Collapsibility Screening for Tailings Dam Foundations Supported on Saprolite

Hafeez Baba & Ljiljana Josic
SNC-Lavalin Inc., Toronto, Ontario, Canada

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ABSTRACT
Tropical residual soils or saprolite are less understood than non-residual or normal soils and further their collapsibility potential is rarely explored. Saprolite profiles can extend from few to tens of meters. Where such soils form the tailings dam foundation special site investigation methods and techniques, and advanced laboratory testing are warranted. Some experiences of collapsibility screening of saprolite as a dam foundation which were subjected to major increase in stress regimes and hydraulic conditions are presented. Screening for collapsing nature of foundation saprolite during the site investigation phase is critical and important. Sampling procedures have been improved and laboratory testing procedures have been modified to address foundation design for large tailings dams with high loadings or significant dam heights. Some observations on stress-strain behaviors or yield patterns during high stress regimes are also presented.

RÉSUMÉ
Les sols résiduels tropicaux ou la saprolite sont moins compris et de plus leur potentiel d'effondrement est rarement exploré. Les profils de saprolite peuvent s'étendre de quelques mètres à des dizaines de mètres. Quand ils forment la fondation de la digue à résidus, des méthodes et techniques spéciales d'investigation du site et des tests de laboratoire avancés sont nécessaires. Quelques essais d'effondrement de la saprolite de la fondation d'un barrage ont été soumises à une augmentation importante des régimes de contraintes et des conditions hydrauliques. La détection de la nature effondrée de la saprolite de fondation durant la phase d'étude du site est critique et importante. Les procédures d'échantillonnage ont été améliorées et les procédures d'essai en laboratoire ont été modifiées pour tenir compte de la conception des fondations pour les grands barrages à résidus avec des charges élevées ou des hauteurs de barrage significatives. Certaines observations sur les comportements contrainte-déformation ou les modèles de rendement pendant des régimes de contraintes élevées sont également présentées.

1. INTRODUCTION

In tropical climatic conditions the bedrock is in a constant transformation into soil through a formation of active weathering profile. Weathering profiles can extend from few meters to tens of meters, often referred to as saprolite. These soils are in constant complex geochemical and geomechanical transformational processes. These can be considered as geologically young or recently altered deposits. Some of these weathering profiles are rich in minerals and are used as ore. Mining activities in the tropical regions are on increase, both for the hard rock and/or the weathered product above the bedrock. This is resulting in designing and construction of some high dams for mine tailings containment, and associated surface runoff management dams or water dams founded on the saprolite and/or built with saprolite. Some large-size waste rock piles are also founded on saprolite.

As a dam or waste rock pile foundation these soils are subjected to major increase in stress regime and/or hydraulic conditions (such as saturation, porewater pressures and hydraulic gradients) which may lead to collapse of its soil structure. Collapsible soils here are defined, in a broader concept in relation to the dam or waste rock pile foundation, as the soils which may become very compressible and weak in shear under either on saturation and/or pressure, and these pressure increases (porewater and effective stress) are relatively large in comparison with buildings and conventional municipal infrastructure.

Groundwater usually mimics the topography and often the saprolite is saturated in the valley bottom and partially saturated on the valley slopes. Intensive leaching for a prolonged period may create low density potentially collapsible structure.

This paper presents the nature of investigation required and observations there on. The data presented is based on literature review and from the site data collected from some large mining projects in central/south American and African regions where high stress regimes were applied. Figure 1 shows a photo of a saprolite profile in central America, where it is shown clearly manifestation of saprolite to maintain its intact rock structure yet is weaker than some normal soil deposits. Figure 2 shows a 2-year starter dam for a 30-year mine tailing facility in Africa as an illustration. This facility will be raised by few meters every 1 or 2 years.

Figure 1. Saprolite Soils Maintain the Intact Rock Structure – A Saprolite Excavation Profile at a Site in Panama

Figure 2. A 2-Year Starter Dam for a 30-year Mine Tailing Facility in Africa, as an Illustration of a Tailings Facility.

It is hoped that this paper will provide a better understanding of the geotechnical investigation processes undertaken to better define the fundamental behaviour of saprolite.

