer/EOR/Operator changes. There must be a strong tailings governance team on the mining company that provide a reliable efficient counterpart to the EOR/Designer team. However, consequence is a key concept, I would by any chance lean towards a high risk high consequence facility.

1.7.- Yes, it is. The most fundamental requirement is that such facility be underpinned by sound, representative and relevant design. Such design should ensure that: (1) the design is underpinned by rigorous analysis; (2) the analysis is based on sound modelling tools; and (3) the modelling tools used are underpinned by relevant and representative characterization of tailings and their engineering design properties. Once the three features highlighted above are established, additional monitoring strategies may be considered as well to produce supplementary information and performance-based assessments.

1.8.- Yes, there are many examples where this has been done successfully. The main prerequisites to achieving this are to maintain a sufficiently wide structural zone that is unsaturated, dense (dilatant) or both. Given the uncertainties surrounding measurement of saturation, the most reliable way to preclude liquefaction in an upstream tailings dam is to compact the structural zone. Examples of this are available in the Alberta oilsands in Canada."

1.9.- Some precautions taken in the design and management of upstream tailings dams can guarantee a certain level of stability, especially in the long term. Over time, in particular following the closure of the facility, the stability of the structure tends to increase as the pressures in the pores tend to dissipate and an aging process starts which produces a cementation and interlocking effect between soil particles. A successful design of a upstream tailings dam consists in implementing all those measures useful to remove water and at the same time not developing overpressures or too fast and intense flows that could lead to erosion processes. Therefore fundamental aspects not to be neglected in the design phase of tailings dams are: an excellent drainage system at various depths of the dam and the basin together with a canalization and drainage system of surface waters, maintenance during all phases of a beach of adequate dimensions and permeability and provide a capping system following the closure of the structure.

1.10.- Yes I think it is fully possible. Depending on the permeability and shear strength properties of the tailing materials, the long-term stability of the upstream tailing dams can be guaranteed when the drained shear strength of the tailing materials can resist the potential slope failure.

1.11.- The requirements shall be that the slopes of tailing dam do not cause flow failure even under the action of strong earthquake effects. The Japanese Ministry of Economy, Trade and Industry (METI) has established the seismic design code for tailings dams to insure safety against Level 2 earthquake motion, which is extremely strong but very unlikely to strike a structure during its lifetime. Prof. Yasuda led the technical committee and Dr. Kiyota and myself were members. The outline of the code and its applications are reported in Yasuda et al. (2017).

1.12.- Yes. It is possible to design upstream tailings dams while maintaining their long term stability. However, it is not an easy task. It must be designed by competent designer and managed strictly by the owners. Any potential changes to the design conditions must be checked carefully before proceeding to ensure stability criteria are still satisfied.

1.13.- I believe we can design upstream tailings dams as long as the parties during design and construction follows a strict rules of best practices. For example, a geotechnical model for the tailings dam base on high quality site investigation.

1.14.- Yes, despite upstream tailing dam is comparatively more vulnerable in stability comparing with other methods (centreline and downstream dam), it is possible to design with acceptable stability if the design is properly planned, designed, constructed and maintained. Most of the problems in upstream dam failures is the operation team stretching the containment beyond the design limits when the storage capacity is reached without advanced planning to divert the tailings storage.

Who think that it is not possible

1.1.- Not possible for conventional old type of upstream tailings dam, without any compaction effort, rather steep downstream slopes (typically 2H:1V) with no or poor tailings grain size segregation, as the ones built for example in Chile until 1965, in Perú and in Brazil until recently, especially when associated to high seismicity and/or high rainfall. This was the type of upstream dam construction that was banned in Chile in 1970, Perú in 2014 and Brazil in 2019.

1.2.- I believe that upsteam tailings dams are inherently prone to failure. Depending on particular conditions (i.e. height, properties of underlying tailings), some may be stable on the long term. However, I believe it will be a significant challenge to ensure that all upstream dams are stable. Plenty of instrumentation and continuous site characterization would help, but perhaps not solve all the problems.

1.3.- In theory yes. However, ensuring the stability of tailings dams entails a complex interaction and governance involving a number of actors. Among these, are the owner/operator of the dam, as well as various companies responsible for: (i) field monitoring; (ii) site investigation; and (iii) stability analysis and reporting, in addition to environmental agencies. Although it is possible to design upstream tailings dams where their stability can be guaranteed on a long-term basis, several ruptures observed in recent years show that this type of construction calls for great attention. The operation of the dam, the control of the water table, and adequate internal drainage of the upstream tailings dams are weak points. Brazilian legislation has called for suspension of the operation of these dams, followed by the de-characterization of upstream tailings dams.

1.4.- Upstream tailings dams are built on non-engineered fills in the context of stability analysis with inherent high risk of liquefaction failure. Long term requirements for upstream structures are therefore difficult to meet, society must be aware of the high probability of failure and, whenever possible, alternatives should be considered (centreline and downstream dams or dry stacks). For existing structures, requirements for stability entail careful control of disposal methods and water management.

1.5.- Study of the possibility of the disasters caused by the occurrence of earthquakes and heavy precipitation is required for the long-term stability study of tailings dams. In Japan, it is important to keep the tailing dams be safe especially during earthquake due to the high activity of earthquake. In the 1978 Izu Ohshima Kinkai earthquake, liquefaction caused the collapse of upstream tailings dam at the Mochikoshi mine. Also, collapse of upstream tailings dam happened at the Otani mine in the 2011 Tohoku earthquake (Ishihara et al., 2015). Then, upstream tailings dams are estimated not to be stable against large earthquake for the long term. Currently, most of mines have already stopped the operation so that the demand newly to construct tailings storage facilities hasn't existed in Japan. On the other hand, the applications of countermeasures against earthquake as well as the evaluations of the seismic stabilities of existing upstream tailings dams have been conducted because there are many existing upstream tailings dam . In Addition, as the latest application examples, we can refer to the case history of the recovery of the Otani mine damaged in the 2011 Tohoku earthquake (Yasuda, 2021). Another one is the recovery of the Taio mine damaged in the 2016 Kumamoto earthquake (Yasuda, 2021). Furthermore, we can pinpoint an example of tailings dam in Kagoshima where not only the seismic stability inspection study but also applying the countermeasure in order to prepare for the level-2 great earthquake were carried out (Yamada et al., 2019).

1.6.- In principle yes, as long as a beach zone of sufficient thickness remains unsaturated throughout the design life. The ability to meet this condition will depend on well controlled construction and the availability, and maintenance, of drainage features, sized to meet the local weather conditions. While there may be some design challenges, I think that the problem is not so much one of design but rather of construction and maintenance

1.7.- Probably not if the materials are only ever normally consolidated in the zone of influence of potential failure planes, and certainly not without monitoring and pre-emptive measures being taken in perpetuity. Mud farming or other forms of mechanical reworking could assist with increasing resistance to liquefaction in the main zone of influence for stability. How long is long term and how much could the conditions vary over that period of time? These are questions we do not know the answer to. Upstream tailings dams carry significant risk, especially in the long term. Who remains responsible for a tailings dam 100, 200, 300 years later? One major long-term issue is that it will be very difficult to guarantee that the soils will not become saturated or near saturated again in the future, and the likelihood is that normally consolidated tailings (of low plasticity) will be susceptible to liquefaction if they are saturated or near saturated, therefore the only real way to mitigate this long-term risk is to either ensure the tailings are denser than critical state or provide a suitable buttress.

1.8.- It is possible to make a suitable design in the desk. However, correct construction and operation cannot be guaranteed in terms of fulfill all technical aspects established in the design. In other words, it is theoretically possible, but in practice, it is highly risky.

<u>Question 2</u>:
Which are the most appropriate procedures to evaluate the residual undrained strength (shear strength of liquefied soils) in the laboratory and in the field?

<u>Who think in terms of current available tests</u>

2.1.- Triaxial testing. In field CPT testing. It is not perfect but the best we have….

2.2.- At the laboratory probably the simple shear test is one possibility, but on careful triaxial tests could also be possible although more difficult to be sure you have gotten the residual strength at large deformations.
At the site field vane test is an appropriate procedure. The CPTu has been also used in some cases, but it has been mentioned that careful calibration is needed for the type of soil to be tested.

2.3.- In tailings (as rock flour), we should agree in defining "residual" as the critical state, after all bonding and structure are lost but not at strain levels reported in high plasticity clays testing. If this definition is accepted, good practice is:

- Use CPT testing and the procedure by Shuttle & Jefferies (CPT-Widget, which still requires improvement, extensive validation, curation and generalization).
- For material with limited dilation, use the shear stress at the low point in the stress-strain curve where the sample hits the CSL p-q line.

2.4.- In the lab DSS, Cyclic DSS ensuring saturation and low/slurry densities. And on site CPTu, Shear Vanes and Geophysics.

2.5.- A combination of CPT soundings and high-quality laboratory testing including anisotropically-consolidated undrained TX testing.

2.6.- Empirical CPT interpretations are the most appropriate first step. It is often beneficial to supplement these with field vane testing and laboratory undrained triaxial testing undisturbed and reconstituted samples. The testing of reconstituted samples needs to be completed on sufficiently loose samples and consider differences in results associated with load control vs. displacement control and different stress paths."

