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LIQUEFACTION OF MINE TAILINGS

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ABSTRACT

Liquefaction of mine tailings is known to occur during cyclic, quasi-static & static loading cases but is still a relatively misunderstood concept because tailings dam failures continue to occur. In the worst case scenario the results are high costs, hindered public perception, environmental cleanup and worst of all, the loss of life. A better understanding of this issue is essential for any engineer associated with the mining and/or geotechnical industry, and in particular tailings dam construction and maintenance. This paper presents the liquefaction concept, some case histories dealing with failure of mine tailings dams, available testing methods and some dated and recent research conducted on liquefaction of mine tailings.

INTRODUCTION

Liquefaction is a very troublesome issue in both the mining and geotechnical industry. In the mining industry liquefaction of mineral processing plant tailings is a big concern as shown in Fig.1 and can occur because of multiple reasons. Predominately liquefaction is researched more from the surface operations (e.g. tailings dams) side but liquefaction can also occur in the underground operations side (e.g. backfill operations) where cyclic loadings, saturation, re-saturation and quasi-static and static loading of the tailings can occur.

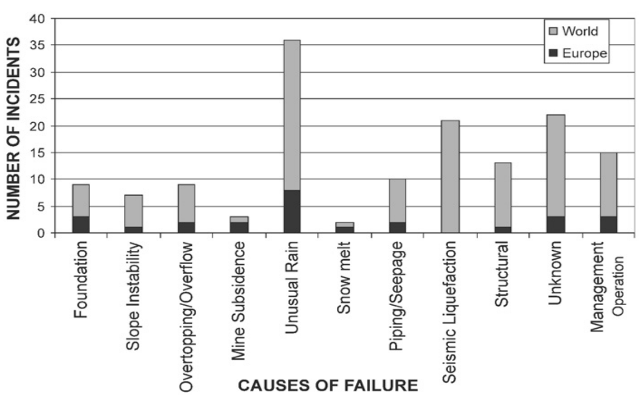

Fig. 1. – Various causes of mine tailings dam failures in the world (Rico, Benito, Salgueiro, Diez-Herrero, & Pereira, 2008).

If tailings dam liquefaction does occur, the risks are high costs, hindered public perception, environmental cleanup and worst of all, the loss of life; as shown in Table 1, which illustrates some of the greatest fatalities due to tailings dam failures up to 2006. Therefore, a better understanding of this issue is essential for a mining or geotechnical engineer. Therein lies the scope of this paper, which is to present the mechanisms behind mine tailings liquefaction by summarizing the concept of liquefaction, an overview of mine tailings application in the mining industry, a few past failure cases of mine tailings dams and finally an overview of some past and recent research that has been conducted to date.

Table 1. Incidents of lives lost due to mine tailings dam liquefaction (Petley, 2008).

Year	Location	Impact
1965	El Cobre New Dam, Chile	>200 fatalities
1966	Aberfan, Wales	144 fatalities
1966	Sgorigrad, Bulgaria	488 fatalties
1970	Mufulira, Zambia	89 fatalties
1972	Buffalo Creek, West Virginia, USA	125 fatalities
1985	Stava, Italy	268 fatalities
1988	Jinduicheng, Shaanxi province, China	20 fatalities
1994	Merriespruit, South Africa	17 fatalities
1995	Placer, Surigao del Norte, Philippines	12 fatalities
2000	Nandan county, Guangxi province, China	15 fatalities
2006	Miliang, Shaanxi Province, China	17 fatalities

MINE TAILINGS

Mine tailings are defined as the material that is left over after a mineral has been liberated from gangue material. Gangue material is the undesired material and the mineral is the desired material from a run-of-mine ore. Run-of-mine ore is the ore directly from the face of an underground or surface operation. The face is the area where the ore is extracted from. Mine tailings is a term used both in hard-rock, soft-rock, surface and underground operations.

Mineral/Coal Processing Operations

Tailings are liberated from the mineral by mechanical, or chemical processes, or both, in a mineral/coal processing plant. In the coal industry for instance, crushing and screening circuits are used to break run-of-mine material down to a workable and saleable size while liberating the mineral (coal) from the gangue (tailings). In mineral processing operations for instance (gold, copper, zinc etc…) processing can be much more complex. Often crushing is used along with grinding and density based and chemical separations.

One of the reasons that mineral processing operations involve a more complex processing plant is because the mineral liberates from the gangue at a much smaller size than for coal processing operations. The typical liberation size for coal processing is near 0.5mm whereas the liberation size for mineral processing can be 0.075mm. It's at this size that mine tailings behave similarly to clean sands under seismic loading, and therefore may be the reason that a huge portion of liquefaction studies have been related to mineral processed tailings as opposed to coal processed tailings. Again, since it is known tailings can behave similar to soils, the terms tailings and soil will be used interchangeable throughout, depending on their use in the case studies which were addressed.

How Are Mine Tailings Generally Used in the Industry?

For surface and underground operations, tailings serve a myriad of purposes, but for the most part, are either re-used as a form of support in backfill operations or as waste rock to the tailings dam. In hard-rock operations, tailings can be used for backfill material underground in under-cut-and-fill and cut-and-fill types of mining methods for instance. In soft-rock operations tailings can be used for support in long-wall mining operations or room and pillar operations. Tailings can also be used for various other construction purposes for the mine but whatever is not used is disposed of to the tailings dam.

LIQUEFACTION: THE CONCEPT

Soil liquefaction "refers to a condition when soil undergoes continued deformation at a low constant residual stress or with no residual resistance, due to buildup and maintenance of high pore-water pressures which reduce the effective confining pressure to very low values" (Prakash, S., 1981).

The fundamental concept of liquefaction was described by Casagrande (1936). He stated that liquefaction is based upon the critical void ratio. The critical void ratio is the void ratio at which sand does not change in volume when subjected to shear. If the void ratio is more than the critical void ratio, the soil is prone to liquefaction. In later years it was determined that a sufficient analysis of liquefaction could not be based upon the critical void ratio alone. Therefore, in the 1960's research began to advance the science further. This extensive amount of research will not be covered here due to redundancy, but can be accessed in various soil dynamics textbooks such as Prakash, S. (1981) and Das and Ramana (2011).

All in all, liquefaction has been studied since the 1930's, and remarkable advances have occurred. This is condition is now better understood and the potential for liquefaction can be generally related to five important factors, namely the relative density, confining pressure, peak pulsating stress, number of cycles of pulsating stress application and the over-consolidation ratio.

Failure of Mine Tailings Dams

There have been numerous tailings dam failures all over the world, and it would be impracticable to try and present them all; therefore a short description of four historical failure cases have been presented herein to refresh the reader of the implications of such a catastrophic failure of a tailings dam.

