Advantages of the concept of Pressuremeter Tests in Tailing Storage Facilities

Avantages du concept d'essais pressiométriques dans les installations de stockage de résidus

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ABSTRACT

Dams for holding the unwanted waste ('tailings') from the mining of minerals such as iron and copper are found world wide. They are significant structures which occasionally suffer catastrophic failure, at a rate an order of magnitude greater than conventional water retention dams. This is due in large part to their construction method, where the waste is itself deployed as a load bearing material. The pressuremeter test is an effective tool for assessing accurately the current state of stress of a tailings facility. Examples are given of how the measured field data can be manipulated to demonstrate liquefaction susceptibility, and also to demonstrate the effectiveness of ground improvement processes.

RESUME

Des barrages destinés à retenir les résidus miniers indésirables ('tailings') issus de l'exploitation de minéraux tels que le fer et le cuivre sont présents dans le monde entier. Ces structures importantes subissent parfois des défaillances catastrophiques, à un rythme bien supérieur à celui des barrages de rétention d'eau conventionnels. Cela est dû en grande partie à leur méthode de construction, où les résidus sont eux-mêmes utilisés comme matériau porteur. L'essai pressiométrique est un outil efficace pour évaluer avec précision l'état de contrainte actuel d'un parc à résidus miniers. Des exemples sont présentés illustrant la manière dont les données de terrain mesurées peuvent être manipulées pour démontrer la susceptibilité à la liquéfaction et l'efficacité des procédés d'amélioration des sols.

Keywords: Dams; Tailings; SBP; Liquefaction

1. Introduction

Mine tailings are the waste product of the mining process. The rock containing the ore has been crushed, sorted and usually chemically treated to extract the marketable minerals. The waste rock is ground to the size of coarse sand and is mixed with vast quantities of water to form a slurry. This is piped into a tailings pond (in practice, more of a lake). The larger grain size solids settle and also form 'tailings beaches' that become an essential barrier between the pond and the embankment. The siltier material ('slimes') lies below the pond. Over time the expectation is that evaporation will remove the water, resulting in a stable arrangement with mechanical properties improving with ageing. In practice, many failures occur long after a tailings disposal facility has been decommissioned.

The scale of these tailing storage facilities (TSF) can be staggering. The Syncrude Tailings Dam, impounding the Mildred Lake Settling Basin in Alberta, Canada, is reputed to be the world's largest man-made structure.

Typically, a TSF is placed in a high dam across a small gully (Figure 2) and can be over 250 metres high. Table 1 lists eight dams over 60 metres high that have failed in the last ten years. However failure rate correlates more closely to the volume of the impoundment. Most failures occur in structures less than 30 metres high (Azam and Li, 2010).

Figure 1. 180 m high tailings dam in Canada (East Tailings Dam at Copper Mountain)

There is no accurate assessment of the rate of failure, but suggestions are that about 0.1% suffer major collapse (more than 1% experience breaches of some kind). This is 10 times greater than the catastrophic failure rate for water retention dams. Tailings dams tend to be 'forever' structures because the material contained in the impoundment is frequently hazardous for the environment. The Mt Polley TSF collapse of 2014 released 134.1 tonnes of lead, 2.8 tonnes of cadmium and 2.1 tonnes of mercury into the ecosystem (Environment and Climate Change Canada, 2016).

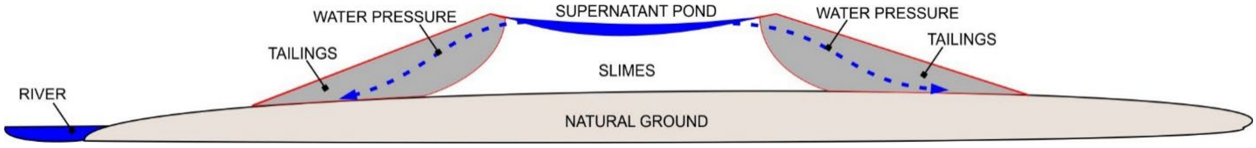

Figure 2. Cross-section of a typical tailings dam in a confined gully

In the worst cases there are significant fatalities. The Córrego do Feijão TSF (Brumadinho) in Brazil was 76 metres high when it collapsed in 2019, resulting in over 270 deaths. The TSF was initially built in 1976 by Ferteco Mineração and was acquired by Vale S.A in 2001. No tailings had been deposited in the facility since 2014.

This paper examines some of the physical processes that leads to these failures and how the likelihood of failure can be predicted.