2. COLLAPSIBLE SOILS

The most common understanding of collapsible soils is that they are loose and unsaturated and undergo a large volume change upon saturation primarily under its own weight, like thawing of ice-rich frozen soils under its own weight. Both these scenarios are explained with a typical void ratio v/s pressure curve including this critical and transition phase of either saturation or melting as shown in Figure 3. Alternative, to void ratio, the y-axis could be expressed as strain. The larger the strain is observed, the more collapsible or more thaw sensitive the soil formation is. Classic examples of collapsing soils are aeolian soils that are wind deposited sand and/or silts such as loess or volcanic dust deposit. These deposits have high void ratio and low unit weights and are cohesionless or slightly cohesive. These have an open packing structure, and which forms a metastable state that can collapse to form a closer packing and more stable structure of significantly reduced volume.

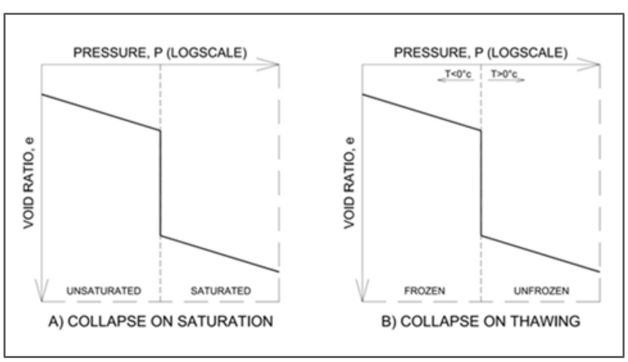

Figure 3. Typical Void Ratio v/s Pressure Curve for a) Unsaturated Soils Subjected to Saturation and b) Frozen Ice-rich Soils Subjected to Thawing

In the context of saprolite as tailings dam or water dam or waste rock pile foundation, in addition to saturation, these may be subjected to high stress regime. These soils may or may not be saturated initially but may become very compressible and weak in shear under either saturation and/or pressure increase and may exhibit collapse type behaviour. Hence identification of collapsing nature of foundation saprolite during the site investigation phase is critical and important.

Saprolite are also used as construction material for dams and are also subjected to saturation and pressure increase. This paper is limited to the screening for dam and waste rock pile foundation only and the screening for saprolite used for dam construction will be presented in a separate paper in future. Also collapse screening of saprolite under dynamic loading conditions is not covered here.

Other situations have also been grouped under collapsing soils such as plastic and fully saturated sensitive clays of Scandinavia and eastern Canada. Some have included liquefaction induced collapse manifestation as collapsing soils, however, these are not discussed here either.

In case of saprolite soil the microfabric plays a great role both its variability and behaviour and so does the presence of soluble and leachable constituents within the soil profile. Given the size and importance of the mine tailings and waste rock facilities, more advanced approaches to define collapsibility are emerging based on critical state and soil liquefaction understandings.

3. INVESTIGATION METHODS

3.1 Sampling Methods

Undisturbed and large-size samples of high quality from saprolite profiles are required for conducting compressibility and strength testing in the laboratory simulating the existing and anticipated loading and hydraulic conditions. Figure 4 presents a photo collage of some typical sampling and testing conditions. In addition to conventional sampling methods more advanced sampling methods have been successfully attempted which include block sample (See Fig. 4a); Mazier sample (See Fig. 4b); and thick-walled Shelby tube sample. Authors of this paper have attempted quality sampling of saprolite with all these sampling methods in the general tropics and had varying degrees of success. All the sampling and handling procedures need to be undertaken with the utmost care to preserve the natural structure of the saprolite, moisture conditions and stress regime.

Sampling, testing program and the logistics associated with it, must be properly planned and coordinated including packing to protect these from moisture change and disturbances, storage in environmental spaces, and shipment of samples usually trans-continental are some challenges. Despite attempting all the best practices and precautions at all phases of investigation and testing, yet there will be still shortcoming in sampling, packaging, handling, and testing to include sample relict or structures, the homogeneity of the ground and in situ stress and hydraulic regimes.