Aberfan and Buffalo Creek. On February 26th, 1972 nearly 176 million gallons of water and coal tailings were released from a failed coal tailings dam at Buffalo Creek. Over 17 miles of stretch was filled with debris and waste. One hundred and twenty-five deaths were reported and four thousand people were left homeless. In the end nearly 50 million dollars in damage had occurred (Jeyapalan, 1982).

A similar failure occurred in 1966 in Aberfan South Wales. As children in the school at the local mining town returned to their classrooms a loud roar came from the hills and minutes later the slide had engulfed the school and nearly twenty homes. One hundred and forty-four people were killed, of which one-hundred and sixteen of them were school children (Jeyapalan, 1982).

Barahona. In October of 1928 a sixty-three meter high copper tailings dam in Barahona Chile released nearly four million tons of material to the lower lying valley which resulted in fifty-four deaths. This was one of the largest tailings dam failures in history and was attributed to liquefaction at the core of the tailings dam which resulted in a slide failure on the downstream side of the dam (Jeyapalan, 1982).

El Cabre Chile. On March 28, 1965 a 7.25 magnitude earthquake occurred in central Chile. In the area were multiple copper mines. The tailings from the mines were hydraulically deposited to local tailings dams of which a large portion liquefied during the earthquake. This was later to be known as the famous El Cabre flow slide. Upon liquefaction nearly 1.9 million cubic meters of material flowed to the town below. Large portions of the town were destroyed and over 200 people were killed with nearly 100 million dollars in damage (Jeyapalan, 1982).

RESEARCH AND CASE STUDIES RELATING TO MINE TAILINGS DAM LIQUEFACTION

The following is a summary of past research through case studies, laboratory and field tests. The laboratory and field test are presented for an overview of testing methods which can be conducted in order to analyze a tailings potential to liquefaction.

Laboratory & Field Tests

Qiu and Sego (2001) presented a study on properties of mine tailings through laboratory tests. The four types of tailings tested in the laboratory were coal waste tailings, gold tailings, oil sand composite consolidated tailings and copper tailings. Some of the basic properties and laboratory tests that can be conducted on mine tailings in order to better predict the behavior of the tailings are presented.

Also, the tests that were conducted by Qiu and Sego (2001) only represent some of the laboratory and field tests that can be conducted to observe the liquefaction potential in the field. Other laboratory and field tests include cyclic tri-axial tests, cyclic simple shear tests, shake table tests, centrifuge studies, cyclic torsional shear tests, piezo-cone tests, standard penetration tests and vane shear tests to name a few.

Properties of Mine Tailings. Qiu and Sego (2001) performed laboratory tests and presented the basic properties of their mine tailings shown in Table 2. Some of the properties that were determined were specific gravity, Atterberg limits and soil classification. The particle size distribution of these tailings is presented in Fig. 2.

Consolidation & Hydraulic Conductivity Tests. Consolidation and saturated hydraulic conductivity tests were conducted on each of the aforementioned samples. This was to observe the behavior of the tailings at different consolidation stress levels. Determining the hydraulic conductivity is important because it can affect "the consolidation and desiccation behavior of the tailing, as it controls the water flow characteristics" (Qiu & Sego, 2001). The stress levels were 0.5, 2, 4, 10, 20 50 and 100 kPa and were chosen because this was the operative range for the majority of mine tailings facilities.

Constant-head hydraulic conductivity tests were conducted to determine the saturated hydraulic conductivity at the end of each consolidation stress increment. The sample was saturated by being placed in a de-airing cylinder, and then placed in a room at 2°C. The reasoning for this was to eliminate the biological process of bitumen in the sample and the bitumen's ability to produce gases during saturation. The consolidation apparatus is shown in Fig. 3 and the results for the tests are shown in Table 3.

Table 2. Laboratory properties of oil sands CT, coal, copper and gold mine tailings (Qiu & Sego, 2001).

	Tailings type			
	Copper	Gold	Coal	CT
Specific gravity, G_s	2.75	3.17	1.94	2.60
pH in process water	7.8	9.7	7.2	7.7
Liquid limit (%)	—	—	40	—
Plasticity index (%)	—	—	16	—
Shrinkage limits (%)	24.4	21.6	21.1	25.2
Clay size particles (< 2 μm; %)	1.3	5.3	22.5	8.9
Sand content (> 0.06 mm; %)	74.5	33.3	40	77
Fines content (< 74 μm; %)*	31.3	81.3	66.4	21.2
D_{10} (μm)	16.28	5.0	1.31	2.7
D_{30} (μm)	72.25	19.0	4.13	11.2
D_{50} (μm)	120.6	44.8	29.2	182
D_{60} (μm)	153.5	54.0	60.0	204
USCS classification	SM	ML	CL	SM

*Fines refer to the particle size less than 45 μm for CT.

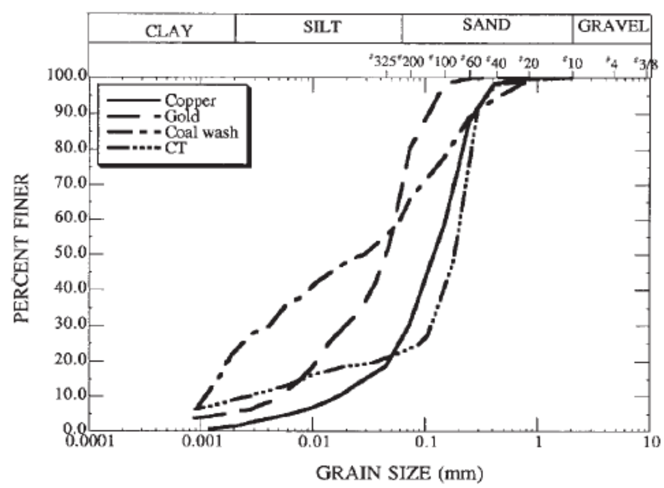

Fig. 2. Grain size distribution of the coal, gold, copper and oil sand CT tailings (Qiu & Sego, 2001).

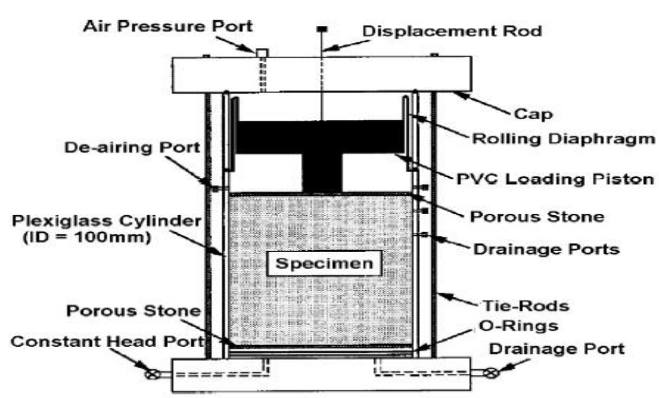

Fig. 3. Consolidation apparatus used for laboratory testing of mine tailings (Qiu & Sego, 2001).