1.1. Construction

Unlike water retention dams, tailings dams are constructed in stages over periods of time, and this is potentially a contributary factor in their higher failure rate. Fig.3 is a sketch of the most common arrangement, the upstream dam. Although increasingly deprecated as a construction method, even if no more dams of this kind were to be built, there would still be several thousand in existence whose potential for failure is currently unknown. As fig.2 indicates, the starter dam is fully supported by natural ground, but over time as the dam is raised, each new build becomes reliant on the mechanical properties of the tailings themselves. Indeed, each raise is likely to use coarse tailings as a constituent of the dam structure. The reason why 30 metres often coincides with failure is that this is the point of raising the embankment, and the imposition of significant strain on the underlying tailings.

It is critical to the integrity of any tailings dam that the separation of coarse material from slimes is carried out effectively. The propensity for failure (the Brumadinho dam is an example) is greatly increased when slimes appear in the tailings making up the embankment or in the material under the tailings beach (fig. 3).

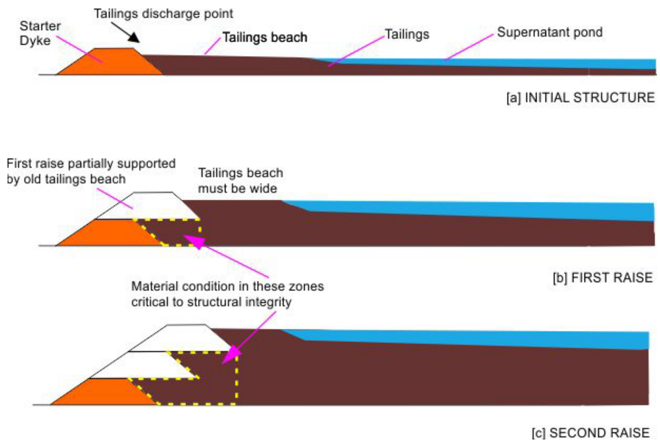

Figure 3. Sketch of upstream TSF construction

1.2. Testing for potential failure – historic

Tailings usually fail through liquefaction, the rapid reduction of effective strength that causes the material to behave as a fluid. This can be dynamic (seismic induced) or static.

Table 1. Tailings dams over 60m that have failed in the last ten years

YEAR	MINE & LOCATION	COMPANY	HEIGHT (metres)
2019	Brumadinho, Mina Córrego do Feijão, Minas Gerais, Brazil	Vale	87
2018	Cadia, New South Wales, Australia	Newcrest Mining	94
2017	Mishor Rotem, Israel	Israel Chemicals	60
2017	Highland Valley Copper, British Columbia, Canada	Teck Resources	140
2015	Fundao-Santarem (Germano), Minas Gerais, Brazil	Samarco	110
2014	Herculano Iron Mine, Itabirite, Minas Gerais, Brazil	MMX Mineração	62
2014	Mt Polley, BC, Canada	Imperial Metals	60

The measurement of the state of the tailings or fine sands to determine their density or compaction at depth is seen as difficult. Historically there have been at least three methods of testing these materials *insitu* to determine their liquefaction susceptibility. Bjerrum (1954) in Norway describes the use of the field vane; Seed (1979) in the US, the use of the Standard Penetration Test (SPT), and Robertson (1986) in Canada, the use of the Cone Penetrometer (CPT). These are all simple tests to perform and the data can be obtained repeatedly but the results have to be interpreted empirically. Figure 4 is a simple design chart, based on Seed ('79), that relates liquefaction susceptibility to dilation (derived from laboratory tests). This version is adapted from Vaide et al (1981). It has alternative scales for relative density and SPT blow count. In practice, due to the limitations of obtaining representative samples for the laboratory, this design chart is conservative and over-predicts the liquefaction risk.

All these insitu testing methods require that the devices be pushed or hammered into the material, the most invasive of all installation techniques. The CPT has a greater potential, but in practice provides only one parameter, the tip stress. In granular material such as tailings the CPT piezometer reads the hydrostatic pressure and the friction ratio remains constant (fig. 10). However if there is a more cohesive layer then the piezometer may show a response. Additionally, if a seismic CPT is deployed, then the maximum shear modulus can be obtained.

The Ménard Pressuremeter (MPM) developed in 1953 is potentially an attractive alternative. The instrument is placed in a pre-bored hole and hence is more difficult to use in the field than the pushed devices. Ménard argued that the MPM test provided data that could be used in any geotechnical design but the recommended interpretation to this day remains largely empirical. Nevertheless, because the test gives co-ordinates of volume change and stress it can be understood using the principles of mechanics (Gibson & Anderson, 1961). The difficulty for the MPM is the small number of data points and the resolution, diminishing the ability to determine stiffness.