3.2 In situ Testing

In additional to conventional in situ tests such as standard penetration test (SPT), dynamic cone penetration test (DCP), shear vane tests (SVT) more advanced methods such as cone penetration test (CPT), shear box test, plate load test, pressuremeter test and dilatometer test are also becoming popular for investigation of saprolite profiles.

3.3 Laboratory Investigations

Laboratory investigations included standard index tests, consolidation, shear strength tests (UCS, Triaxial UU & CU, CID (See Figure 4c – sample condition after TxUU test, static and cyclic simple shear test (SDD & CDD) – see a typical simple shear test set up in Figure 4d).

Figure 4. Typical Sampling and Testing Conditions a) Preparation for Block Sample b) Mazier Sample c) Triaxial sample post Tx UU Test and d) A Simple Shear Setup

3.4 Mineralogy

The qualitative mineralogical analysis is carried out using X-ray diffraction (XRD) technique to explore the collapse mechanism of the saprolite, depending on the amount or specific clay minerals. XRD can be performed on air dried pulverized bulk samples and XRD traces on < 2 µm fines in water-wet and heated conditions. Check on soluble and leachable cations and anions by Induction Coupled Plasma Optical Emission Spectrometry (ICP-OES) analysis is performed on soil wash produced either with distilled water rinse or a sodium acetate solution (acid bath) to assess leachable component.

3.5 Collapsibility Tests

These tests include single oedometer collapse test; collapse potential test; double oedometer collapse test; long period consolidation test and modified plate load test. Collapse potential test is the most popular test among these tests to assess collapse potential.

4. CHARACTERISTICS OF SAPROLITE

The weathering process produces soils with a wide range of index properties including SPT N-values, particle-size distribution, moisture content (including Atterberg limits), unit weights and permeability. This variability is illustrated with the presentation of some relevant data profiles from a site in Panama as Figures 5 to 8.

Soluble and colloidal materials are leached out by weathering, resulting in large void ratios. The fabric of these soils generally takes the form of loose skeleton of grains and thus may form an unstable structure. Saprolite predominantly consist of silt to sand size particles and have usually high void ratios and relatively low dry density. Stress and saturation time histories are essential in understating whether a collapse behaviour will exhibit or not.