2.7.- The measurement of liquefied shear strength in the laboratory is complex and involves several challenges, including selection of the appropriate sample preparation technique in order to represent in situ conditions, the need for accurate measurement of voids ratio, and minimization of sample end friction. Other issues involve determining the type of undrained test to be performed — triaxial compression (TX-C), triaxial extension (TX-E) or direct simple shear (DSS) — knowing that this generally provides intermediate strength values. The mode of shear must also be decided, with strain controlled test being used and recommended most often for measuring the liquefied strength, rather

than load controlled test. Robust laboratory investigation involves determining the critical state line (CSL) and state parameters representative of in situ conditions. In Brazil, CSL is not determined with the expected quality by commercial laboratories. Index tests are fundamental for interpreting the full range of laboratory tests performed. Direct simple shear (DSS) tests and resonant column (RC) tests can complement laboratory studies.
In situ tests are more expeditious and generally considered more reliable than laboratory tests. They should primarily include piezocone (CPTu) and vane shear test (VST) at rates consistent with the undrained condition to be simulated. The CPTu, properly interpreted from recent literature, can be used to estimate the nature of the tailings (sandy, silty, clayey), whether it has contractive or dilative behavior, and the range of values of the liquefied shear strength of the tailings. The seismic cone penetration test (SCPTu) can be an important complement due to the advantages it brings.

2.8.- One of the first researchers who proposed a laboratory method to estimate the shear strength of liquefied soils was Poulos in 1985. This method is based on the critical state theory of soil mechanics and it consists in carrying out undrained consolidated triaxial tests on reconstituted samples and undisturbed high-quality samples. Some other promising methods have been proposed starting from that proposed by Poulos and research on this topic is still ongoing bringing to light new elements that help to understand the phenomenon. Since the 1970s, many empirical methods have also been developed to that correlate the post-liquefaction strength to the results of SPT and CPT tests. These methods are based on back-analysis carried out on cases of failure of slopes, dams, embankments and tailings dams occurred in the past. One of the first studies of the subject was proposed by Seed in 1987. This research topic is also currently under development also in a probabilistic key with the proposal of methods that allow to carry out fully probabilistic risk studies. (Weber 2015)

2.9.- In Japan, after the damage of the Mochikoshi mine in 1978, the design method standard of tailings dams was published considering the effect of liquefaction (Yasuda et al., 2017). This standard ruled the calculation method of the stability of slip failure by using the circular slip method, in which shear strength coefficient obtained by laboratory triaxial compression test as well as quantity of excess pore pressure buildup during cyclic shearing are necessary. Therefore, residual strength in post liquefaction state is not used in this method. In case that the residual strength is required for the evaluation, corresponding N-value of standard penetration test’s result to the strength will be desirable as a way on site. A method to apply monotonic loading after cyclic loading by using cyclic torsional shear test apparatus in laboratory can be regarded as another potent choice.

2.10.- I think there are established methods (perhaps papers of Idriss and Boulanger; Poulos; Duncan et al) in the literature to do this. A number of factors that will affect the residual undrained shear strength of the liquefied soils should be considered, such as the residual pore pressure, water content, saturation degree, relative density, soil fabric and anisotropy, loading manner and direction, and others.

2.11.- In the laboratory, triaxial testing of moist compacted saturated specimens. In the field, CPTu

2.12.- Field: vane shear, cyclic T-bar or ball testing, shaft friction from CPT may provide useful information
Lab: ring shear, where the specimen need to be prepared to be similar to in situ conditions.

2.13.- Field test such as SCPTu should be conducted to evaluate the residual undrained strength, at the same time, a calibration model based on site characteristic should be conducted.

2.14.- As the failure of the tailings dam involves the structural material of the dam containment and also the tailings material, in which the engineering behaviours can have different degree of strength mobilisation from the inception stage of shearing until the total collapse, the conventional of strength tests, likes triaxial tests, direction shear box tests and in-situ strength tests (vane shear or piezocone) for the fine tailings, coarse granular tailings and compacted earthfill that form the structural containment are still practical and relevant. The shear stress-strain model at peak strength, critical strength and residual strength of the above materials are important for evaluation of the strength mobilisation and deterioration of static liquefaction.

2.15.- Lab: Undrained tests using Simple Shear and Triaxial in compression and extension. Special attention is needed in the sample preparation to reproduce the actual fabric and in the equipment in order to reach large deformation in the tested samples.
Field: Vane Shear with adequate rotation speed and sleeve resistance from CPTu.

<u>Who think in tests plus something else</u>

2.1.- In laboratory is very difficult, not reliable, on site the Vane test may be the only way, but it is very hard to measure it directly. Best to do the State parameter, with the CPTU measure on site, and mixed with the lab data, and the Norsand characteristics.

2.2.- Residual undrained strength is a function of insitu state relative to the critical state line and behaviour under shear stress/strain i.e. strain softening or hardening. The best way to assess a soils residual shear strength is to take the following steps:
Carry out CPTu programme and screen the data using the Plewes screening method to assess likely behaviour in shear by estimation of the state parameter.

Carry out insitu sampling of soils in area of interest.

Attempt to carry out insitu undisturbed sampling to assess the insitu state (density, moisture content and voids ratio).

Carry out laboratory assessment of the CSL using 3 loose tamped (with freezing method if required) CIU triaxials, 1 loose CID and 2 dense CID triaxials.

Preferably carry out Resonant column tests and/or bender elements.

Use lab data to build a constitutive model using Norsand to predict residual strength for a given insitu state.

2.3.- The notion of post-liquefaction strength (s_r) intrinsically invokes critical state soil mechanics. This immediately leads to the very simple expression:

$$2s_r/p'_0 = M \exp(-\psi/\lambda) \qquad [1]$$

…where p'_0 is the pre-liquefaction insitu mean effective stress (ie there is an effect of K0 on post-liquefaction strength if expressed in terms of vertical effective stress). M, λ are soil properties. The problem with [1] is that experience originally suggested that while [1] was fine for truly loose soil states it was too optimistic, based on back-analysis of liquefaction slumps/run-outs, for soils near their contractive-dilative boundary (which is a lot of natural soils). However, there is an unacknowledged mis-step in these case histories with workers comparing the pre-liquefaction insitu state (commonly judged from CPT) with what is in the flowslide. There is considerable soil mixing during a liquefaction slump, readily seen in the Brumadinho video record as well as the records at Cadia. This was investigated at Cadia with the CSL determined for the 'predominant' and 'sandier interlayers' of the insitu tailings as well as the mixture of these soils in the slump, see figure below (from Cadia ITRB report). The effect of mixing – which occurs at constant average water content – is a shift in the CSL that has the effect of moving the soil to a looser state even though the average water content has not changed. In my view this is an important, and presently unrecognized factor, in relating s_r from slump geometry to the pre-failure soils insitu.

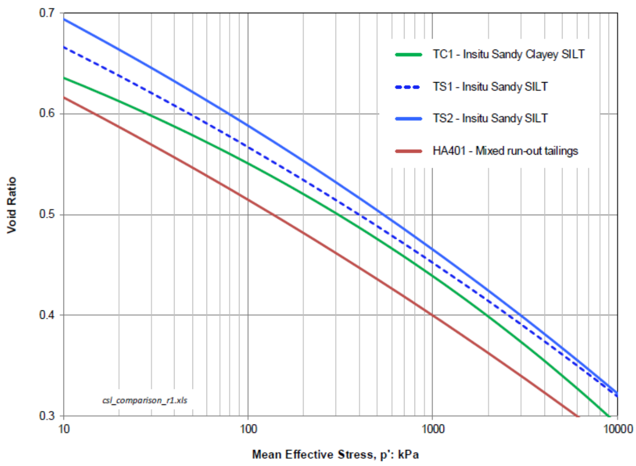


Figure 5-14: Comparison of CSL for NTSF tailings

The case-history approach started by Seed (1987) based in part on the Lower San Fernando Dam liquefaction slide, the approach directly relating s_r from assessment of the liquefaction slump geometry (sometimes including inertial adjustments, depending on the investigator) with pre-liquefaction penetration resistance.

Robertson (2010) presents what amount to the current evolution of this approach, figure below.