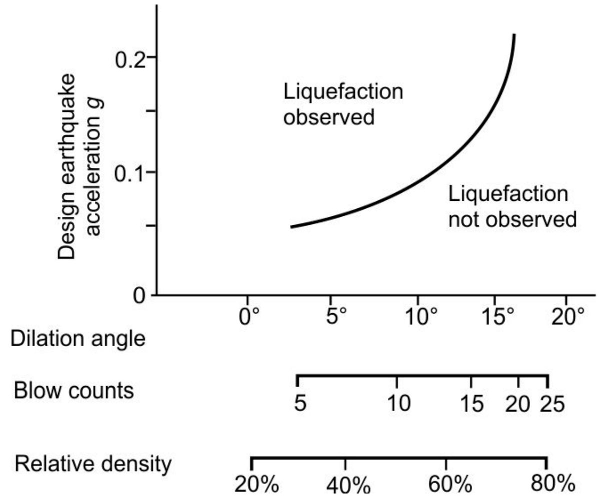

Figure 4. Liquefaction potential (*after* Seed, 1979)

Regardless of the significant limitations of these techniques, any of these would be better than what is normal practice for a TSF. Silva, Lambe, and Marr (2008, 2010) were brought in to investigate the TSF arrangements at Mt Polley and Copper Mountain. They report minimal testing of the tailings, except density tests at 3m from the surface. In addition, more than 50% of the piezometers installed to determine water levels were either inoperative or broken.

2. Self boring Pressuremeter test and interpretation

The MPM test is more often used in cohesive soils. By contrast, the Self-Boring Pressuremeter (SBP) was initially developed for use in granular materials such as beach sands and the interpretation of the data is fundamental. Hughes et al (1977) and Houlsby et al (1986) are solutions for cavity expansion and contraction respectively in a purely frictional material. Carter et al (1986) is a solution for the expansion case that includes for potential cohesion and the effect of elastic sand compressibility. These methods differentiate the field data curve obtained from the SBP test to calculate engineering parameters for strength, stiffness and the insitu state of stress. Unlike the MPM test, the SBP test is comprised of hundreds of coordinates of displacement and pressure (Fig. 5).

Every data point is a function of the same set of input parameters. This means the whole curve can be used numerically to determine the properties of the soil. Those properties will indicate whether the material is likely to increase in volume as it undergoes shearing, meaning that the material is stable. Alternatively, if when sheared to the yield condition the volume collapses, it is in a dangerous state, particularly if any excess fluid cannot escape.