Table 3. Consolidation and saturated hydraulic conductivity results for the gold, copper, coal and oil sand CT tailings (Qiu & Sego, 2001).

Tailings type	C_c	c_v (m^2/year)	m_v (m^2/MN)	k_s (cm/s)
Copper	0.056–0.094	22.32–104.23	0.63–19.76	4.5×10^{-5} to 9.8×10^{-5}
Gold	0.083–0.156	13.58–80.07	0.29–162.50	2.7×10^{-5} to 6.7×10^{-5}
Coal	0.370–0.396	1.48–17.26	1.08–188.20	4.0×10^{-7} to 1.1×10^{-5}
CT	0.271–0.319	0.310–8.46	0.61–379.90	2.2×10^{-7} to 6.3×10^{-7}

Note: The effective stress range is 0.5–100 kPa, and the void ratio range is 0.5–1.6. C_c, compression index; c_v, coefficient of consolidation; k_s, saturated hydraulic conductivity; m_v, coefficient of volume compressibility.

Lysimeter Tests. Next lysimeter tests were conducted to analyze the evaporation behavior of the tailings. This was conducted by utilizing an apparatus termed lysimeter, or column. A lysimeter or column is a PVC or Perspex cylinder usually 100-300 mm in diameter (Wilson, 1990); (Swarbrick, 1992). The potential evaporation rate, actual evaporation rate, the water content, temperature profiles and settlement of each tailing can be measured from a lysimeter/column drying test. From the laboratory tests the normalized evaporation rate was determined, which is the ratio of actual evaporation rate to the potential evaporation rate. From these tests a normalized evaporation rate vs. drying time chart was generated, as shown in Fig. 4.

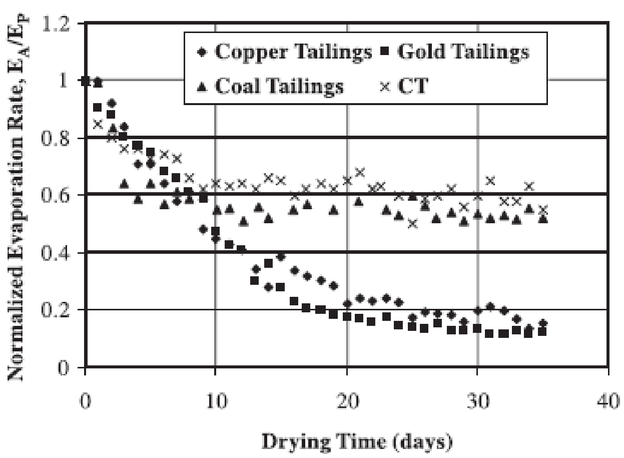

Fig. 4. Evaporation rate changes from column drying tests, E_A is actual evaporation and E_P is potential evaporation rate (Qiu & Sego, 2001).

Qiu and Sego determined that the drying process of tailings occurs in two stages. In the first stage, "the normalized evaporation rate drops quickly to around 0.6 [0.64 for coal wash tailings and CT]. Since the tailings surface desaturates as drying continues, the hydraulic conductivity of the surface decrease significantly, and thus the actual evaporation rate of the tailings drops dramatically (Qiu & Sego, 2001)."

In the second stage, "the hydraulic conductivity of the surface layer decrease slowly, and therefore the evaporation rate eventually drops from around 0.6 to 0.2 for copper tailings, from 0.6 to 0.15 for gold tailings, from 0.64 to 0.52 for coal tailings, and from 0.64 to 0.6 for CT" (Qiu & Sego, 2001).

Shrinkage Limit & Shrinkage Curve Tests. In order to analyze how the tailings behave when changes in moisture content occur (i.e. either a volume expansion and/or contraction), a shrinkage limit test and a shrinkage curve test were conducted. A shrinkage limit curve represents the change in void ratio to the change in moisture content of the sample. The results for the shrinkage limit test and the shrinkage limit curve test are presented in Fig. 5. It was concluded that the results from this study were similar to the results of a study conducted earlier by Fredlund and Rahardjo (1993).

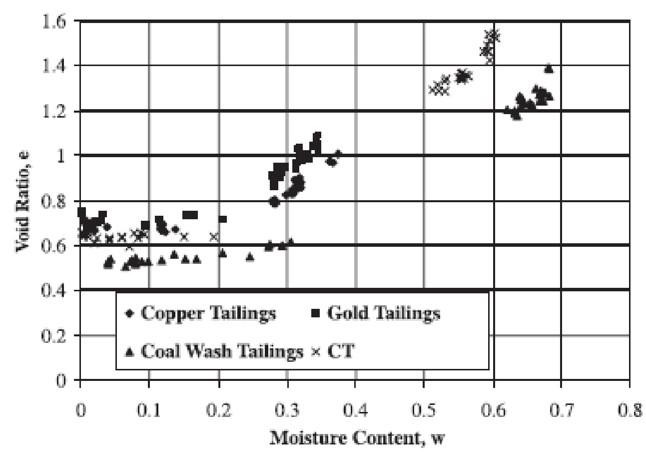

Fig. 5. Shrinkage curves developed from shrinkage curve tests on tailings (Qiu & Sego, 2001).

Water Retention Characteristic Tests. As it was important to test how tailings "release" water upon saturation, it was also of interest to determine how tailings retain water during water ingress. Additionally the soil-water characteristics provide a link between contained water and soil suction. These are important properties for unsaturated soils. This test is also important because the unsaturated hydraulic conductivity can be derived using the saturated hydraulic conductivity test results and the retention curve for the tailings and water.

The water retention curve was determined over a suction range by using pressure-plate extractors to measure the curve from 0 to 1500 kPa suction. Glass desiccators were used to measure retention from 1500 - 290000 kPa of suction. It was also of interest to the authors to retain the fines in the test as it was a saturated sample. The process to retain the fines was described in the paper but will not be covered here as it is rather detailed.

From the tests the water retention curve for the tailings, the air-entry value and residual moisture content were determined. These results are presented in Fig. 6 and Table 4. The authors concluded that the desaturation process of tailings occurs in three stages, which are the boundary effect, the transition and the residual stages of desaturation.

Table 4. Water retention test results (Qiu & Sego, 2001).

Tailings type	Air-entry value (kPa)	θ_r (%)	Suction (kPa) Boundary effect stage	Transition stage	Residual stage
Copper	5	3.4	<5	>5, <1500	>1500
Gold	6	2.2	<6	>6, <1500	>1500
Coal	18	18.0	<18	>18, <3900	>3900
CT	6	6.2	<6	>6, <3900	>3900

Note: The suction is a negative pressure. θ_r, residual volumetric water content.

