Liquefaction in Heap Leach Piles – A Primer

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Abstract

Even though liquefaction of heap leach piles has not been a very common phenomenon, it has occurred. With increasing demands for and prices of certain metals, their extraction from lower grade ores using heap leaching becomes economically feasible and the number of operations utilizing the process is ever increasing. The pilot heap leaching program of Rio Tinto's Bingham Pit operation in Utah, USA, in spite of the modernized concentrating and flotation operations running successfully since Rio Tinto's acquisition of the mine in 1989, is a good example of this trend. A large number of heap leaching operations in South America and around the world, including the Bingham Pit operation, are in active seismic zones. Moreover, leach pile heights have been steadily increasing, with piles of 150 m or greater becoming common. These facts point to the possibility of liquefaction-induced failures of leach piles becoming less rare, and lately, several heap leach and ripios pile liquefaction issues have occurred.

A number of treatises on heap leaching with some reference to liquefaction and a few technical papers describing the liquefaction analysis of specific heap leach piles have been published, but a complete dossier of various issues related to liquefaction of heap leach piles does not exist. This paper is expected to be a liquefaction primer for heap leach projects, exploring liquefaction potential and functioning, ore types and treatment producing vulnerable heaps or ripios dumps, material characterization and various design and analysis practices currently in use. Some issues of gross mischaracterization of the situation stemming from either generally bad overall practice, failure to adequately consider long-term aging in an acid leach environment and the possibility of liquefaction not necessarily related to seismic loading, will be referenced with the ultimate aim of developing a more complete and safer basis for designing and developing the heap leach piles.

Introduction – what is liquefaction?

Liquefaction of soils is a phenomenon in which the strength and the stiffness of soil are suddenly reduced due to a critical change in loading conditions. Liquefaction is typically a concern only in saturated or near-saturated soils, and the critical change implies an alteration of the external loading resulting in an increase in the pore water pressure. This increase occurs when the soil particles are loosely packed and the bulk material attempts to contract under the loading; the contraction reduces the pore space, creating excess pore pressure. With sufficient excess pore pressure, the soil can behave like a viscous liquid or a frictional fluid, with little or no shear resistance. In terms of effective stresses, when the excess pore pressure in the soil skeleton equals the total stress, the effective stress contributing to shear strength or shear resistance becomes zero and the soil liquefies.

Various definitions, describing this condition differently, exist in the literature; for example, Seed (1979) described liquefaction as a condition where a soil undergoes continued deformation at a constant low residual stress or with low residual resistance due to the build-up and maintenance of high pore water pressure. On the other hand, to avoid confusion between many related or similar phenomena triggered by different mechanisms, some have labeled them differently and put them in different categories like flow-liquefaction, cyclic mobility, fluidization, etc. The subtle differences between these are important, but will not be focused on or elaborated in this paper

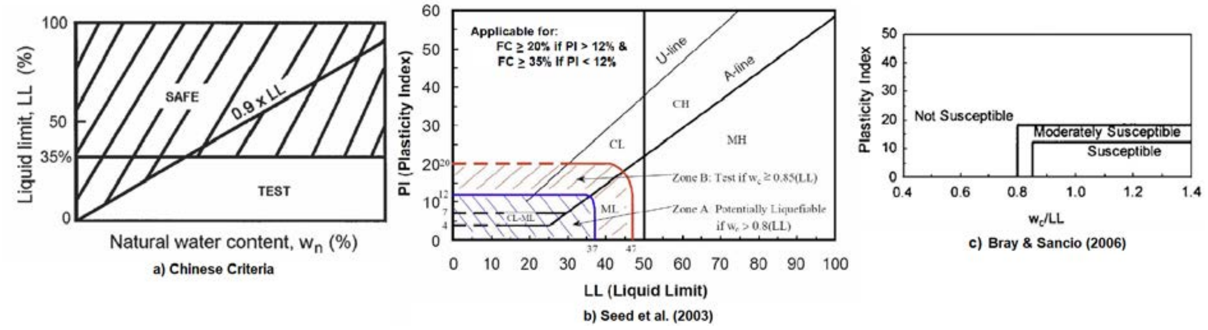
The most common changes in external loading associated with liquefaction in a leach pile or tailings facility are excessive rate of rise and earthquakes, the former leading to what is referred to as static liquefaction, which can be a contributing factor in failures of upstream constructed tailings dams.