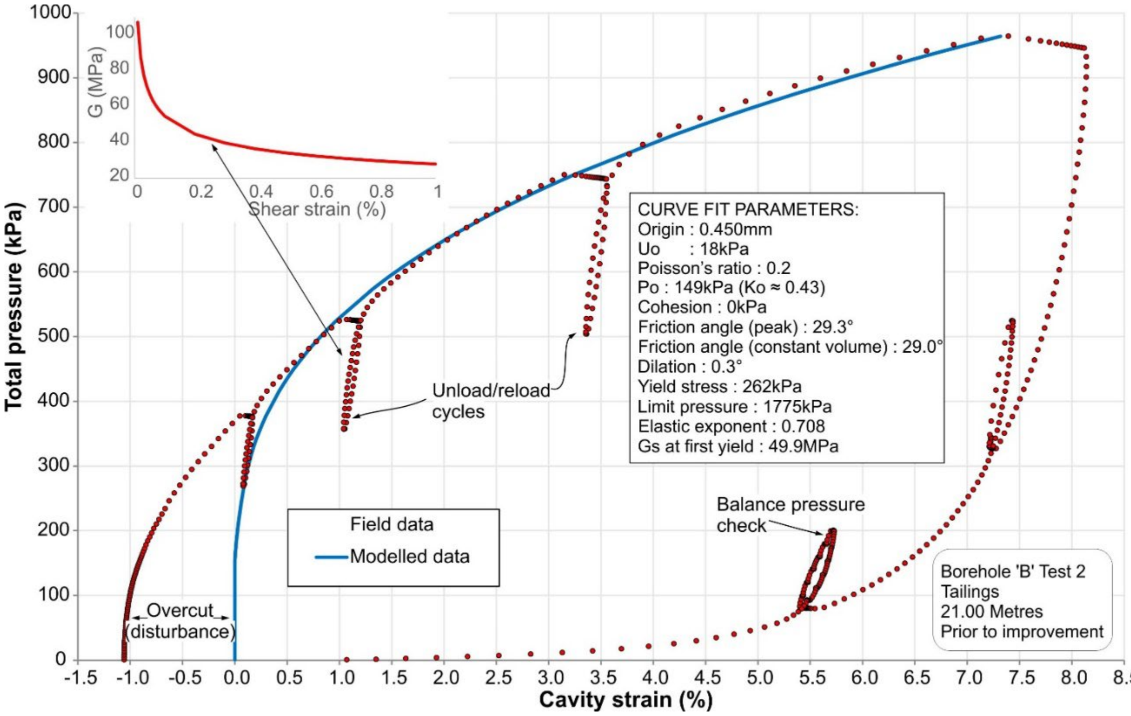

Figure 5. SBP test in tailings, as measured and curve modelled

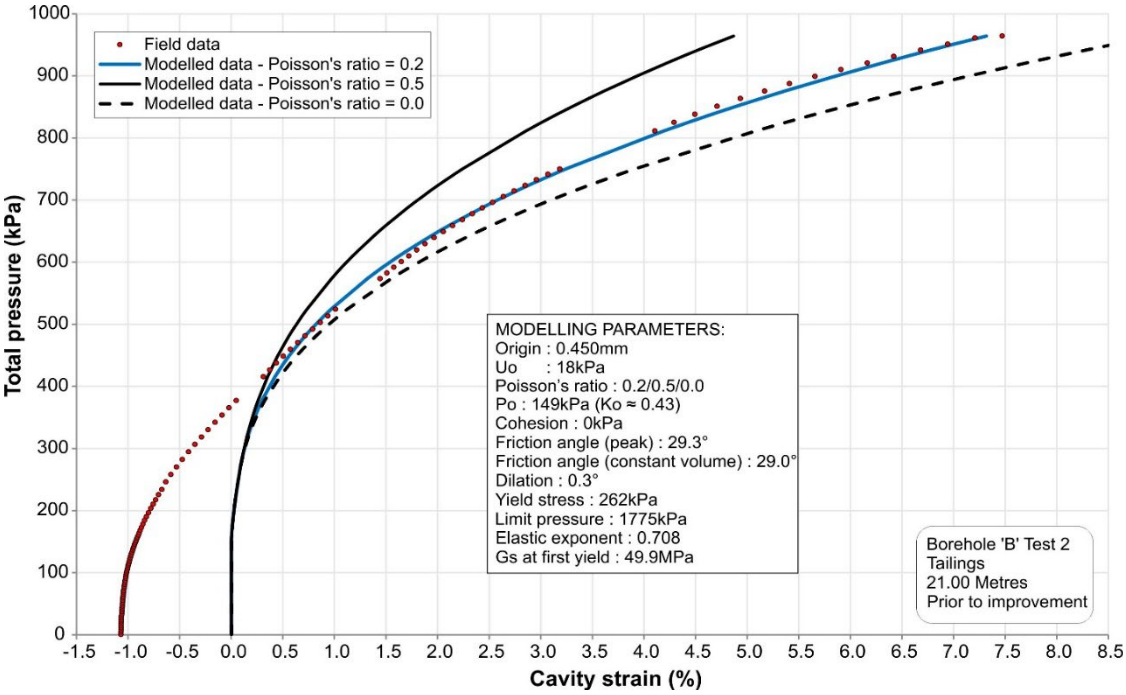

Figure 6. Potential for liquefaction, Hughes et al (1997) method

The standard SBP is fitted with opposing facing piezometers that move with the expanding surface and give the excess pore water, if any is generated.

It is possible to use iterative modelling to match the field data without knowing any of the input parameters but the resulting data set will not be unique. In practice analytical solutions are used in the first instance to provide initial input and to constrain the modelling. Their reliability in isolation is dependent on an assessment of the insertion disturbance. The exception is shear modulus from unload/reload cycles. Cycle 2 in fig.5 has been expanded and shows an accurate and repeatable description of the strain dependency of stiffness. This assessment of stiffness is a critical constraint on the modelling process – the only difficulty is identifying the yield strain and then reading the yielding value of modulus from the stiffness/strain curve. As fig.5 indicates, modelling also evaluates the early movement due to insertion disturbance. In this example the material has been over-cut a small amount whilst the probe was being self-bored into position (in this case, by jetting).