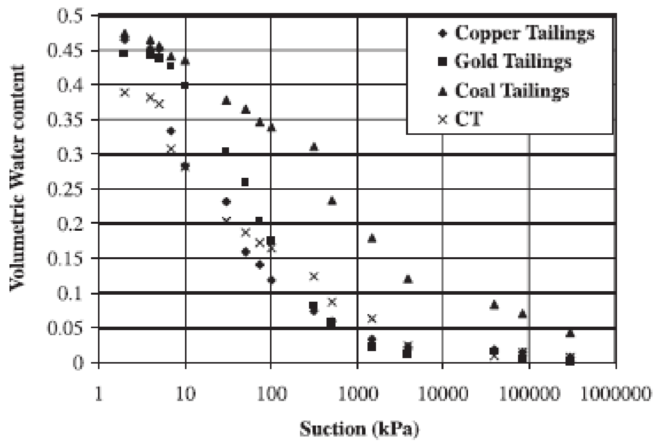

Fig. 6. Water retention curves from test results (Qiu & Sego, 2001).

Strength Tests. The effective shear strength parameters of tailings was also of interest, therefore a consolidated un-drained compression tri-axial test was carried out. Prior to testing, the saturated specimens were consolidated under effective stresses of 25, 50 and 100 kPa. The results for the tests are presented in Fig. 7 and Fig. 8 and Table 5.

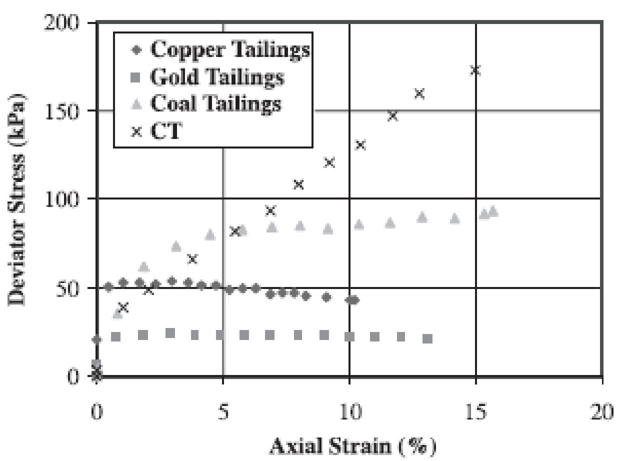

Fig. 7. Strain vs. Deviator Stress after 50Kpa of consolidation (Qiu & Sego, 2001).

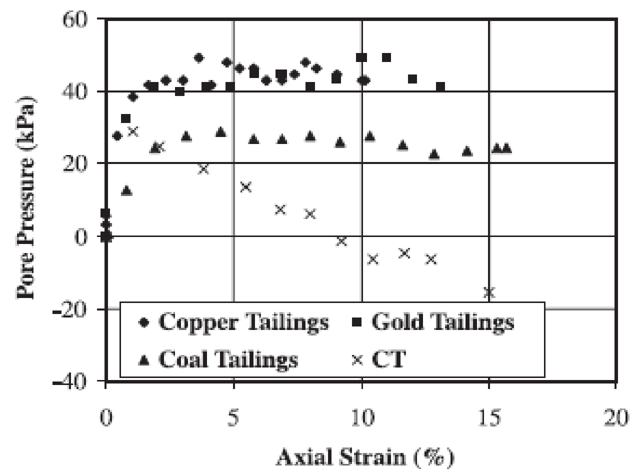

Fig. 8. Change in pore-pressure vs. strain plot (Qiu & Sego, 2001).

Table 5. Strength properties of the mine tailings (Qiu & Sego, 2001).

Tailings type	c'	ϕ' (°)
Copper	0	34
Gold	0	33
Coal	10	32
CT	3	30

Note: c', effective cohesion intercept; ϕ', effective angle of internal friction.

The results in Table 5 were determined empirically by the Mohr's circle technique. It was concluded that gold, copper, and oil sand CT behave as non-plastic cohesion-less soils. In addition gold and copper tailings behave as sandy soils, whereas the oil sand CT has unusual behavior due to the bitumen and clay mineral. The coal tailings behave as plastic cohesive soils. The coal and CT tailings undergo strain-hardening behavior post-failure, whereas copper and gold tailings undergo strain-softening behavior post-failure. Therefore, the role of pore-pressure increase in design of tailings facilities, particularly mineral mines, as sandy soils has both cyclic and static liquefaction potential. Of course this potential can be mitigated by providing proper drainage systems.

THEORY & CASE STUDIES

Critical State Concept/Steady State Line (SSL)

The critical state concept is another means to quantify liquefaction potential. The critical state concept states, "a soil with a mean effective stress, p', and void ratio, e, that plots above the critical state line (CSL), will contract during drained loading, or generate excess pore pressure, reducing the effective stress during undrained loading, until it reaches the CSL. Conversely, soil with a p' and e below the CSL will dilate during drained loading, or decrease pore pressure, increasing the effective stress during undrained loading, until it reaches the CSL. Once the CSL is reached a soil continues with no change in e or p' " (Anderson & Eldridge, 2011).

This concept, which was recently presented by Anderson and Eldridge (2011), is shown in Fig. 9. It is important to note that contractive behavior is indicative of strain-softening behavior and dilative behavior is indicative of strain-hardening behavior.

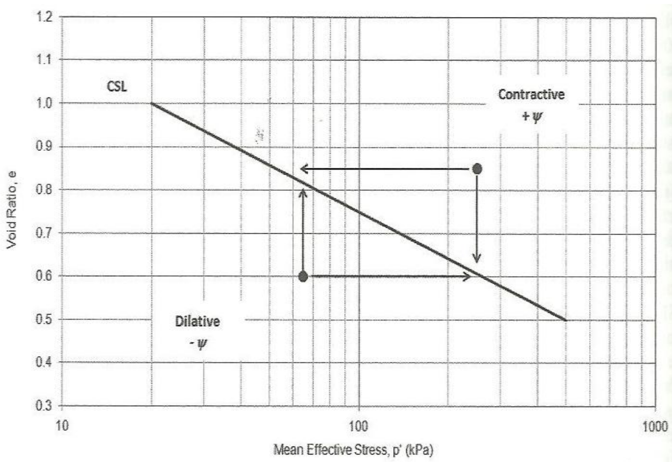

Fig. 9. Concept of critical state soil mechanics (Anderson & Eldridge, 2011).

The three factors that control the SSL/CSL, as proposed by Fourie and Papageorgiou (2011) are the confining effective stress, specimen preparation technique and resulting fabric and particle-size distribution.