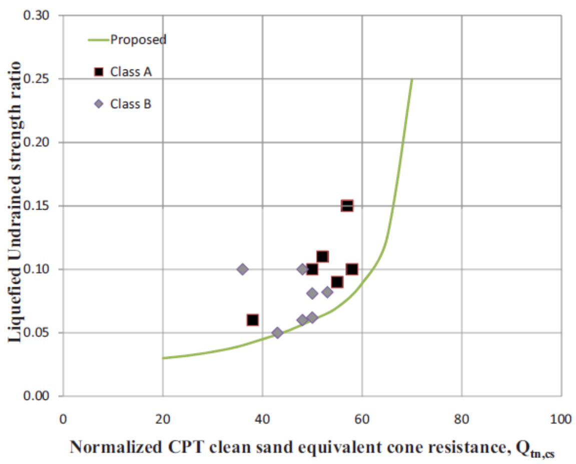
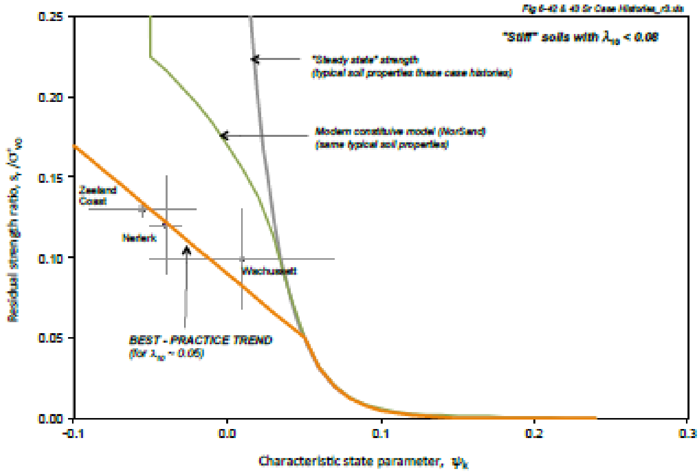
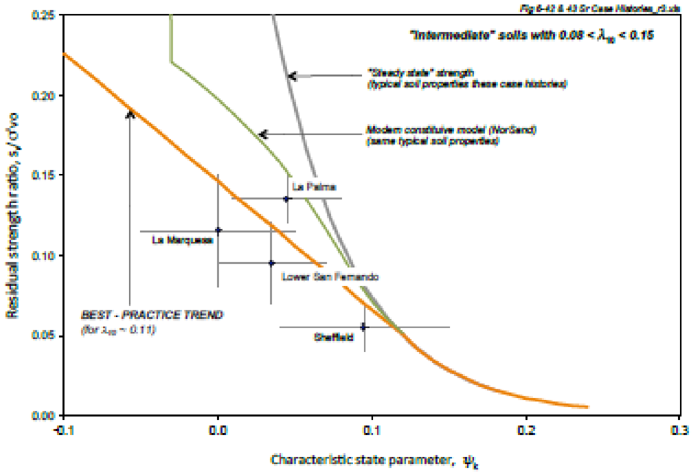


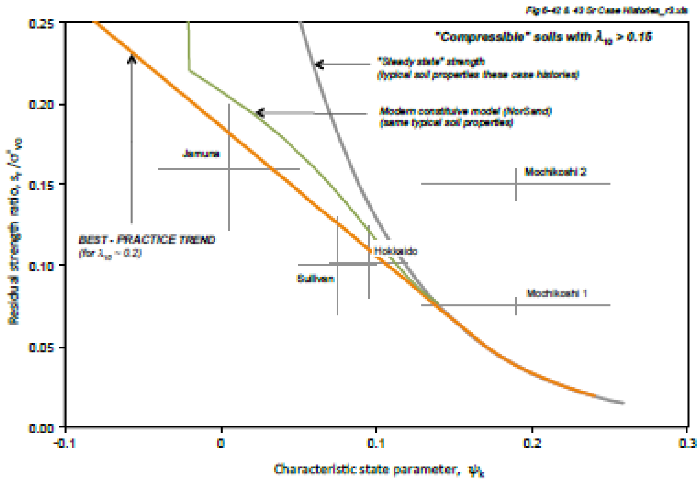
Fig. 7. Liquefied shear strength ratio and normalized CPT clean sand equivalent penetration resistance from Classes A and B flow liquefaction failure case histories

The 'strength ratio' plotted is s_r/σ'_{v0} so that there is a missed effect of K0; and, there is no role for M either although the data used is largely natural soils which commonly show M~1.27 and is thus an embedded constant (and which will be conservative when applied to tailings). The fundamental concern with this approach is the normalized CPT resistance $Q_{tn,cs}$. This normalization traces to constant relative density, and thus has a missed stress-level correction effect since state parameter (which drives post-liquefaction strength, [1] above) does not correspond to constant Dr. Further, the 'cs' factor applied in the normalization is somewhat mapping the soil property λ that appears in [1] but doing so based on 'soil behaviour type' – an averaging of properties that has considerable scatter. In effect, what we have with this approach is a "screening level" assessment of post-liquefaction strength.

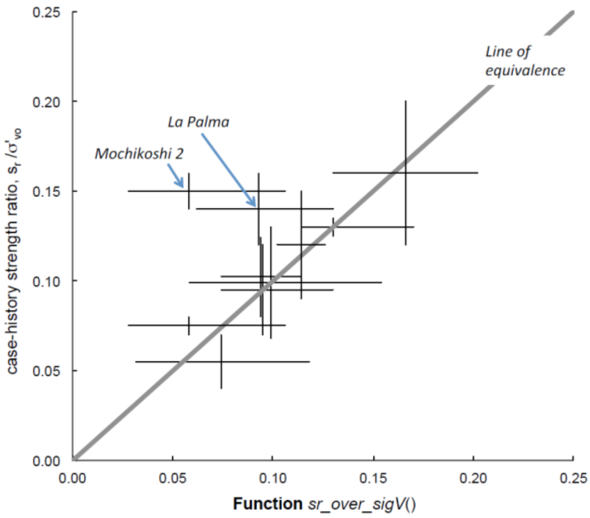
The use of this case-history experience can be more precise. The same case-history data can be presented in terms of ψ, λ with consistent trends, figure below. The uncertainty in each case-history is shown, but the middle point should not be presumed as the 'most likely' (or even the same as the single-points shown on Robertson's figure) as there is often opinions/analyses at each end of the uncertainty bar.



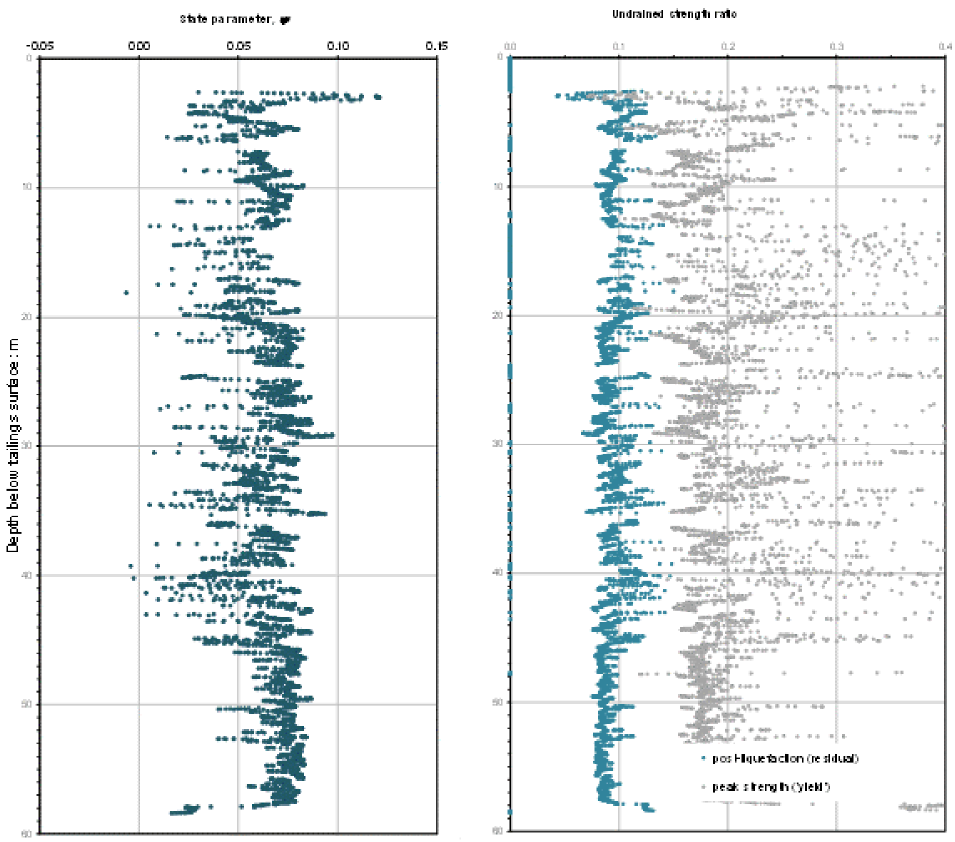




The best-fit trends, classified by compressibility (ie λ), shown above as the brown lines, can be integrated into a single function; the performance of that function in recovering the input data is shown on the figure below. Two tailings failures have conservative strength estimates, with all other case-histories recovered close to there central estimate and without bias.



Thus, the best approach to estimating s_r is to independently assess for the strata in question and then use the case-history data in terms of the relevant ψ_k, l. That is, do not use CPT data directly but rather fully assess the formation. A 'Class A' test of this approach can be seen at Cadia, with the function referred to above being used to compute s_r using the measured λ as shown below and at the location of a CPT that was in the zone of subsequent liquefaction. A reasonable characterization is $s_r/\sigma'_{v0} \approx 0.095$, possibly decreasing slightly with depth. The initial post-failure geometry is also shown below (it became a little flatter with multiple regressions over the subsequent two days); depending on your eye as to how you want to characterize the slump geometry (an overall toe-to-crest of about 7H:1V was suggested by the ITRB), this strength ratio is reasonably consistent.