The model can be further constrained if the cavity reference pressure p_o can unambiguously be identified fig.5 shows a small reload/unload event towards the end of the cavity contraction, labelled 'balance pressure check' (BPC). This is a series of short pressure holds used to find the direction of creep. Above p_o, creep movement is outwards, below p_o creep movement is inwards. The null point is p_o (Hoopes and Hughes, 2014). For the test in fig.5, the BPC value is 152kPa, compared to the modelling value of 149kPa. Assuming p_o is representative of the total insitu lateral stress σ_{ho}, for this test the coefficient of earth pressure at rest, k_o is 0.43.

The result of the modelling is a collection of parameters that describe the initial state of stress, the shear modulus at yield, the internal angles of friction and dilation and the limit pressure, P_{lim}. The only one of these parameters with which the CPT tip stress or SPT blow-count might correlate is P_{lim}, but the constituent components of the P_{lim} estimates that they provide can only be derived through empirical relationships.

Fig.6 shows the same field data as fig.5 but edited for clarity. Because the constant volume friction angle ϕ_{cv} and the peak friction angle ϕ'_{pk} are almost the same, the procedure suggested by Hughes et al (1997) can be carried out. The optimum curve modelling curve is repeated, with additional curves that use alternative values for Poisson's ratio, ν. This approach is a simple illustration of the potential risk of liquefaction. If the field data plot above the lines given by $\nu = 0$ and $\nu = 0.5$, then the material is inherently stable. As the example indicates, potentially for these strata there is risk. In this context note that fig.5 shows a small amount of excess pore water pressure being generated at large strain. This simple visual representation of the relative position of the field pressuremeter curve to the constant volume pressure-expansion curve is equivalent to the concept of the state parameter.

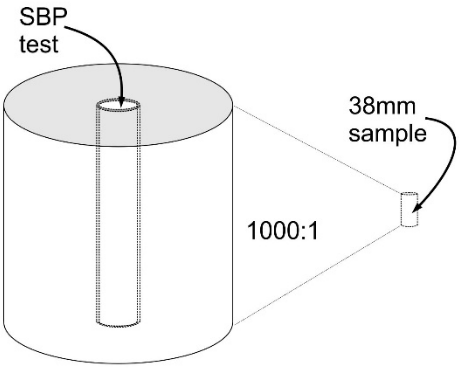

Figure 7. The difference in scale

Alternative models for the drained pressuremeter test have been developed (Roy, 1995, Morris et al, 1997) that make it possible more easily to relate the cavity expansion test to the triaxial test. These use finite difference techniques, but require additional information that the pressuremeter test itself does not measure. Unless the tailings samples for laboratory tests are obtained following ground freezing (as for the Canadian Liquefaction Experiment, CANLEX) it is unlikely that the soil fabric will be preserved well enough to make laboratory test results representative of the material behaviour insitu. There is also the importance of scale. Fig.7 shows a schematic of the volume of soil influencing an SBP test compared to a 38mm triaxial sample.

2.1. Inserting the Self boring Pressuremeter

In many ways tailings are the ideal material for the self boring method, being largely homogeneous with isotropic properties in the horizontal plane.

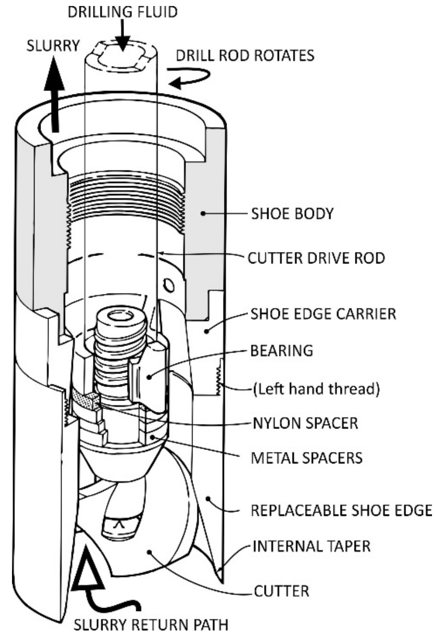

Figure .8. Drag bit

Reduction to a slurry for transport to the surface requires little effort. Fig.8 and fig.9 show two common methods that can be deployed. Of these, jetting is fast and