The Role of Fines on Liquefaction Potential

Ishihara (1993) addressed the effect of fines on the liquefaction potential of sands. He concluded that sands with some fines were less likely to liquefy than the contrary, which are clean sands. His reasoning was, as confining stress increased, a soil which has higher friction occurring between its particles is less likely to deform and therefore less likely to liquefy. With the addition of fines, the cohesion develops between these particles which provide resistance to deformation because of the cohesion which binds the particles together.

Opposing this argument Sladen, D'Hollander & Krahn (1985) contended, based on their study of hydraulically placed sand. They concluded that as the fines increased, it became much more difficult to achieve their desired density for this placement technique and therefore the material was more likely to liquefy. Considering this was a study on hydraulically placed fill it is unknown whether the authors considered segregation of the particles due to shearing stress by hydraulic placement, which could have hindered the soil that was tested.

Mine Tailings Liquefaction: A Case in Central Japan

Okusa, Anma and Maijuma (1978) presented a study on the liquefaction of mine tailings after the 1978 Izu-ohshima-kinkai earthquake in Central Japan. On January 14^{th} two dikes on a small gold and silver tailings dam failed due to the initial earthquake and then due to the aftershock. Construction of the dam used the upstream method with hydraulically placed tailings of 35% solids by weight. The particle distribution was relatively uniform and the tailings were crushed rock from quartz veins. Two other local dams also failed, the Hirayama and Norosawa.

Based upon the research post failure the cause for liquefaction of the dams was determined. The dams were deposited with alterations of a silt layer and sandy silt layer. The layers ranged from 3-7 cm. thick. These layers were confirmed by in-situ cone penetration tests. It should be noted that the sandy silt was of low plasticity. Okusa et al. concluded that it was these layers of silty sand which caused the liquefaction of tailings dams, mainly because of their non-plastic and non-cohesive nature.

Critical State Liquefaction Assessment: Upstream Tailings Dam

Anderson and Eldridge (2011) presented a paper regarding mine tailings liquefaction, in particular silt tailings (slimes). They performed laboratory tests and in situ piezocone tests and soil-specific calibrations. The mine for which this research was carried out at was developing a new upstream raise to an existing tailings dam. Based upon in situ piezocone sounding tests the existing tailings dam had coarse tailings that were well understood. However, silt tailings were also present in relatively large bands that were not as well understood. Further research was therefore necessary before construction of a future dam was to take place. Figure 10 illustrates the existing tailings dam as well as the location of the future raise.

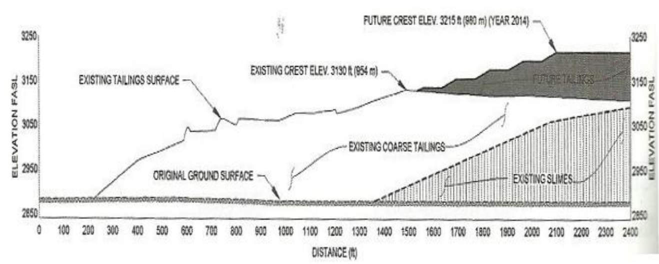

Fig. 10. Existing tailings dam and future raise location (Anderson & Eldridge, 2011).

The proposed raise was 25 meters and the current crest height was 70 m. The dam provided containment to three sides of the tailings pond and the crest length was approximately 3500 m. Upon CPTu sounding investigation of on-site tailings, the following was found:

- Coarse tailings down to about 25 m which consisted of sand and silty sand.
- Below 25 m existed soft “fine” silt tailings interlayered with coarse tailings. This extended to depths up to 70m and the interlayered silt material extended from 1-20 m in different areas.

The CPTu soundings which show the upper coarse layer and lower silt layer are shown in Fig. 11 and the particle size distribution of the tailings are shown in Fig. 12. The silt material was soft with a relatively high plasticity. It was understood to behave in an un-drained manner as a cohesive soft material with low permeability. Again it was not well understood by how this silt would behave under rapid loading or earthquake loading.

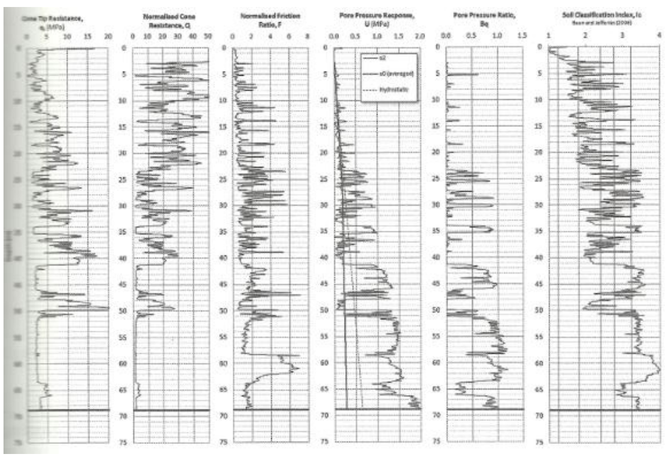

Fig. 11. CPTu sounding results (Anderson & Eldridge, 2011).

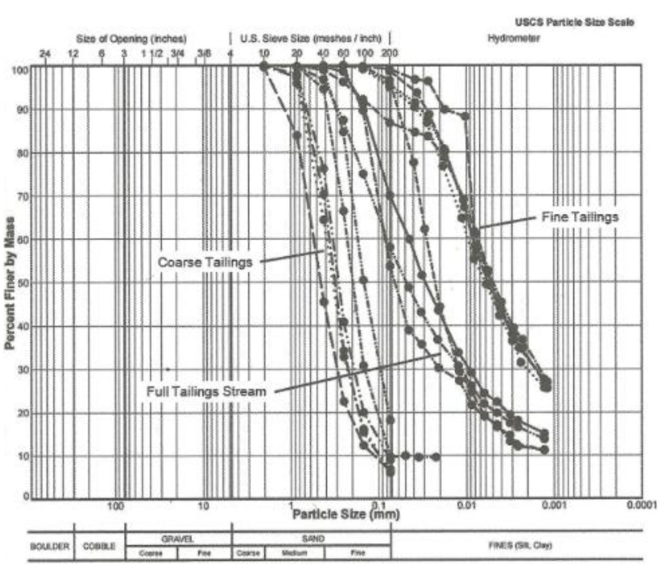

Fig. 12. Particle size distribution of tailings material (Anderson & Eldridge, 2011).

Based upon laboratory, in-situ testing & numerical modeling the authors were able to draw several conclusions. A conservative approach to observe liquefaction susceptibility is to observe the soil behavior type index (I_c) and plasticity index (PI) below a threshold value; however it is believed this approach may not be as conservative as previously thought. Finally, the silt tailings in this study were believed to behave in a strain-softening manner which would result in liquefaction upon cyclic loading.