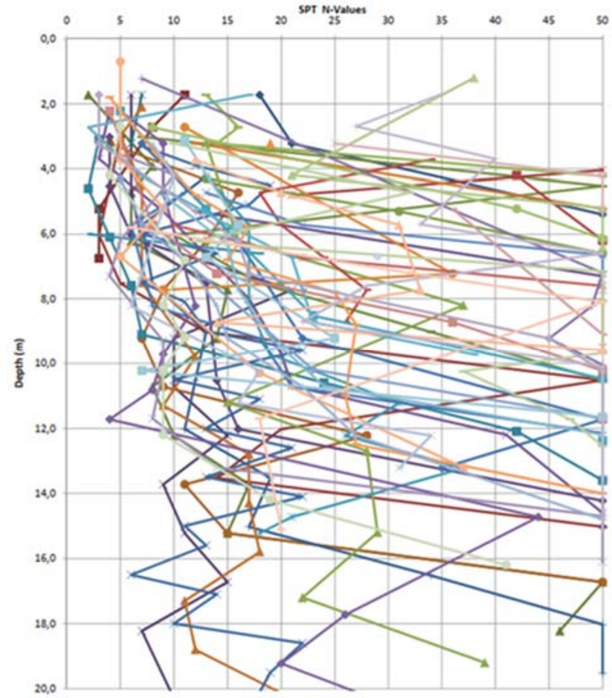

Figure 5. Variability of SPT N-values Profiles

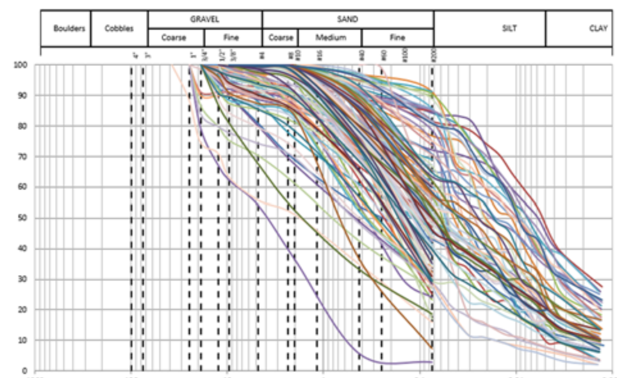

Figure 6. Variabilities of Saprolite Particle Size Gradations

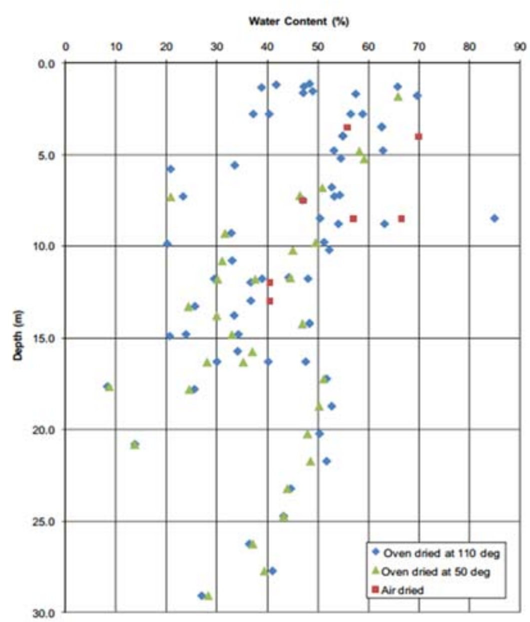

Figure 7. Variabilities of Moisture Contents of Saprolite Profile

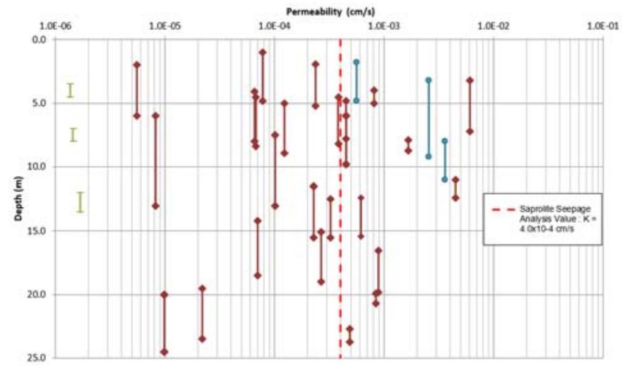

Figure 8. Variabilities of Permeability of Saprolite Profile

5. COLLAPSIBILITY SCREENING

Screening is generally qualitative to identify if a soil is potentially collapsible or not, and it may lead to estimate settlement due to collapse. Several researchers have attempted to predict collapse as a function of material characteristics and developed pre-screening criteria. These pre-screenings methods are based on correlations with the index properties such as: particle size distribution (The Water Authority of Western Australia 1990); liquid limit and plasticity index (Dudley 1970); liquid limit and dry density (Gibb and Bara 1962); Atterberg limits, saturation, and natural moisture content (Feda 1966); and dry density (Clevenger 1985).

The more direct methods of assessing the magnitude of settlement are often referred to as quantitative screening. These screenings are based on laboratory or in situ testing and include single oedometer collapse test; Collapse Potential Test (Jennings and Knight 1975 and ASTM D 5333); double oedometer collapse test; and modified in situ plate load test.

These are primarily compression tests and compressibility are by far the most used and accepted means to assess the collapsibility of foundation saprolite soils. Saprolite soils at their natural moisture content can withstand a larger applied vertical stress with small compression but may exhibit much large settlement upon wetting with no increase in vertical stress or a saturated sample may exhibit strain softening at high stresses. Compressibility behaviour observations from a series of compressibility tests are used for quantification of collapse or for screening of collapse potential and design for it. These tests are further briefly discussed below.