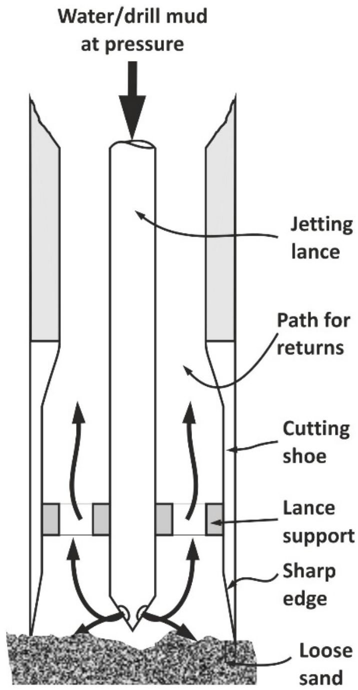

Figure 9. Jetting

easier to arrange (because rotation of the inner rod is not required) but possibly more prone to disturb the material. A jetting episode in tailings can take up to 20 minutes, but can also be less than 5 minutes. Whilst the probe insertion is taking place, the operator is monitoring the SBP piezometers and adjusts the insertion speed to keep the pore water pressure response constant. The need to avoid disturbance is always important but provided it stays close to or under the yield condition, then curve modelling will recover the true trend.

3. Ground remediation

This section examines two sequences of testing carried out in borehole 'B' and its vicinity, separated by two years.

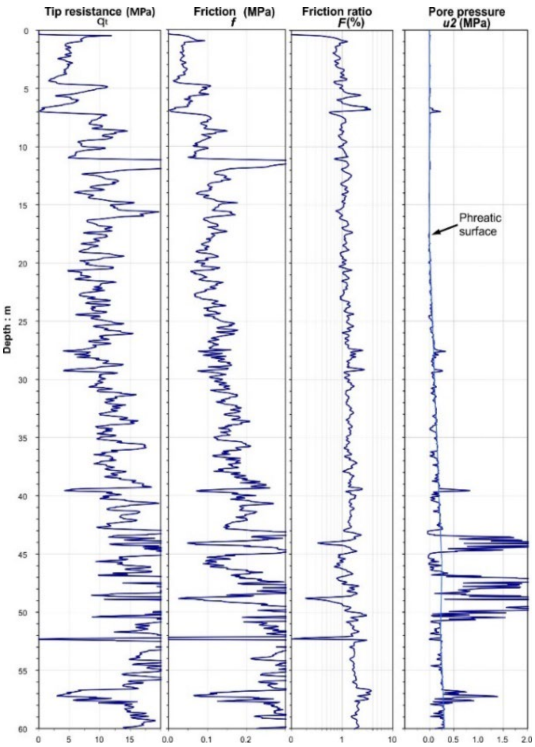

Figure .10. Pre-improvement CPT sounding adjacent to borehole 'B'

Fig.10 is the CPT sounding nearest to borehole 'B' (fig.5 and fig.6 show the SBP test at 21 metres). Fig.10 and fig.11 are the sub-yield and post-yield values from a series of SBP tests. Almost all the tests were self-bored by the jetting method.

The first series of tests carried out show that the tailings were then largely under-consolidated, particularly in the deeper material. The post-yield response indicates that the material is generally below the critical state, and so the volume will reduce when sheared.

In the following two years attempts were made to improve the engineering properties of the tailings, especially the insitu horizontal stress, using buttressing. The effects are apparent in the sub-yield data for the later tests. k_o is now in the normally consolidated range (over-consolidated at ≈ 28 metres), although still showing a reduction with depth.

In the post-yield data, there is almost no change of significance. The peak friction angle is slightly lower but that is because the constant volume friction angle ϕ_{cv}has also reduced. The earlier tests found that ϕ_{cv} was ≈ 30°, but two years later this had fallen to ≈ 28°, implying that the grain size of the tailings is becoming finer with time.

Although not plotted here, secant shear modulus for the same shear strain was also largely unaltered by the ground improvement.

The limit pressure values in the later tests are clearly higher, but that is due to the increase in the yield stress, a consequence of the improvement to the lateral confining stress. Essentially the limit pressure is the integration of the yield stress to infinite strain.

It is arguable whether the ground improvement has changed the liquefaction susceptibility. The improved confining stress will result in greater resistance to dynamic liquefaction, but static liquefaction is largely resisted by the strength properties of the material, which do not as yet seem to be greatly altered.

The understanding of the material gained from an SBP test with the knowledge of how it will behave when stressed is comparable only to a laboratory test. That approach is limited by the quality of the sample, and self-boring is considerable cheaper than ground freezing.

Each sequence of tests shown in fig.11 and fig.12 took about 2 site days.