Critical State Liquefaction Assessment: Gold Tailings Dam

Bedin and Schaid (2012) conducted a study where they performed drained and undrained triaxial tests on gold tailings in the laboratory and analyzed the results using the critical state concept. The gold tailings were classified as low-plasticity or non-plastic silty sand with a solids content of about 30%, moisture content of 35% and specific gravity from 2.89-3.2.

Based upon one-dimensional compression and hydraulic conductivity tests the normal compression line (NCL) and hydraulic conductivity of the tailings were determined. For initial void ratio of 2.0 the slope of the NCL was determined as 0.048. This was determined from the compressibility curve of change in void ratio vs. change in the logarithmic vertical stress. The hydraulic conductivity of the tailings was $2x10^{-6}$ m/s.

The stress-strain-pore pressure and effective stress-volume-strain behavior was determined using drained and undrained triaxial tests. For the lowest confining stress range, strain-softening behavior, loss of stability, rapid increase in shear strains and controlled pore pressure development occurred. It was concluded that at 15% maximum axial strain was enough for critical state soil conditions to occur.

For the undrained triaxial tests it was observed that positive pore water pressure developed in shear, which indicated contractive behavior which can lead to liquefaction. These results were then confirmed by used of drained compression and extension triaxial tests.

The critical state concept was then used for drained and undrained triaxial tests. From this a high non-linear critical state line was defined and four state conditions were occurring for this gold tailings sample. The first stage was flow liquefaction. Flow liquefaction occurred at low confining stresses and a contractive behavior occurred which in turn created high excess pore presses which lead to the second mode of liquefaction, instability. Flow instability occurred from the low to moderate stress levels. In this mode large deformations and high pore-water pressures are associated. In this mode a sample undergoes strain-softening but no liquefaction as it reaches an unchanged position at critical state. The next mode is stable conditions. Here the sample “sheared from the isotropic normal compression line show strain-hardening to critical state with compression response and increase pore pressure" (Bedin & Schnaid, 2012). The final stage was particle breakage. At particle breakage the sample exhibits a steeper slope than at the stable conditions which indicates the void ratio reduces a significant amount at low stress increments resulting in densification of the sample. These four modes are illustrated in Fig. 13.

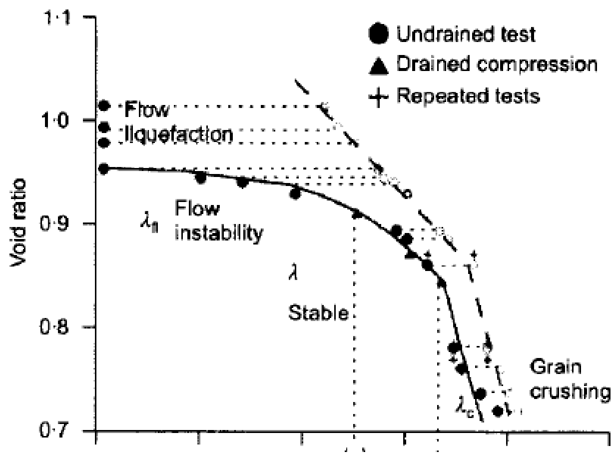

Fig. 13. The four modes describing behavior of gold tailings (Bedin & Schnaid, 2012). The x-axis is effective stress on a log scale.

Steady State Line for the Merriespruit Gold Tailings Dam

Fourie and Papageorgiou presented a paper in 2001 in which they researched the Maerriespruit gold tailings dam which failed in 1994 in South Africa (Fourie & Papgeorgiou, 2001). This tailings dam failure was of particular concern to the authors, and those that worked near the dam failure, because of the nature of the tailings, dam construction and the fact that this was the first gold tailings dam failure on this scale which had been recorded in South Africa.

Prior to the failure it was originally thought that these gold tailings exhibited strain-hardening behavior when subjected to loads, and this was because the tailings were deposited in a way which allowed consolidation because of drying from the sun. They, therefore, tested Marriespruit tailings taken from near the failure area of the dam at four different particle size distributions. The goal being to determine where these samples lie on the steady state line with difference in fine particles (>75 µm.) of the test specimen. The results indicated that as the samples with the greater percentage of fines plotted above the steady state line and therefore needed to be increased in relative density in order to prevent stain-softening behavior. Finally the authors concluded that particle-size distributions change from location to location in a tailings dam. It is for this reason they determined it was more appropriate for use of multiple steady state lines for determining the susceptibility to liquefaction of a tailings dam, as opposed to a single steady state line to represents the behavior of the entire tailings dam.

Static Liquefaction Analysis for the Merriespruit Tailings Dam Failure

In the previous section the failure of the Merriespruit tailings dam was discussed. To refresh our memory, this was a particularly interesting case of a tailings dam failure because of the gold tailings material (i.e. thought to exhibit strain-hardening behavior when subjected to shear) and because of the consolidation due to drying which the tailings were subjected to. Fourie, Blight and Papageorgiou (2001) took another look at the failure of the tailings dam to try and a provide reasoning to this particularly interesting failure case.

The authors suggested that the dam began operation in 1978 and followed the upstream daywall paddock construction method which was followed by most gold tailings dams in South Africa. The tailings material was deposited in the dam after processing, and after settling, the water on top was extracted to a local sump for re-use in the mineral processing operation; however, in this case the sump was much smaller then needed therefore water that should have been stored in the sump was left at the top of the dam until storage space was available at the sump. Additionally at the point of failure an exit pipe existed, but due to operational reasons, this pipe was moved and what remained were the finer materials from the tailings.

In early of 1993 the dam that failed was authorized to suspend tailings deposition in this area, however for various reasons deposition continued. On the night of failure of the dam a large storm swept through the area, and water began overtopping the dam. Water flowed over the top of the dam and down the tailings slope effectively washing away in situ material. Gradually, a point was reached where tailings, which were in a metastable state, were unearthed and a subsequent erosion of the slope took place. A domino effect of slope failure occurred in this area until the entire global slope failure occurred.

Laboratory and field tests were conducted on samples in the area of failure. The tailings that had liquefied were far removed from the site so the best chance at analyzing these tailings was to use the tailings that didn't liquefy, but were located near the failure zone. Based upon the laboratory and field research it was determined that the overtopping was the main cause that led to a static liquefaction incident at the failure area. The authors also confirmed that a large amount of the tailings had void ratios which plotted above the generated steady state line and were also in a metastable state. Also, the vane shear and piezocone tests near the test site confirmed that the tailings were in a very loose state and not at a "safe" relative density. The overtopping that occurred during the night of the storm, washed away the stable tailings on the slope of the dam, unearthed tailings which were at a high void ratios and liquefaction of the failed section occurred thereafter.