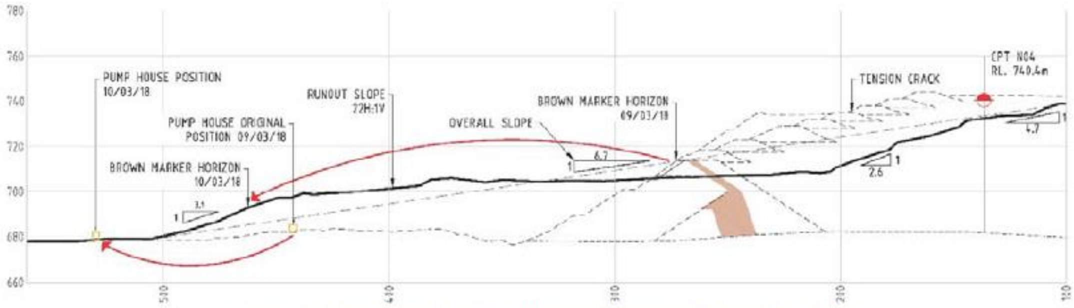


Figure 2-2: Annotated Section Through Slump on March 10, 2018

A kernel of the case-history approach is its use of limit equilibrium analyses. Different results are obtained if complete finite-element analyses are use. The liquefaction slump at Tar Island has been analysed using Plaxis/NorSand and the computed transition from drained conditions to undrained failure used all inputs as measured; this analysis gave near perfect match to the measured crest settlement and extent of liquefaction. Three 'marker points' in the liquefied tailings were tracked, A-C as shown below.

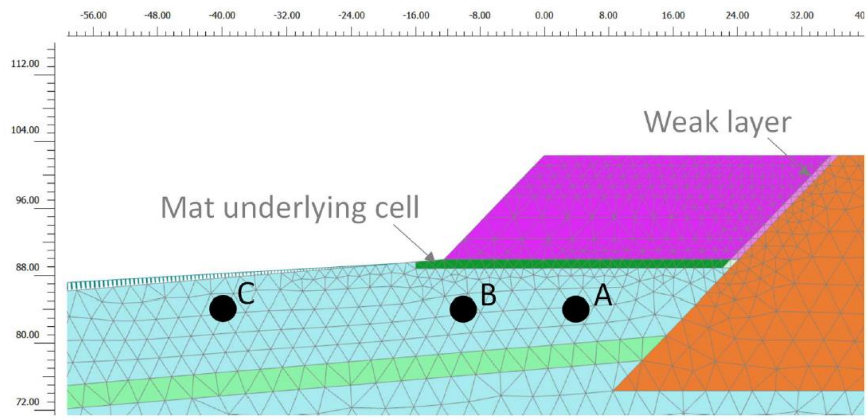


Figure 25: Finite element discretization in the vicinity of the slide with locations used for stress-paths

All three of the points A – C developed their critical state strengths during liquefaction, evident from the stress-strain curves at each location as shown on the figure below. But there is not a single post-collapse strength ratio because each location experienced differing amounts of 'shear-induced densification' during its drained loading as the cell was constructed. So, even though starting from the same assessed characteristic ψ_k in the greenfield condition, significant divergence developed in ψ between the three locations. Taking the mean effective stress p_{5a} at the end of constructing cell lift 5a as a normalizing stress, the post-liquefaction strength ratios realized were s_r/ p_{5a} = 0.101 at A (= mid-point beneath cell), a slightly larger s_r/ p_{5a} = 0.143 at B (= toe area, with most densification pre-collapse) and s_r/ p_{5a} = 0.042 at C (= a reasonable characterization of tailings still in the greenfield state)

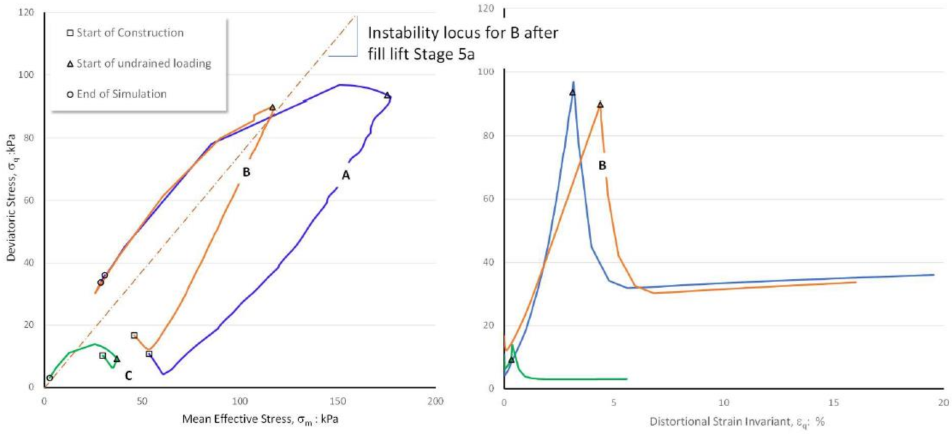


Figure 32: Stress-paths and tailings response at Points A – C (locations on Figure 25)

The corollary I draw from the Tar Island finite-element analysis is that most (all ?) of the confusion in the literature over s_r is a direct consequence of using limit equilibrium analysis. Limit equilibrium simply does not account for the effect of stress-path nor brittleness, and that leads to apparent operating strengths that do not reconcile with theory. But, if we allow for stress-path using full stress-analysis, theory works well with properties 'as measured'. Hence, I believe a switch from LE to FE is required.

2.4.- This question appears to be missing a more fundamental point: by the time a given liquefied soil strength is mobilised (the selection of which depends on the analysis being conducted), the entire process that may ultimately lead to the collapse of a Tailings Storage Facility (TSF) may have already started (i.e., the strength of a liquefied TSF geomaterial at large strains can only be mobilised after the geomaterial experiences and overcomes earlier key behavioural states such as undrained instability and/or phase transformation, whose deformation levels may be already sufficiently large to cause irreversible damage to the structure). Thus, a more crucial and perhaps more challenging question might be: which key soil states should be assessed (and how) in order to properly evaluate the true, strain dependent performance of a real TSF (and of all geomaterials associated with it)?

2.5.- Estimating undrained residual (post-liquefaction) shear strength ($S_{\_(u,r)}$) of a liquefied material, soil or tailings, which behaves as non-Newtonian fluid, whose viscosity decreases drastically with increasing shear strain rate, is still an unresolved issue. Current engineering design practice tries to overcome the uncertainty in assessing $S_{u,r}$ by the use of relationships established directly from field performance experience, which gives only rough estimates of $S_{u,r}$, and limits our ability to approach static liquefaction stability through total stress analysis. In summary, the undrained residual strength of saturated loose sand cannot be estimated with any degree of precision neither from laboratory or nor from field tests and consequently design cannot and should not be based on this quantity.

2.6.- Evaluation of possible occurrence of flow failure is rather difficult especially in engineering practice, since cause of the flow failure is not mechanical properties of tailing material (e.g. residual undrained strength of the material) alone but many factors including geometry of dams, stratifications of sedimentation, the drainage condition and stress distributions and earthquake motions. Slopes of soil which have sufficient residual undrained strength to sustain static driving shear stress occasionally flow long distance.

<u>Question 3</u>:

In an upstream dam with zones of potentially liquefiable tailings, what would be the most appropriate instrumentation to monitor the dam for preventing flow failure?

<u>Who think an instrumentation is useful</u>

3.1.- Pore-pressure development. Not in a single point but a row of pore pressure gauges in a row, from deep down to the top. This is to be done in several sections identified as critical. Movements and deflection of the dam. Gives a picture of strains and how these develop over time. If movements are too large additional supporting berms should be considered. Inclinometers or similar. Fibre optic cables. Any other equipment being accurate enough to give a picture of movements from surface and downwards. InSAR can sometimes be of some help. Static liquefaction is a strain related phenomena. Therefore, strains and movements are important.

3.2.- It will be better to measure pore pressures, through Vibrating Wire Piezometers

3.3.- Brumadinho had a reasonable array of instrumentation and none indicated impending failure. This is also the theoretical expectation. So, there is a basic problem with the Observational Method when dealing with liquefaction. That said, even though it may be a 'stiff/brittle' situation there are things that must be monitored. However, instrumentation cannot be specified without knowing and understanding triggers – and these likely differ from one dam to another. My great concern remains the foundation. Thus, it is not just the dam. For the foundation we need electronic piezometers with data loggers and displacement measurements (fibre optic ?). For the dam itself, also similar. Plus, easy-to-do movement markers.

None of these instruments will indicate 'safety' as absence of change from expected does not mean 'OK'; but, a change from expected will show the need for action.

What I have found striking is the satellite monitoring of displacement patterns. Although not used at the time, these measurements were recovered from archived data and clearly showed the developing problem at Cadia (which was in the foundation) a couple of months in advance. Given the low cost of satellite monitoring, at least when compared to liability, this kind of monitoring ought to be mandatory as it is just so easy to do and shows the whole situation. But, building on my answer to Q2, I believe we actually need to understand any dams stress-history and finite-element analysis will be needed for this. Which then leads me to a potential use of self-bored pressuremeter testing to supplement ubiquitous CPTu. Not 'instrumentation' as such, but rather needed analysis to help understand the expected behaviour and what might be diagnostic of an impending problem.

3.4.- Accurate pore pressure measurements using fast-response instruments are essential. Permanent tiltmeters (e.g. employing MEMS) where creeping materials in the dam body or foundations are expected.

3.5.- A wide array of distributed inclinometers and piezometers, monthly analysis on satellite imagery. CPT soundings every couple of months to monitor changes in properties.