4. Conclusions

A tailings dam does not necessarily fail because some of the material is liquifiable, but liquefaction amplifies the harm done when a failure event occurs. The purpose of this paper is to demonstrate that, using a moderately sophisticated but well-understood tool such as the self-boring pressuremeter, the liquefaction potential of the material in a tailings dam is a quantifiable risk. Testing can be carried out at any stage of a TSF development. Analyses that have been in existence for at least 40 years are ideally suited to producing the stress/strain properties of tailings.

The SBP is not the complete answer. The shear planes are vertical, therefore normal to the direction of material deposition. The closest corresponding laboratory stress path to this configuration will be a triaxial extension test.

A CPT is particularly effective at identifying stratigraphic variability and SBP testing can be targeted at strata of interest. Potentially, CPT site specific correlations could be developed from SBP results.

In the ideal case, a numerical model of a TSF would be calibrated against SBP tests and would be required to predict the SBP field curve.

Acknowledgements

The authors are grateful for permission to present data from Dam 'B'.

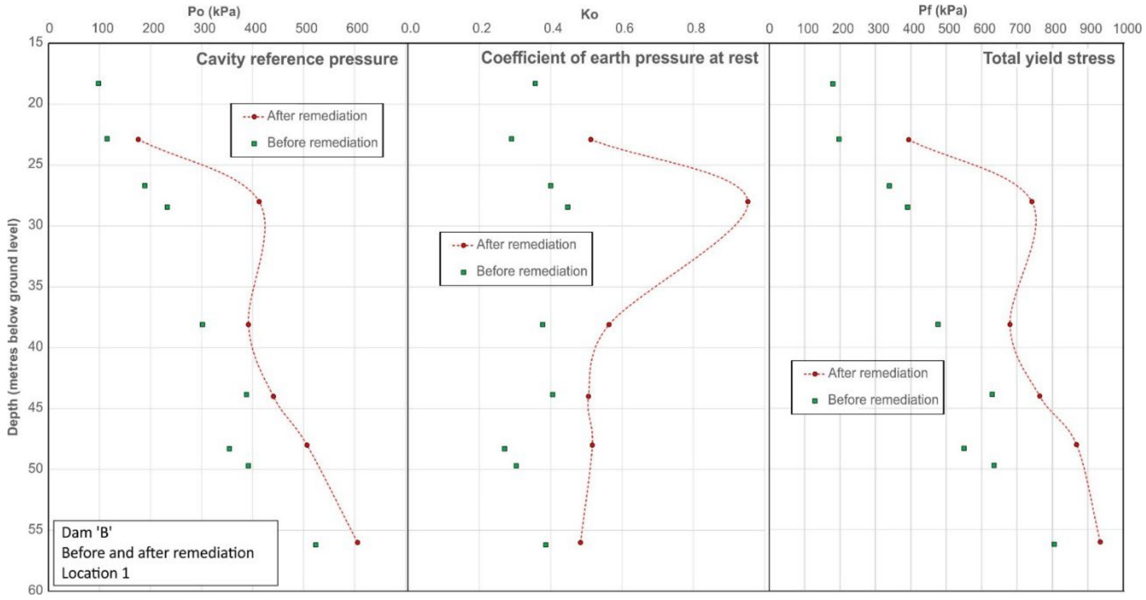

Figure .11. SBP results, sub-yield data, before and after remediation

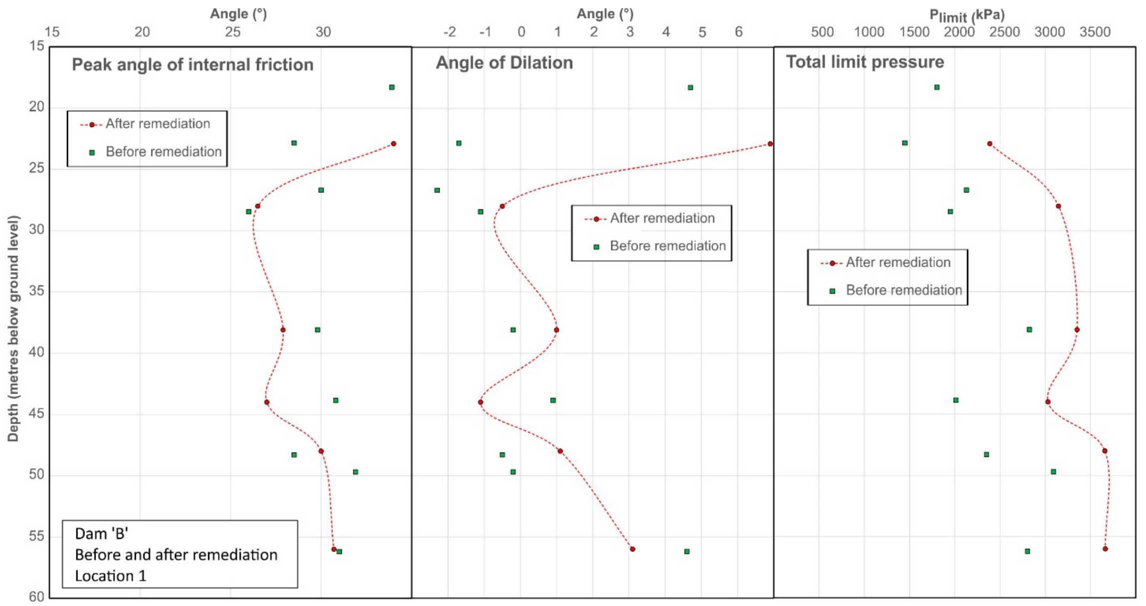

Figure .12. SBP results, post-yield data, before and after remediation

References

Azam, Shahad and Li, Qiren. 2010. "Tailings Dam Failures: A Review of the Last One Hundred Years (PDF).". Available at www.infomine.com.

Bjerrum , L. 1954. "Geotechnical properties of Norwegian marine clays".. Géotechnique, **4** (2), pp. 49-69. (also published in Norwegian Geotechnical Institute. Publ., 4).

Carter, J.P., Booker, J.P., and Yeung, S.K. 1986. "Cavity expansion in cohesive frictional soils". Géotechnique **36** (3), pp. 349-358.

Environment and Climate Change Canada. 2016. "Canadian Environmental Sustainability Indicators: Releases of Harmful Substances to the Environment". Consulted on March 25, 2025. Available at: www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=3C4C1124-1.