Static & Dynamic Strength of Silty Sand Tailings

Hai-ming et al. (2012) conducted a study to observe the behavior of silty sand tailings from a local copper mine in China. The tailings were from the Dashan mineral processing plant of the Dexing copper mine. Based on the results of dynamic triaxial tests, it was concluded that the silty sand was less susceptible to liquefaction at deeper depths than at the shallow depth. Their explanation was that the soil structure at deeper depths must be more stable than at shallow depths.

Shake Table Tests and the Influence of Inclusions During Cyclic Loading of Tailings

Pepin et al. (2012) conducted laboratory tests on tailings samples to determine the effects with and without inclusions (e.g. drainage and rigid inclusions). The tests were done on a shake table. The tailings were taken from two local hard rock mines. Upon testing the tailings were determined to be a non-plastic silt and therefore be susceptible to excess pore water pressure build-up and possibly liquefaction. They were able to determine that an acceleration of 0.12g was sufficient to impose high excess pore water pressure. They also determined that the liquefaction was more likely to occur at the initial density, and if the tailings would have been denser than they would have had a greater resistance to excess pore water build-up. Finally they concluded that the inclusions not only dissipated the excess pore water pressure upon loading but also provided mechanical reinforcement to the structure. In contrast they notice that drainage inclusions can prevent excess pore water pressure build-up in their vicinity, while the rigid inclusions also provide some reduction in excess pore water pressure. For this reason they determine the drainage inclusions outperformed the rigid inclusions in the lab. Lastly they determined that the inclusions were the main component in drainage of pore water pressure after cyclic loading and that they may also play a role in the consolidation of tailings prior to loading.

The Resistance of Tailings to Cyclic Loading

Geremew and Yanful (2012) conducted stress-controlled undrained cyclic triaxial tests on soil samples and mine tailings. The goal of the study was to inspect the liquefaction potential of the samples. The mine tailings were taken from four different mines located in Ontario Canada. A kaolinite and bentonite mix soil and a silty sand soil were also tested. The properties obtained from lab tests are shown in Table 6.

From the lab tests several relevant conclusions were drawn with regards to tailings liquefaction. First, the soils with similar particle size distributions void ratio and plasticity index had less resistance to liquefaction than the mine tailings. In regard to liquefaction resistance, the mine tailings were only marginally affected by the plasticity index when the tailings were of low plasticity. Finally, from 100 samples of mine tailings that were tested a boundary curve relationship between the void ratio and the normalized cyclic strength ratio was developed and this is shown in Fig. 14. Based on these findings laboratory tests can be conducted and a range of boundary curves can be established which can assist in determining the tailings and soils liquefaction potential.

Table 6. Mine tailings and soil properties for stress-controlled and undrained cyclic triaxial tests from (Geremew & Yanful, 2012)

Sample description	Percentage of fines		G_s	Consistency index			Cyclic strength	
	(<2 μm) (%)	(<5 μm) (%)	(–)	LL (%)	PL (%)	PI (%)	e_c (–)	CRR (–)
Mattabi mine tailings (MAT tailings)	2.56	3.20	3.29	20.1	7.5	12.6	0.65	0.345
							0.70	0.312
							0.80	0.250
							0.85	0.195
							0.92	0.141
Shebandowan East Cell mine tailings (SHEEC tailings)	1.29	1.29	3.22	12.0	11.0	1.0	0.70	0.305
							0.75	0.267
							0.80	0.207
							1.00	0.144
Shebandowan West Cell mine tailings (SHEWC tailings)	4.31	5.70	3.3	23.0	15.3	7.7	1.02	0.147
							0.89	0.197
							0.85	0.238
Sudbury mine tailings (SHEEC tailings)	1.77	3.06	3.88	23.61	19.32	4.3	0.99	0.227
							1.03	0.166
							1.16	0.139
Musselwhite mine tailings (MW tailings)	2.02	5.96	3.32	24.48	20.13	4.3	0.85	0.262
							0.90	0.208
							0.70	0.344
							0.95	0.173
Musselwhite-5% kaolinite mix (MW tailings—5K)	6.52	10.40	3.2	20.7	15.2	5.5	0.82	0.170
							0.77	0.186
Musselwhite-5% bentonite mix (MW tailings—5B)	6.88	8.00	3.23	29.5	21.3	8.2	0.991	0.158
							0.775	0.274
Musselwhite-15% bentonite mix (MW tailings—15B)	14.09	15.89	3.2	44.5	21.3	23.2	Not liquefied	
London-Casco silty sand (LC silty sand)	4.00	15.0	2.74	20.6	15.5	5.1	0.668	0.224

G_s, specific gravity; LL, liquid limit PL, plastic limit; PI, plasticity index; e_c, void ratio after consolidation; CRR, cyclic resistance ratio that corresponds to 20 cycles required to produce 5% double amplitude axial strain

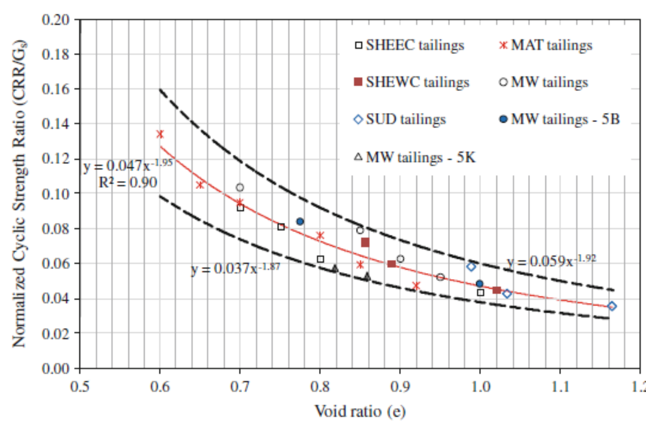

Fig. 14. Boundary Relationship developed by Geremew and Yanful (2012) for Normalized Cyclic Strength Ratio and Void Ratio.

Fine-Grained Mine Tailings and their Shear Response to Cyclic Loading

Wijewickreme, Sanin and Greenaway (2005) conducted a study on the response of fine-grained mine tailings to cyclic shear. Three different types of tailings were tested by utilizing a constant-volume cyclic direct simple shear device which simulates loading under earthquake conditions. This study only focused on the response of fine-grained tailings for the obvious reason that fine-grained tailings are more susceptible to liquefaction, also because at the time of this research, a limited number of cyclic shear response fine-grained tailings tests had been conducted. The three specimens tested were copper-gold, laterite tailings and copper-gold-zinc tailings. Based upon their results the following conclusions were made. First the laterite tailings had less potential to liquefaction as the confining pressure increased. Therefore, "for this material any dilative tendency arising due to stress densification seems to have overcome the possible contractive tendency due to increase in confining stress" (Wijewickreme, Sanin & Greenaway, 2005). It was also concluded that copper-gold-zinc tailings were unaffected by the confining pressure and that the copper-gold-zinc-tailings had a response similar to normally consolidated clays.