3.6.- Monitoring and anticipating the brittle performance of structures is a challenge in civil engineering. Yet, dam instrumentation plays a fundamental role in understanding the foundation and structural performance during construction and operation, especially in controlling possible trigger liquefaction mechanisms. Radar and InSAR ground movement detections systems are options to be considered.

3.7.- As is well known, the phenomenon of soil liquefaction is strictly connected to the increase in pore pressure. This pressure must be kept under constant control in order to guarantee an adequate safety margin against the liquefaction phenomenon. In order to detect the pore pressure, piezometers equipped with transducers have been developed that allow to carry out continuous measurements of pressures, flows and the water level in the volume of interest. If a network of this type of piezometers is well designed and integrated with a sophisticated data processing system and forecasting models, it can be used to monitor the plant and, if necessary, to trigger a pre-alarm system to allow early evacuation of the areas which could suffer damage following a possible collapse of the structure. (Morton et al. 2008)

3.8.- Implementation of pore pressure sensor in liquefiable ground will be recommended for the most appropriate way. Then it is desirable that the stability study is conducted, estimating the excess pore pressure of the ground in large scale earthquake by using the observational data of pore pressure recorded during middle scale earthquake. In 1990, there is an observation project to instrument pore water pressure meters and seismometers at Veta del Aqua in Chile as international collaboration research of JICA, Japan International Cooperation Agency, and Pontifical Catholic University of Chile. An attached word document file of some photos of the project is for your information. Professor Troncoso possess the observational data.
Due to spreading of economical accelerometer in geotechnical engineering, measuring acceleration of ground surface will be expected as a cost-effective monitoring method to target on the whole ground behavior (Yamada et al, 2020). For instance, initial rigidity, and nonlinear behavior under cyclic loading will be evaluated if seismic ground response is obtained by measuring ground accelerations during small/ middle range of earthquake. Especially, in case of monitoring and evaluating stability of slope of tailings storage facility by effective stress analysis, if the analysis model is improved base on the observational data, there is a possibility to estimate the stability more accurately under

large-scale earthquake, In addition, measured acceleration will be compared with not only those of design earthquake waves also predicted acceleration response so that the record of ground response can be expected to one of index of real-time monitoring to fast safety judgement of the slope of tailings storage facility.

3.9.- The displacement and pore pressure within the zones of potentially liquefiable tailings should be monitored.

3.10.- If the conditions are such that liquefaction flow failure is possible, monitoring will be useless to prevent it, as there are conceivable scenarios in which catastrophic failure will be triggered without any meaningful reaction time. On the other hand, monitoring may be helpful to enforce a design that cannot conceivable lead to flow failure (see 1 above). Again, the long tem issue is one of maintenance and upkeep.

3.11.- Instrumentation cannot prevent flow failure. Instrumentation can provide indicators that a trigger mechanism capable of triggering flow failure may be present. Triggers may include sudden changes in pore pressure, excess pore pressure development over time or excessive strain, particularly where very brittle tailings are present that are susceptible to strain softening. Monitoring should employ an array of instruments which may include some of the following:
Standpipe piezometers to measure phreatic surface
Vibrating wire piezometers to measure pore pressure and estimate excess pore pressure
Total pressure cells in combination with vibrating wire piezometers to aid in the assessment of peak stress as a function of assessed credible failure plane
Survey monuments and/or possibly satellite movement monitoring as well as movement arrays/inclinometers, fibre optics (3D strain measurement)
Regular visual inspection for movement indicators (cracks, bulges, seepage etc....)

3.12.- Recent development of using InSAR ground movement detection (not good for surface movement in north-south direction due to the limitation of the satellite obit transverse, but vertical settlement can provide secondary evidence of impending surface movements) or on-site RADAR for ground movement detection system shall be able to provide early warning of preceding plastic deformation before the drastic collapse movement. Review of historical InSAR ground movements over the existing tailings dam facility will also be beneficial for planning of other conventional geotechnical instruments (piezometers, inclinometers, ground surface movement markers, etc) at strategic locations for effective reflection of the engineering responses as expected in the failure model.

3.13.- Instrumentation must be programmed and planned based on the expected behavior of the structure. Prior good quality numerical modeling with reliable constitutive models and geotechnical parameters provide a better understanding of the dam behavior. The instruments to be installed (dam massif, foundation and shoulders) must be preferably of vibrating wire, fiber optic or electric with automatic data acquisition and transmission, avoiding as much as possible manual measurements. Instrumentation should include surface marks, tassometers, piezometers, inclinometers (these rarely installed), radar and satellite displacement measurements of the dam face, seismic and microseismic measurements, in addition to flow measurements. The processing and submission of the measurements by the consulting company responsible for the dam behavior report must be carried out expeditiously so that a decision on the rate of the dam raising can be made in a timely manner.

3.14.- There is no perfect instrumentation to detect potential for flow failure. My opinion is to use periodically assess soil characteristic and monitoring displacement using radar satellites

Who think instrumentation is not useful

3.1.- To my knowledge there is no field instrumentation that could give on time indications that could prevent flow failure due to the brittle nature of strain softening soils as most of tailings and sand tailings are. There are some indirect methods through detailed satellite images that have been reported they are able to show very minor deformations on the surface of a tailings deposit that could give an indication of a condition that could anticipate a possible flow failure. But these methods as well as other geophysical methods are in a developing stage. In potentially liquefiable soils is important to accurate detect the saturated zone but also the zone above with saturation down to 80 -85%, where a continuity of the liquid phase could exist and pore water pressure could be generated as they would be full saturated, for both static and seismic/cyclic conditions

3.2.- There is not a unique perfect instrument to monitor for flow failure. One key aspect of flow failure is water and water should be kept low and a way to do it is to its a system of piezometers with redundancies.

3.3.- The most relevant probing tools for such analyses are the ones that can provide for a thorough understanding of the three-dimensional variation and distribution of geomaterials deposited within the TSF. Whether this most crucial goal can be achieved with CPT testing is a question that must be opened for debate, particularly if the reliability of CPT outputs is to be taken into account in a rigorous manner. Nevertheless, once this part of the site investigation programme is completed and fully validated by high-quality laboratory testing, this dataset can then be complemented by additional measurements of pore pressure, stiffness and/or inclination. There would be no point in having measurements of pore pressures and/or stiffness, for example, if there is uncertainty about what geomaterials they might be actually referring to.

3.4.- Instrumentation is of limited effectiveness in preventing the onset of liquefaction; however, typical design practice to prevent the development of a flow failure if liquefaction is triggered is to target a satisfactory factor of safety using post-liquefaction strengths. Piezometers are helpful in defining the existing water level in the dam so that factor of safety can be calculated. If a deformation analysis has identified specific stress paths of concern, such as an unloading stress path resulting from foundation displacements (similar to the mechanism at the Fundao Dam failure), inclinometers can be used to set limits associated with this; however, this would not want to be the primary design control because once the onset of liquefaction is identified, it will occur too quickly for the instrumentation to provide advanced warning."

3.5.- In order to keep the stability of tailing dams high, lowering the water level in dams is crucial. Ground water level affects the seismic stress ratio, the thickness of unsaturated cover layer which hold strength even after seismic cyclic shearing and resist to occur flow deformation of slopes. For dams with bottom drain system effectively working, water pressure may be lower than the hydrostatic pressure, especially near the bottom. This enhances the effective stress and thus, stability of the slope. Monitoring of ground water table as well as pore pressure distribution is believed to be important and effective.

3.6.- As evidenced by the past failures, the vast majority of the flow failure cannot be prevented by monitoring. If any, monitoring may be able to give a warning beforehand. We should focus more on the design of the dams and buttress, if required.

3.7.- A flow failure is a brittle failure that occurs suddenly, so any instrument will give information practically when the flow failure is occurring. In this sense, there is no instrument that can provide useful information on time.

<u>Question 4</u>:

Is it correct to evaluate the stability of tailings dams using limit equilibrium analysis? If so, what would be the acceptable factor of safety for static and pseudo-static conditions?

<u>Who think that it is correct</u>

4.1.- Yes. It depends on the loading curve (for Static) and for pseudo static, it will be needed to evaluate also more scenarios.

4.2.- Limit equilibrium analysis is a numerical tool that could be used to have a first idea on where you are in terms of safety, but the question is that you don´t have a good idea on how the deformations are being produced when static or seismic loads are applied. On the other hand, limit equilibrium is assuming constant factor of safety along the sliding surface, and liquefaction of a certain extremely weak layer could represent a trigger effect to induce liquefaction on nearby layers. Today I would say that, in dams with medium to high failure consequences I wouldn´t rely only on limit equilibrium analyses and numerical stress – strain analyses should be run in parallel. Careful analyses of the results with both methods should be carried out. Also, careful probabilistic analyses or sensitivity analyses should be considered with regard the shear strength of these soils, considering the variable nature of tailings because of differences on the characteristics of the ore that is being processed at any moment as well as the milling process that could change to improve metal recovery or the way the tailings are deposited. In critical cases the probability of failure should be estimated with detailed analyses considering the variability of different elements, soil strength, geometry, pore water pressure. I wouldn´t rely only on limit equilibrium. The value of acceptable FS would depend on how good and reliable the available information is and also what are the failure consequences. Maybe for a high consequences situation the decision should be not to build the dam or to require a higher FS that normally.
I don´t feel comfortable suggesting a factor of safety, but for the sake of discussion a FS>1.5 with respect peak strength and FS > 1.2 with respect residual strength could be reasonable as a reference, but I would run some numerical stress – strain analysis in parallel as well as a probabilistic or sensitivity analysis with regard soil characteristics.