5.1 Collapse Potential Test

Conventional one-dimensional consolidation test is used to determine the magnitude of one-dimensional collapse that occurs when unsaturated soils are inundated with fluid. ASTM D5333 describes the test method and determination of Collapse Index Ic or collapse potential (relative magnitude of soil collapse) which is used for rating the potential collapsibility. Collapse index is defined as collapse potential at 200 kPa and inundation with water, as shown in Figure 3a. However, actual groundwater can be used to represent any geochemistry impact. This forms the basic index property in screening collapse potential that is comparable to thaw strain. The collapse index criteria as a collapse screening are shown in Table 1. 200 kPa loading represents typical foundation bearing pressures and the test is used to predict the foundation deformation that may take place upon subsurface wettings; a loading to the anticipated field loading condition is recommended.

Table 1. Classification of Collapse Index

Degree of Specimen Collapse	Collapse Index Ic, %
None	0
Slight	0.1 to 2.0
Moderate	2.1 to 6.0
Moderately Severe	6.1 to 10.0
Severe	>10

A typical collapse test curve is shown in Figure 9 and from that tests a profile of Ic can be generated together with other index property profiles for soil classification as shown in Figure 10.

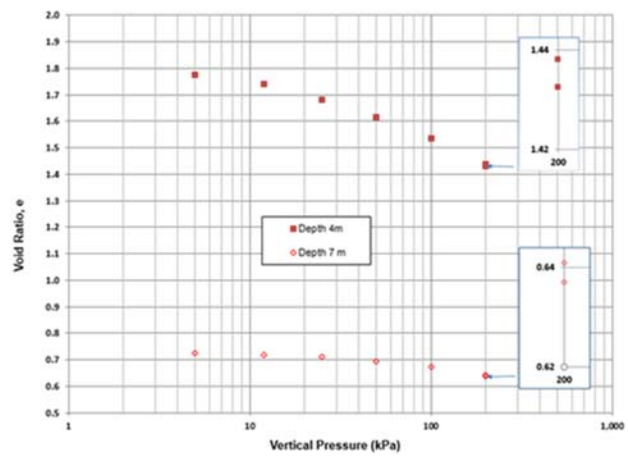

Figure 9. Typical Collapse Test Results for Saprolite

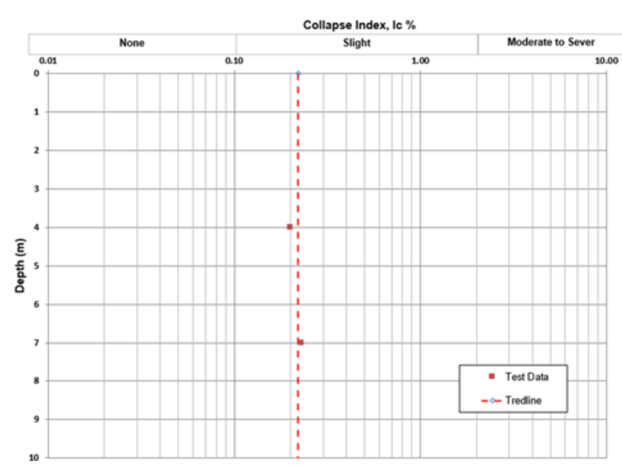

Figure 10. Typical Collapse Index Profile for Saprolite

This investigation did not indicate any serious concern of collapsibility in saprolite for that project. Similar observations were noted at similar depths in Brazil by Pinheiro et al (2008) using in situ CPT before and after wetting, however no external stresses were applied. Some collapsibility concern was identified at shallow depths.

5.2 High Pressure Consolidation Test

Wesley 2010, recommended using in linear pressure scale and not log scale to predict if a strain softening behaviour exits under high stress range, see Figure 11.