Simple Shear Testing on Gold Tailings

In a study conducted by Al-Tarhouni, Simms and Sivathayalanin (2011), simple-shear tests were conducted on gold tailings in order to better understand the liquefaction potential of tailings under monotonic, cyclic and post-cyclic loading. The gold tailings were silt-sized and of low plasticity. The tailings were reconstituted and considered desiccated-rewet thickened gold tailings. An in-depth analysis of the tailings properties and the preparation techniques for these tailings is included in the paper, but for redundancy purposes, will not be re-discussed here. Conclusions drawn from this study were that for 3.75% shear strain, liquefaction occurred regardless of consolidation pressure and showed behavior similar to highly compressible sands. Drying the specimen to the shrinkage limit appeared to increase the tailings resistance to liquefaction.

Liquefaction Assessment of Gap-Graded Mixtures of Waste Rock and Tailings

Wijewickreme, Khalili and Wilson (2010) conducted liquefaction studies on "paste rock" in the laboratory. Monotonic and cyclic un-drained tri-axial shear tests were conducted. The paste rock consisted of a mixture of sedimentary waste rock and tailings from a gold extraction process. The mixture was close to 4.8:1 ratio of waste rock to tailings. The amounts of tailings used were enough to just fill the void spaces between the larger coarse rock particles. Results from this study indicated that the paste rock was highly unlikely to liquefy under cyclic loading based on the strain-softening behavior and loss of shear strength which did not occur during the tri-axial tests. Generally, the paste rock was concluded to behave as a coarser rock material as opposed to the fine-grained tailings material alone. It contrast to a coarse-only material though, paste rock had the ability to handle higher loadings because of the fine tailings in the pore spaces. The fine tailings in the pore spaces reduced the interaction of the coarse particles in the skeleton during loading which led to higher loading capacity (Wijewickreme, Khalili & Wilson, 2010).

DISCUSSION

Based upon the review of available information it may be observed that:

- Implications of tailings dam liquefaction are high costs, hindered public perception, environmental cleanup and worst of all, the loss of life.
- The majority of research conducted to date has dealt with mineral processing tailings dams. Most likely this is because the typical liberation size for coal processing is near 0.5mm whereas the liberation size for mineral processing is near 0.075mm. It's at these sizes that mine tailings behave similarly to clean sands under seismic loading.
- Various lab and field tests can be conducted to analyze tailings liquefaction susceptibility. These tests include, but are not limited to column drying tests, cyclic triaxial tests, cyclic simple shear tests, shake table tests, centrifuge studies, cyclic torsional shear tests, piezo-cone tests, standard penetration tests, vane shear tests, consolidation and hydraulic conductivity tests, shrinkage limit and shrinkage curve tests, water retention characteristics tests and strength tests.
- Based upon the water retention tests by Qui and Sego (2001) the desaturation process of tailings occurs in three stages, which are the boundary effect, the transition and the residual stages of desaturation.
- Qiu and Sego (2001) concluded that gold, copper, and oil sand CT behave as nonplastic cohesionless soils. In addition gold and copper tailings behave as sandy soils whereas the oil sand CT has unusual behavior due to the bitumen and clay mineral. The coal tailings behave as plastic cohesive soils. The coal and CT tailings undergo strain-hardening behavior post-failure, whereas copper and gold tailings undergo strain-softening behavior post-failure.
- The critical state concept/steady state line is based upon the void ratio and effective stress of a tailings sample. The concept describes the liquefaction potential of tailings based upon their post-yield strain-softening or strain-hardening behavior.
- The three factors that control the SSL/CSL, as proposed by Fourie and Papageorgiou (2001) are the confining effective stress, specimen preparation technique and resulting fabric and particle-size distribution.
- Ishihara (1993) concluded that sands with some fines were less likely to liquefy than clean sands. His reasoning was, as confining stress increased, a soil which has higher friction occurring between its particles is less likely to deform and therefore less

likely for liquefaction. With the addition of fines, the cohesion develops between these particles which provide resistance to deformation because of the cohesion which binds the particles together.

- Sladen, D'Hollander & Krahn (1985) argued the opposite for hydraulically placed tailings. They stated as the fines increased, the desired density became lower, compressibility was higher and therefore the material was more likely to liquefy for this placement technique.
- Upon investigation of the tailings dam failure in 1978 caused by the Izu-ohshima-kinkai earthquake in Central Japan. It was determined the cause of failure was layers of sandy silt with low plasticity. If the tailings were not of the non-plastic and non-cohesive nature then liquefaction may not have ever occurred.
- In a study by Anderson and Eldridge (2011) they determined that the silt tailings/slimes behave in a strain-softening manner which can result in liquefaction upon cyclic loading.
- Bedin and Schnaid (2012) described the behavior of gold tailings in 2011. They stated that the critical state behavior of the tailings when subjected to undrained triaxial loading was not a linear line as in theory. Instead the critical state line described four modes of behavior. These modes were liquefaction, flow instability, stable conditions and particle breakage.
- Fourie and Papgeorgiou (2001) studied gold tailings at a mine in South Africa. They determined that samples with the greater percentage of fines plotted above the steady state line and therefore needed to be increased in relative density in order to prevent stain-softening behavior.
- Fourie and Papgeorgiou (2001) also recommended that it may be more appropriate for use of multiple steady state lines for determining the susceptibility to liquefaction of a tailings dam, as opposed to a single steady state line to represents the behavior of the entire tailings dam.
- The Merriespruit tailings dam failure was attributed to static liquefaction due to overtopping which occurred because of poor monitoring and management overtime. The overtopping washed away stable tailings which then exposed tailings which were in a metastable state which then led to static liquefaction (Fourie, Blight & Papageorgiou, 2001).
- Inclusions can be used to mitigate the threat of liquefaction of tailings dams. Pepin, Aubertin & James (2012) concluded that the inclusions not only dissipated the excess pore water pressure upon loading but also provided mechanical reinforcement to the structure.

CONCLUSIONS

The scopes of some of the case histories on failures of mine tailings dams, due to liquefaction, have been presented in this paper. With this information the focus was to improve safety and present the engineer associated with any tailings dam construction and maintenance, a general overview of some case studies, theoretical background, testing methods and implications of such a catastrophic failure. From the available information in mine tailings behave like sands and sands with plasticity fines. However the available information does not justify a general conclusion for all cases and the practicing engineer must dictate the behavior of each case through personal site and laboratory testing and experience.

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