4.3.- The only relevant LE calculation is at residual state: assuming residual undrained shear strength, check that FoS>1.0. LE calculations at peak strength add no value.

4.4.- Static under drained or undrained peak and post peak is reasonable, Factors of safety of 1.5, 1.5 and 1.2, respectively are reasonable. However, for pseudostatic will depend on the behavior of the materials involved under seismic conditions (prone to softening), but generally I would disagree, rather an a factor of safety I would prefer a performance based approach.

4.5.- Limit equilibrium analyses are an appropriate method; however, should not be applied to the peak strength with an aim of preventing liquefaction triggering. They should be used to evaluate the post liquefaction condition. An appropriate factor of safety of 1.1 to 1.3 should be applied to that conditions. Pseudo static methods of analysis are outdated and no longer relevant.

4.6.- Yes, it is correct, but not enough. The limit equilibrium analysis (LEA) must be performed with reliable geotechnical parameters of the materials involved, both from the dam massif and from the foundation. The concepts of ruin probability must also complement the analyses. The relevance of 3D analysis should also be evaluated, as should the use of non-circular/composite rupture surfaces. Failure modes such as piping and foundation failure should also be analyzed. As for the safety factor to be adopted, on the one hand, the available recommendations should be taken into account, for example, the values proposed by the Canadians of the CDA (2019) in tables 3-4 and 3-5 for static conditions (1.2 < FS < 1.5 depending on the loading condition) and seismic (pseudo-static FS > 1.0; post-earthquake FS > 1.2). On the other hand, LEA has as its inherent hypothesis the rigid-plastic behavior of the soils involved, so the numerical stress-strain analysis, to be discussed in the next item, is a natural complement. FS > FSmin is a necessary but not a sufficient condition. Stresses, strains, displacements and gradients must be evaluated, in addition to the FS, in order to gain a holistic view of the problem.

4.7.- Slope stability analysis should be performed to verify that all safety factors associated with the governing load cases of all possible modes of slope failure meet or exceed the minimum requirements of standards. However, it should be recognized that for strain softening materials, limit equilibrium calculates the ultimate limit state of the slope without providing assessment of the development of progressive failure in the structure and its foundation. Given to this limitation, results can be misleading, and the method should not be used alone. Minimum required factor of safety recommendations should comply with ANCOLD (2019)

4.8.- To evaluate the stability of a tailings dam, the limit equilibrium method can be adequate especially in a preliminary phase of the design also because more sophisticated numerical methods require a large number of data often obtainable only from tests on undisturbed soil samples which are difficult to obtain for materials not cohesive like those that comes from these structures. Also, materials involved are in some cases quite homogeneous and this would meet the assumptions of limit equilibrium methods. Establishing safety factors to assess the stability of this type of structures, perhaps starting from the back-analysis carried out on collapse cases that occurred in the past (Weber 2015), also in relation to different risk scenarios would be very useful but, it is also a delicate and difficult task to discussed also starting from the current national regulations.

4.9.- In Japan, based on design standard, which was defined in 1980, slip failure analysis method considering excess pore pressure and design seismic intensity has been conducted on seismic design. In which, the required safety factor for slip is set at 1.2. This method match for the safety evaluation during middlescale earthquake.

4.10.- Generally speaking, limit equilibrium method (LEM) is well established and can be used for most slope stability problems. However, for tailings dams experiencing undrained liquefaction and progressive failure, caution should be exercised when using the LEM.

4.11.- I think the limit equilibrium analysis is one of promising choices for the time being.

4.12.- I do not think “correct” is the right word. LE is not suitable to evaluate possible liquefaction triggers and cannot handle brittle failure. On the other hand, LE, with appropriate inputs, may be usefully employed to interpolate within a large experience gained by the profession and summarized in relevant codes. It may thus be employed as a screening method to evaluate alternatives and compare similar cases.

4.13.- Limit equilibrium analysis can be used if the residual undrained strength is used. Otherwise it may well be inappropriate. The acceptable FoS will depend on what is the adopted strength.

4.14.- I would say LE is useful, but in those cases where liquefiable soils exist, it is necessary to use the residual undrained resistance. In any case, this type of analysis should be seen as a reference data. Normally, static FoS greater than 1.5 is required and pseudo-static FoS greater or equal to 1.2 is adopted for the MCE. However, for these values of FoS the potential failure surfaces are accepted to compromise an important part of the tailings dam.

Who think that it is not correct

4.1.- No. Limit state analysis should just be carried out to get a first over-view of the design. Design has to be based upon methods where strains are considered. FEM and similar

4.2.- NO. And for several reasons. If we start from undrained analysis for initial failure (sometimes denoted as “yield” in the literature), how is that strength to be determined ? There are back-analyses indicting trends with penetration resistance but with large uncertainty, the uncertainty arising because two soil properties are more important to undrained strength than void ratio (which is what is being measured with the CPT): plastic hardening and elastic modulus.

Further, $s_u/s'_{v0} \approx 0.2$ as a lower-bound almost independent of how loose the fill is. Thus, a FS= 1.5 (say) will not distinguish between "minor slump" and "catastrophic liquefaction" because the difference between these two outcomes depends on brittleness; and, brittleness is not included or implied by FS. And then we have the situation where the foundation controls. If that foundation shows strain-softening and/or creep, this will not be captured in any limit equilibrium analysis. Such foundation movements caused Los Frailes, Mt Polley and Cadia. Of course, one can anticipate potential brittleness and seek to compensate by setting a higher target for FS. But, what quantitative guidance is there in doing this? Potts explored these issues for foundations in his Rankine lecture, and nearly all he discussed applies equally to analysis of tailings dams. Let me now invert the question. If we look at car design, aircraft design, even building design, none use the methods of 1950 today. So, why should geotechnical engineering? In part the answer to my inverted question is lack of experience, with so few published studies of case-histories using numerical analysis. One can find contributions from Imperial, Barcelona, Manchester, TU Delft but none have really come into wider acceptance – just look at EN 1977 which has zero guidance on the use of numerical methods and what might replace a factor of safety. So, what is an engineer of record to do ?
If I have any wish for the outcome of this TC221 initiative it is that it will advocate many more supporting studies to develop design protocols that reflect the stress-strain behaviour of the soils we deal with. In my view we are at least several years away from where we need to be as engineers.

4.3.- No, because limit equilibrium assumes that all the soil within the failure surface mobilizes its strength simultaneously, which is incorrect.

4.4.- No, limit equilibrium analysis is a highly inadequate and oversimplistic approach that trivialises the problem. TSF stability is a much more complex problem than any limit equilibrium method can handle (please see answer to Question 2 above). The use of limit equilibrium analysis also leads to the overlooking of much more crucial and important aspects of tailings behaviour such as their stiffness degradation or strength variation over time and space. These issues can only be properly assessed through a robust analysis of the boundary value problem of interest. Rigorous analysis of TSF may only be properly carried out following the 3-level approach outlined above in the answer to Question 1.

4.5.- Limit equilibrium analysis is a handful way to assess the stability of a slope. However, important structure such as tailings must use a more sophisticated approach such as a numerical analysis (stress – strain). As for an acceptable factor of safety, I would say we should emphasized more on other analysis rather than relies on only a FS static and pseudo-static.

4.6.- Assessment of the stability of tailings dams using limit equilibrium methods is suitable for specific situations, but more advanced techniques may be warranted. In static, pseudo static and post liquefaction conditions the Factor of Safety should not really be a single figure since it really should depend on the level of confidence in the data set that informs the analyses. Currently the standards generally appear to ignore this best practice approach. There may be merit in moving towards a partial factors approach similar to that developed by Eurocode 7 that would then take cognisance of this issue. I accept that partial factors are typically used in the pseudo static analyses.
Coming back to the early point, in some instances pseudo static analyses is not always the best approach, since the reduction in strength and resultant residual strength is not necessarily going to trigger flow, but rather lead to excessive deformation. Basic Static and psuedo static conditions assessed in limit equilibrium can provide a good screening tool for potential liquefaction triggers however, in the seismic condition and the post seismic condition it may be necessary to consider carrying out FE analyses to look at stress-strain development and deformation and the development of CSR for comparison with DCSS test results. This is more likely to be considered where liquefaction is considered a risk, but the materials behaviour in shear is not clear cut.

4.7.- As the development and practices of engineering analysis evolve, those traditional analytical methods have their merits in advancement of the practices. Safety margin is a reflection of the designer's confidence on the uncertainty in the accuracy of determining the strengths, geometry of the structures, environmental loadings, limitation of analytical models. It is difficult to have universal scheme of factor of safety to cover the wide range of uncertainty in the above factors if the designers make no effort in containing the variation and uncertainty due to inadequacy of investigation programme other than the inherent ground variability. With the potential of progressive failure, which is more prominent for huge geotechnical structure, it will have limitation in limit equilibrium stability analysis to evaluate the progressive more of failure in successive mode. Perhaps finite element method (FEM) or any other advanced numerical method with proper simulation of the constitutive models is more suitable for analysing the stability and to design the structures with clear failure mechanisms in minds.