From a project site in central America, 8 consolidations tests carried out on a saprolite profile are presented in accordance with Wesley format in the Figure 12

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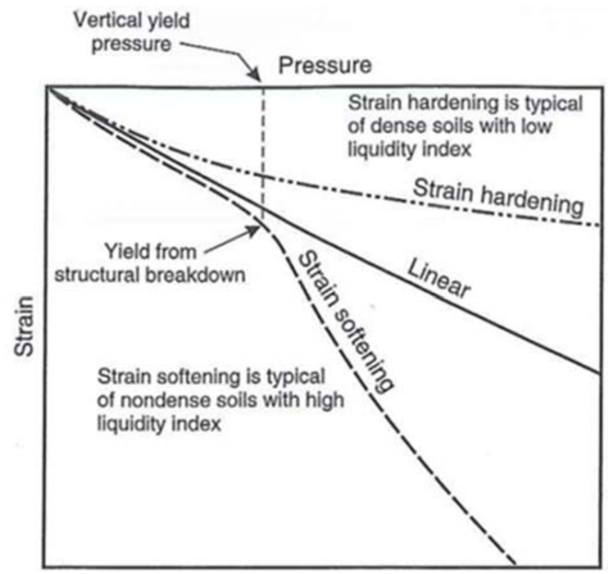

Figure 11. A Conceptual Illustration Compressibility Behaviour after Wesley (2010)

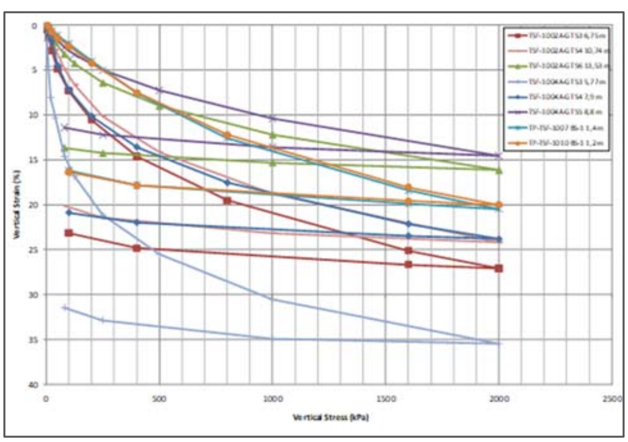

Figure 12. High pressure consolidation test Results on a Saprolite Profile

Wesley (2010) pointed out that soils with low liquidity index generally show strain hardening behavior without a distinct yield pressure. The behavior observed during testing and the average liquid limit of 37% measured are in good agreement with the literature. The initial void ratio of all tested samples is relatively high and is reflected in the cumulative vertical strain obtained following testing, which varies from about 15 to 35% at a vertical effective stress of 2,000 kPa.

5.3 Double Consolidation Test

Principally routine consolidations tests are conducted on two undisturbed similar samples: One is carried out with inundation by water (soaked - conventional odometer test); and the other is carried out at natural moisture content without flooding. The e-log p curves generated can be used for estimating settlements corresponding to an applied pressure both due to without change of natural moisture content and due to soil soaking under applied load remains constant. Clemence and Finbarr (1981) presents the double consolidation test procedure and method of estimating the settlement corresponding to applied load arising from both under natural moisture content and inundation.

5.4 Long Period Consolidation Test

Fonseca (2003) reported that primary consolidations are generally negligible, problems may arise in long term loading situations. Therefore, the importance of secondary compression, and generally creep, of this soil is being analysed by testing in one dimensional consolidation setup conditions over a long period of time at different loading levels. Figure 13 illustrates a typical result on a saprolite sample under long term loading conditions. It indicates long term settlement or creep needs to be considered.

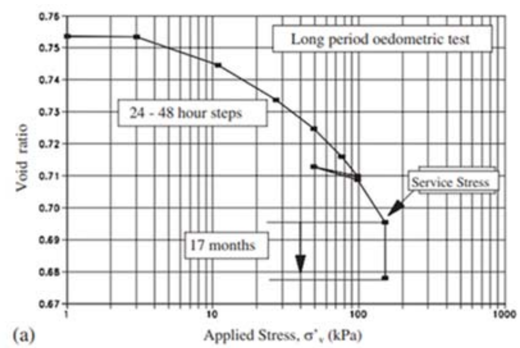

Figure 13. Results of a Long Period One Dimensional Consolidation Test after Fonseca (2003)

Further collapsibility of these soils was estimated by multistage one-dimensional consolidation testing of natural moisture state specimens, incrementally saturated with stress levels below and above the apparent preconsolidation stress, concluding that this soil is moderately expansive for low stress levels and moderately collapsible for high ones.