Gibson, R.E. and Anderson, W.F. 1961. "In situ measurement of soil properties with the pressuremeter", Civil Engineering and Public Works Review, Vol. 56, No. 658 May pp. 615-618.

Hoopes, O and Hughes, J.M.O. 2014. "In situ Lateral Stress Measurement in Glaciolacustrine Seattle Clay Using the Pressuremeter" . J. of Geotechnical and Geoenvironmental Engineering, **140** (5).

Houlsby, G.T., Clarke B.G. and Wroth P.C. 1986. "Analysis of the unloading of a pressuremeter test in sand". *The Pressuremeter and its Marine Applications: Second .International Symposium,* pp. 245-262.

Hughes, J.M.O., Wroth,C.P. and Windle, D. 1977. "Pressuremeter tests in sands". Géotechnique **27** (4), pp. 455-498.

Hughes, J.M.O., Campanella, R.G. and Roy, D. 1997. "A simple understanding of the liquefaction potential of sands from self-boring pressuremeter tests". *Proc. 14th Int. Conf. Soil Mech. & Found. Eng.,* Vol 1, pp. 515 – 518.

Morris, D.V., Debasis Roy, Hughes, J.M.O. 1997. "Liquefaction Resistance with Self-Boring Pressuremeter Testing." Unpublished paper, available from the Authors.

Robertson, P.K., Campanella, R.G., Gillespie, D. and Greig, J. 1986. "Use of Piezometer Cone Data". Proc. ASCE, In-Situ 86 Specialty Conference, Blacksburg, 23-25 June, pp. 1263-1280.

Robertson, P.K., Melo, L., Williams, D.J., Wilson, G.W. 2020. "Report of the Expert Panel on the Technical Causes of the Failure of Feijão Dam I". Available at: https://bdrb1investigationstacc.z15.web.core.windows.net/assets/Feijao-Dam-I-Expert-Panel-Report-ENG.pdf .

Seed, H.B. 1979. "Soil Liquefaction and Cyclic Mobility Evaluation for Level Ground during Earthquakes". J. of the Geotech. Engng Div., 105, pp. 201-255.

Silva, F., Lambe, T.W. and Marr, W.A. 2008. "Probability and risk of slope failure". J. Geotech. and Geoenviron. Engng, vol. 134, pp. 1691-1699.

Silva, F., Lambe, T.W. and Marr, W.A. 2010. *Closure to* "Probability and risk of slope failure": J J. Geotech. and Geoenviron. Engng,, vol. 136, pp. 769-771.

Vaid, Y. P., Byrne, P. M. & Hughes, J. M. O. 1981. "Dilation rate as a measure of liquefaction resistance of saturated granular materials". J. Geotech. Engng. Div. Am. Soc. Civ. Engrs 107, GT 7, pp. 1003-1008.