<u>Question 5</u>:

Would you consider stress-strain analysis with appropriate constitute models a necessary requirement for design?

<u>Who think it is a necessary requirement</u>

5.1.- Yes

5.2.- YES, and for all the points discussed above. But, we need supporting studies showing examples of how this is to be done, we need to define what "safety" means in such analyses, and we need to move it all to codes of practice.

5.3.- For dams with medium to high failure consequences, I consider appropriate and necessary stress -strain analyses. I understand that most of commercially available numerical models can include for instance the NorSand constitute model that has been broadly used for strain softening soils. The experience with these models must be built. But in parallel I would run also limit equilibrium analyses.

5.4.- Yes, modelling of triggers should be mandatory for strain-softening tailings. Also, an approach I find useful is to go beyond "strain compatibility in LE" and perform "safety analyses" using finite elements, where the peak strength is reduced but the residual strength is kept constant, thus being compliant with FoS>1.5 at peak and FoS>1.0 at residual at the same time, see picture.

5.5.- Under certain conditions it should be for static conditions, but for seismic conditions it should be, particularly when the seismic scenario is the most likely to control.

5.6.- Yes. Considering the consequences of a failure, a full stress-strain analysis by experts should be required for design.

5.7.- Yes, but this in itself would not suffice. It is important to highlight here that Part (3) of answer to Question 1 above is an issue that can be as critical or perhaps more critical than Parts (1) and (2) of answer to Question 1. A stress-strain analysis that is underpinned by a low-quality tailings characterisation process that is not representative of the actual materials encountered in the TSF may be as inadequate as an overly simplistic limit equilibrium analysis (i.e., regardless of the apparent complexity and degree of sophistication of the stress-strain analysis selected).

5.8.- Stress-strain analyses using numerical methods with reliable constitutive models and geotechnical parameters are currently part of geotechnical design in the case of large projects. Classic elasto-plastic models, such as Cam-clay and Mohr-Coulomb (this one, if possible, adopting stress-dependent modulus – Janbu), available for decades in various commercial software programs are commonly used in these analyses. On the other hand, the experience with constitutive models representing the complex behavior of mining tailings, such as NorSand, is still relatively incipient, and the model has only recently been incorporated into these programs. Also of concern is the large number of NorSand parameters and the laborious effort involved in obtaining them. Importantly, NorSand has not shown yet the necessary robustness, presenting conceptual problems that practicing engineers are unaware of. A stress-strain analysis is considered appropriate as a desirable complement in the design of tailings dams under the following conditions: 1) provided that the constitutive models adopted (ideally from the Cam-clay or Mohr-Coulomb families mentioned above) are previously benchmarked by simulating laboratory tests carried out on the soils involved; 2) that the analyses be performed by engineers experienced in numerical modeling.

5.9.- With the potential to progressive failure, advanced numerical modelling for slope stability analysis should be performed to assist geotechnical design.

5.10.- For this type of structures it is not only important to verify the stability with respect to generalized collapse, but are also fundamental evaluations on the behavior such as the estimation of deformations which, even if small, could compromise functional systems of the facility, or drainages, or the increase in pore pressure which could lead to liquefaction of parts of the dam. This type of analysis can only be performed with numerical methods and adequate constitutive models. Unfortunately the materials involved have specific properties to which more common constitutive models are not applicable and thus they would need appropriate models specifically built and calibrated on laboratory test results.

5.11.- Yes the complete stress-strain analysis with appropriate constitute models is a more rigorous approach for the design, especially for the tailing dam that is subject to the complex material, loading and drainage conditions.

5.12.- Yes.

5.13.- Yes, if the material is susceptible to strength degradation.

5.14.-NorSand will be the more appropriate model since the model can mimic static and dynamic.

5.15.- Yes where appropriate, see above. Where such techniques are used we often consider 1D shake models first and then develop 2D models and in some instances where necessary 3D models.

5.16.- For detailed design of high hazardous structure, it is certainly worthwhile to promote the use of advanced constitutive models that have been well calibrated with the back-analyses of previous failure incidents. Usually the forensic investigation will provide evidences of the most probable failure mechanism rather than having limited failure mechanisms attached to the simple analytical model.

5.17.- Yes. Definitely. Today it is not possible to justify the non-use of numerical methods. Obviously, this requires both an adequate characterization of the materials involved in the stability and the use of constitutive models duly calibrated through tests and/or field measurements.

<u>Who think it is not required</u>

5.1.- Not all, only specific cases (definitely upstream construction TMFs).

5.2.- No. They can be useful for establishing conditions that could trigger liquefaction with an aim to set trigger-action-response plans (TARPs) to avoid that occurring; however, they should not be used as the primary means of design. They are a useful supplement to limit equilibrium analyses.

5.3.- Currently, in Japan, although most of mines have already stopped their operations, there are many existing upstream tailings storage facilities. So great demand to inspect and strengthen the tailing dams to keep those stability during earthquakes has existed. Then such inspections or application of indispensable improvement have been conducted for those tailings’ dams according to the standard which was filed in 1980. But three tailings dams received damages in the 2011 Tohoku earthquake. The magnitude of the 2011 Tohoku earthquake, Mw＝ 9.0, was so great that those damaged dams experienced stronger seismic motion than the design earthquake’s ones for their inspection based on the standard from 1980. By the way, most of Japanese seismic design codes for infrastructures was revised so as to apply 2 step considerations of level-1 earthquake motion and level-2 earthquake motion for the seismic design after the 1995 Kobe earthquake because strong seismic motion worked for the infrastructures in the Kobe earthquake. So, the inspection and improvement of tailings dams has been required for the level-2 earthquake consideration after the Tohoku earthquake. Because the slip failure safety factor method make it possible to evaluate the stability of the dams for the level-1 earthquake ground motion but impossible to do so for the level-2 earthquake motion, evaluation of the deformation for level-2 ground motion has been necessary. Subsequently, Professor Ishihara had simulated and reproduced the damage by applying the earthquake response analysis using stress-dilatancy model for the tailings dam which damaged in the Tohoku earthquake (Ishihara et al., 2015). It was an effective stress earthquake response analysis result considering liquefaction phenomena. There are other analysis programs like FLIP, LIQCA and so on as effective stress earthquake response analysis which can consider liquefaction, and such application have been used for the seismic design for infrastructures in Japan. However, the number of the application examples is few on the analysis of tailings dam and the internationally spreading of the methods is insufficient. It would be favorable to make SD-model type earthquake response analysis method easily apply for the international use on the stability evaluation of tailing dams. If necessary, Professor Ishihara could ask Professor Misko Cubrinovski to do the arrangement. On the other hand, responding to the damage in 2011 Tohoku earthquake, in the Ministry of Economy, Trade and Industry in Japan, technical committee was established. Some examples of the inspection methods against level-2 earthquake ground motion as one of committee's achievements were shown to the public. After that, the methods were applied for the inspections of twenty tailings dams on the real sites. An inspection method at that time which was Newmark method considering the influence of excess pore water pressure buildup as an easier method than effective stress earthquake response analysis method had been applied for the evaluation of the displacement due to the slip failure(Yasuda et al., 2017). This method is so simple that it is possible to create manual to apply the method internationally. As a further simple method, residual displacement evaluation method (i.e. ‘ALID’ developed in Japan) might be useful. This method, ALID, has been currently used in the displacement analysis of river dike and the countermeasures of the dikes have been studied on various sites in Japan.

5.4.- I feel it is rather difficult to decide parameters in constitutive models to appropriately estimate deformation of tailing dams. In order to determine many parameters in constitutive models, better understanding of soil behavior as well as experience in simulation using the models are important. I doubt that we have sufficient knowledge regarding mechanical behavior of variety of tailing materials. Accumulation of laboratory and field test data and verification of existing constitutive models are needed before implementing complicated stress-strain analysis in engineering practice.

<u>Question 6</u>:

Do you think it would be useful to write a technical document that addresses the stability of tailings dams built upstream, or on materials that may potentially lose strength?

<u>Who think it would be useful</u>

6.1.- I guess so.

6.2.- A guidance document for upstream dams, can be useful, compiling all the information regarding stability, seismic analysis, Tailings characterization, instrumentation requirements, trigger levels.

6.3.- Very much so, this is overdue as ICMM documents do not tell engineers 'how' to do what is being asked for under 'governance'. I also think it appropriate that a 'how' document comes from a 'professional' rather than a 'client' organization. BUT, see Q5: we need supporting studies.

6.4.- Certainly, I consider quite necessary for the TC221 to work on a written document on the issues of strain softening soils behavior, design of dams involving totally or partially strain softening soils and discussion of the meaning of FS determined by limit equilibrium when this type of soil is involved and a final discussion on requirements for safe design of tailings dams.

6.5.- Yes, definitively yes. The process, not just the product, will add value to our industry.

6.6.- 100%, it would help the community to understand what is the problem behind these materials.

6.7.- I would be more enthusiastic about the second option, which often times is unavoidable. I do believe that geotechnical engineers should push the industry to move away from upstream dams. A technical document would help with existing structures, but it would need to be carefully written as to not promote future construction of such containment structures.