5.5 Shear Strength Testing

The pertinent design strength properties, as listed in Table 2, of the various materials within the dam foundation profile are required for any stability analyses. The determination of these design shear strength parameters require attention to the predicted stress range, stress-deformation behavior, and the foreseen degree of protection of the dam structure.

Table 2. Shear Strength Parameters of Saprolite

Soil Characteristics	Cohesion	Friction Angle
Peak	X	X
Undrained	X	X
Residual	X	X
Su/Po ratio	X	

Stress strain path or critical state concepts are used for understanding the generalised behaviour of potentially collapsible soils or also sometimes referred as loose soils. Typically, shear strength parameters increase in unsaturated soils due to matric suction which is usually neglected providing a conservative design approach. Liquefaction models are also used to interpret soil collapse behaviour. It helps to understand failure triggering mechanism and contributory factors. Liquefaction involves collapse with little or no warning, resulting in mobility or flow of these soils. It may also help in understanding the progressive failure involving stress redistributions in strain softening materials or significant yielding.

Conventional limit equilibrium method's input shear strength parameters may not necessary be conservative if the material is prone to collapse with notable strain softening behaviour. This can also be seen as the possibility of liquefaction upon saturation and loading, and development of mobility.

Figure 14 presents selected results of a multipass direct shear test, where shear tests were performed at consolidation stresses of 100, 200 and 400 kPa respectively. The results have shown a nonlinear behaviour at about 150 kPa.

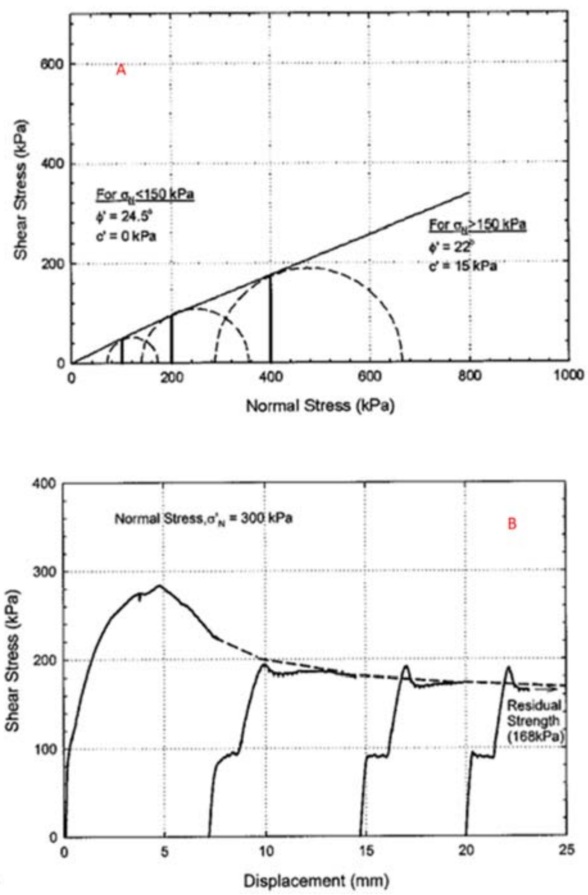

Figure 14. Multipass Direct Shear Test Results a) Residual Strength Envelope b) Load-displacement response

A selected result of a high pressure consolidated undrained triaxial compression test are presented as Figure 15, and a selected result from a cyclic dear shear tests on samples with high static loading bias is presented in Figure 16 for illustration.

These results did not indicate any abnormal stress strain behaviour or stress ratio but in line with expectations of any normal soil.

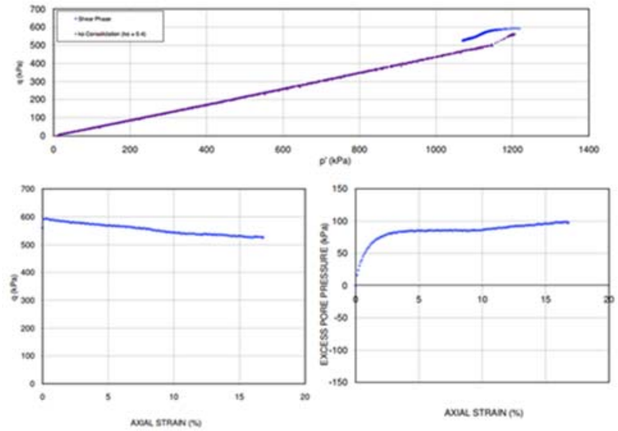

Figure 15. Typical Stress Strain Results from Consolidated Undrained Triaxial compression test.