6.8.- Yes, but such document would have to be innovative, consider the state-of-the-art in this topic (not just the state-of-the-practice), and should be based on sound methods of analyses that are underpinned by the 3-level approach that is outlined above in the answer to Question 1.

6.9.- Tailings dams built using the upstream technique exist in several countries and have the potential to lose strength. Despite the tendency to de-characterize these dams, their stability is a concern for their owners and for society in general. Therefore, the availability of a document that addresses the stability of these dams developed within the scope of TC211 would be extremely useful and important. There is a lack of guidelines specifically addressing design requirements for: (a) stress-strain analysis, which is in most cases a compilation of colored outputs; (b) definition of the pseudo-static factor kh = f(amax) to be used; (c) seismic design in intraplate regions such as Brazil, where although the seismic risk is low, it cannot be ignored. Further studies need to be developed to understand whether low-intensity earthquakes can induce liquefaction in tailings dam deposits and how these loads can be integrated into the design of dams built upstream.

6.10.- A technical document that reported the general characteristics, the problems related to these structures and the possible ways of dealing with them edited by experienced professionals would be of enormous support to the engineers and technicians who work with these structures. The document should contain an introductory part which describes the evolution and the necessity of these structures, their constructive and functional characteristics together with the impact they cause on the territory in which they are built. Then the issues related to their implementation and management should be reported including a database of past collapses with more in-depth descriptions of the most catastrophic and documented ones highlighting the mistakes made during the design or management phases. A chapter dedicated to monitoring the structure would also be fundamental, to be foreseen already in the design phase and to be integrated with the progress of technology and research. Finally, it would be desirable to have a part dedicated to the evaluation of the safety of the structure under various aspects, from stability to the risk of pollution of the surrounding area.

6.11.- Technical documents proposed in this question will be useful for not only newly constructed tailings dams but also the existing ones.

6.12.- Yes I think it is useful to write such a technical document that covers all the critical issues involved in the design of the upstream tailing dams.

6.13.- Yes.

6.14.- Certainly, some good guidance will be useful

6.15.- Yes. There are too many “tailings practitioners” who do not understand even the basics. We still see people who haven’t even considered undrained analyses, let alone have an appreciation for the nuances of liquefaction risk and critical state soil mechanics.

6.16.- Yes. All forms of documentary guidance and standards are important to align the best practices recognised in the geotechnical industry at current time. At the same time, updating of the direction of undergoing research projects for expected contribution for updating will also help the industry to have collective focus the intended developments for the betterment of the industry. One outstanding example is the Large Open Pit Project (https://www.lopproject.com/) with clear mission statement that produces many good guidelines for the valuable reference in the practicing industry.

6.17.- Yes. Because it is a difficult subject and it requires a high expertise about soil behavior, this document should be of great use to the profession.

Who think it would not be needed

6.1.- There are several documents already in development by ICOLD, ICMM, SME and others, so I don’t think this is needed.

6.2.- A technical document could be required only if there is a sense that it can enhance global practice, otherwise the committee can select key publications addressing specific issues.

6.3.- I believe there are many such documents out there. A practical guideline regarding proper soil investigation, laboratory testing and numerical modelling may be more useful, together with courses, webinars, and workshops, etc. The missing question is "What is required soil characterization program for site investigation and laboratory testing?" Currently there is too much emphasis on numerical modelling, while the adopted material characterisation technique does not provide sufficient definition of the parameters required for the modelling.

6.4.- I think the best way to communicate is by video or a picture. The final decision is often from the client (mining engineers, field engineers, so on). They often prefer watching a video or a picture than a thousand words.

OPINIONS, COMMENTS

A.- Let me present my opinion on tailings dams as follows (please forgive me if I don't provide the detailed answers to your specific questions).

It is well known that tailings impoundments are very complex systems, characterized by a large variety of physical and chemical phenomena. Available records indicate that most failures are due to embankment overtopping, inherent poor stability of the tailings dam and/or the foundation soils, piping or earthquakes. It follows that simple design rules (e.g. minimum safety factors) could be misleading.

With specific reference to tailings dams built with the upstream method, embankment stability is highly questionable and therefore the upstream method should be avoided if possible or at least implemented using particular care in both design and monitoring. In fact, for tailings dams built with the upstream method, embankment stability relies on the mud shear strength which in turn depends on the mud ability to settle and consolidate progressively, during reservoir filling, under the action of its own weight. This process could be simulated by proper laboratory experiments including a first step of sedimentation-consolidation, followed by a second step based on triaxial or simple shear testing. A third design step of dynamic triaxial testing would be required for tailings dams built in seismic regions, in order to check pore-pressure build up and assess liquefaction resistance in case of earthquakes.

Numerical modelling should be tailored in order to follow the construction and the post-construction sequence. Limit equilibrium analysis could eventually be applied (but only for static analysis) by introducing proper values of undrained and/or drained shear strength, selected by the above-mentioned experimental and numerical procedure.

Settlements and pore-pressures monitoring plus in situ testing (e.g. CPT) should finally be implemented during and after construction for checking the design assumptions.

I attach a paper presented in 2016 at the Silesian University of Gliwice in Poland (16th Conference of PhD Students of Faculties of Civil Engineering, May 5-6, 2016)

B.- don't have experience with the design of upstream tailing dams but in terms of item 3, (In an upstream dam with zones of potentially liquefiable tailings, what would be the most appropriate instrumentation to monitor the dam for preventing flow failure?), my comments as follows:

1. Rotational Failure Mechanisms. A similar approach to our early warning system solution for Network Rail earth embankments or cuttings can be adopted. High resolution

tilt sensors can be fixed to embedded stakes (or similar) in a grid pattern across the slope face to monitor for movement – translational or rotational. Generally, nothing just happens without warning and if you can detect the early warning signs in small trends of movement/tilt high resolution sensors, there usually is a sign that something is happening. The finer the resolution of the sensor, the quicker you are able to detect the changes in trend. These wireless sensors can be setup post construction of the dam.

2. Geotechnical Properties of the Dam. Soil moisture sensors (wireless) could be installed as the dam height is increased periodically. Other geotechnical sensors could also be installed that connect to wireless nodes (piezometers for example).

3. Physical Displacement. Optical displacement sensors placed at the dam crest could be used to check for lateral displacement (as long as could set up a fixed reference point outside any zone of influence and within 150m from sensor to determine if the dam is being deformed.

Note, all monitoring should be about first understanding normal behaviour throughout the year, to cover all seasonal variations and comparing against the design performance metrics. By looking for trends in the movement, soil moisture or changes in tilt is it then possible to interpret the magnitude of change from normal behaviour and quantity the change to the risk. The longer the time before monitoring is carried out, normal behaviour cannot be ascertained and you don’t know at which point of the asset life cycle degradation behaviour curve you are starting and the existing magnitude of performance degradation.

References of 11) Johann Facciorusso, Andrea Geppetti and Claudia Madiai

Martin, T. E., and E. C. McRoberts (1999), Some considerations in the stability analysis of upstream tailings dams, inProceedings of the SixthInternational Conference on Tailings and Mine Waste, vol. 99, pp. 287–302, A.A. Balkema, Rotterdam, Netherlands

Morton, Kym & Muresan, M.C. & Ramsden, E.. (2008). Importance of pore pressure monitoring in high walls. Journal- South African Institute of Mining and Metallurgy. 108. 661-667.

Poulos, S.J., Castro, G. and France, W. (1985a). “Liquefaction evaluation procedure.” Journal of Geotechnical Engineering, ASCE, 111(6), 772-792.

Seed, H.B. and de Alba, P. (1986). “Use of SPT and CPT tests for evaluating the liquefaction resistance of sands.” Proc., INSITU '86, ASCE Specialty Conference on Use of In Situ Testing in

Weber, J.P. (2015). “Engineering Evaluation of Post-Liquefaction Strength.” A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Engineering – Civil and Environmental Engineering in the Graduate Division of the University of California, Berkeley.

References of 12) Susumu Yasuda and Takemine Yamada

1) Ishihara, K., Ueno, K., Yamada, S., Yasuda, S. and Yoneoka, T.: Breach of a tailings dam in the 2011earthquake in Japan, Soil Dynamics and Earthquake Engineering, 68, 3–22, 2015.

2) Yasuda, S.: Soil investigations and soil tests required for seismic inspection of abandoned tailings dams in Japan, Proc. of the 6th I. C. on Geotechnical and Geophysical Site Characterization, 2021. (to be published)

3) Yamada, T., Hikita, T., Ichimura, T., Fujita, K., Umedara, M. And Seo, T.: Seismic response of tailings storage facility applied liquefaction mitigation, Proc. of the 7th ICEGE, pp.5697-5704, 2019.

4) Yasuda, S., Fukui, K., Kunimatsu, S., Okamura, M., Kiyota, T. and Koguchi, K.: Revised seismic design code for tailings dams and its application to existing dams in Japan, 16WCEE, Paper N° 934, 2017.

5) Yamada. T., Hikita, T., Ichimura, T. , Fujita, K., Umedera, M., Nakamura, T., Seo, T.: Evaluation of seismic behavior of upstream tailings storage facility applied liquefaction mitigation by wide-pitchlattice-pattern-walls type soil solidification, 17WCEE, Paper N° C000935, 2020.