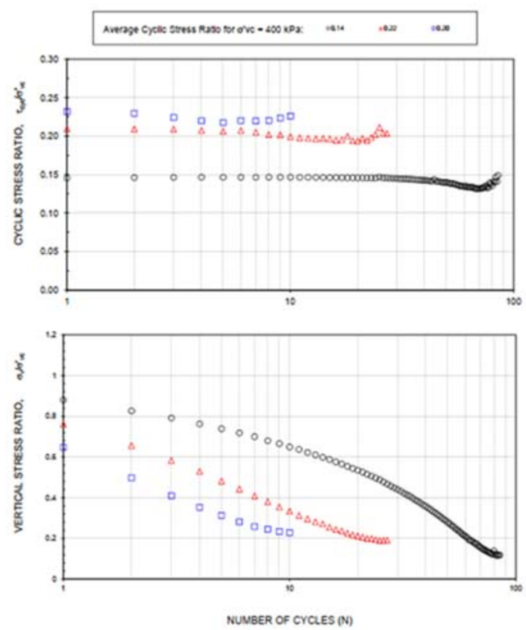

Figure 16. Stress Controlled Cyclic Direct Simple Shear Test

6. CONCLUSIONS

Given the risks associated with tailings dams a robust design is needed. For a robust tailings dam design on saprolite foundation quality geotechnical data is a must. Saprolite soils exhibit a wide range of engineering parameters depending on parent rock, state of weathering, leaching and location in the profile. Therefore, a comprehensive geotechnical investigation campaign consisting of both field and laboratory tests is required to determine reliable design soil parameters.

Our experience with saprolite as a dam or a waste rock pile foundation is that the collapsibility behaviour needs to be thoroughly investigated. It may be a concern at shallow depths but may not be a serious concern at greater depths.

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REFERENCES

ASTM D 5333. Standard Test Method for Measurement of Collapse Potential of Soil. ASTM Standards.

Clemence S.P. and Finbarr, A.0 1981. Design considerations for collapsible soils. Jr of Geotechnical Engineering Division, ASCE Vol 107, GT3 PP305-317.

Clevenger WA1985. Experience with loess as a foundation material. Trans ASCE 123 PP 51-80.

Dudley JH 1970. Review of collapsing soils. Jr of SMFE ASCE.

Feda 1966. Structural stability of subsidence loess from Praha-Dejvice. Engg Geology 1, 201-219.

Fonseca A. V. 2003. Characterising and deriving engineering properties of a saprolitic soil from granite, Inn Porto. Characterisation and Engineering Properties of Natural Soils – Tan et al. (eds.).

Gibbs HJ and Bara JP 1962. Predicting subsurface subsidence from basic soil tests. Soil Engineering Report No. EM658 USD Bureau of Reclamation.

Jennings JE and Knight K1975. A guide to construction on or with materials exhibiting additional settlements due to collapse of grain structure. Proc. 6 Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Johansberg, pp99-105.

Lutengger AJ and Saber RT 1988. Determination of collapse potential of soils. Geotechnical Testing Journal. ASTM Vol 11, No 3, PP 173-187.

Pinheiro M., Anjos G.J.M., Cunha R. P. 2008. Collapsibility potential of Brazilian latosol using CPT results. GeoEdmonton 2008.

Schwartz k 1985. Collapsible soil. Problems of soils in south Africa, sate of the art. The Civil Engg. South Africa 27, 379-393.

Water Authority of Western Australia 1990. Collapsible soils: identification and design consideration, ground engineering section, July 1990.

Wesley, L.D., (2009). Fundamentals of Soil Mechanics for Sedimentary and Residual Soils, John Wiley and Sons, 64 p.