From classical to critical state soil mechanics

The term liquefaction was first used in reference to the failure of the Calaveras hydraulic fill embankment dam in California, when the upstream shell slid off as the dam was reaching a height of 64 m (Hazen, 1918). Historically until much later in the century it was considered to be a phenomenon associated with loose coarse-grained soil or sands, and most studies conducted were on sands only. Over time, liquefaction has also been observed in gravel and silt, and much emphasis has been placed on establishing firm criteria for determining the soil susceptibility to liquefaction. For example, an analysis of the major earthquakes in China for a period of ten years established the common characteristics of the liquified soils in terms of limited ranges of some index properties (Wang, 1979). Dubbed as "Chinese Criteria", this became the norm for judging the susceptibility of soils to liquefaction for some time, with the limits being modified later as "clay content ≤15%, liquid limit ≤35 and water content ≥90% of liquid limit," and the standard set as, "liquefaction of fine-grained soil will occur only if all three criteria are met with" (Seed and Idriss, 1982).

Later, Seed et al. (2003) suggested a criterion based on Liquid Limit and Plasticity Index, separating the soils into three groups of varying liquefaction susceptibility to cyclic pore pressure increase, with the applicability limited to certain ranges of fines content (FC) and plasticity index (PI).

Subsequently Bray and Sancio (2006) came up with still other criteria similar to Seed et al. by way of defining three different levels of liquefaction susceptibility (susceptible, moderately susceptible, and not susceptible) for soils with FC ≥50%. Figure 1 shows a graphical representation of the three criteria mentioned above. There have been some other similar developments, but the three mentioned above seem to have been or are being the most commonly used.



a) Chinese Criteria

b) Seed et al. (2003)

c) Bray & Sancio (2006)

Figure 1: Graphical representation of some liquefaction susceptibility criteria (reproduced and adapted from Green and Ziotopoulou, 2015)

With more earthquakes and cases of liquefaction around the world since then, any criterion focusing mainly on moisture content and plasticity of soil seemed to be inadequate to explain the phenomenon in every case and, thus, focus has shifted. Research, analyses, laboratory testing, and field investigation early in the last century had led to the finding that coarse-grained soils or sand in an initially loose state have a tendency to contract upon shearing under a constant normal stress or pressure, while the same sand in initially dense state tends to dilate, both approaching the same steady state void ratio, as the shearing continues. This steady state void ratio, labeled as the "critical void ratio", was found to be a function of the normal pressure applied during the shearing process, giving rise to a unique curve on the void ratio (e) versus logarithm of the normal pressure (log p) plot, identified as the Critical State Line or CSL (Casagrande, 1938). This was in a sense the onset of the field of Critical State Soil Mechanics and a new approach to the treatment of liquefaction.

Figure 2 shows a modified version of the diagram mimicking some direct shear test results that Casagrande used to explain these characteristics of lose sands leading to liquefaction. A soil consolidated under an effective pressure p_1 to a void ratio e_1 represented by the point C_1 above the CSL in Figure 2, if sheared, will tend to contract, while the same soil with the initial conditions represented by the point C_2 with consolidation pressure p_2 and void ratio e_2, below the CSL, if sheared will tend to dilate. However, if the volume changes in the two cases are prevented, or the shearing is too fast to allow the re-adjustment of the granular structure, the soil responds by transferring part or all of the inter-granular stresses to the pore water – the stipulated contractive and dilatative tendencies until the critical state is reached, giving rise to positive and negative pore pressures, respectively. As shown by the line C_1D_1 representing the undrained shearing (no volume change allowed) of the soil with contractive behaviour, this results in a significant drop in effective stress and thereby a loss of strength, causing liquefaction. On the contrary, the path C_2D_2 representing the undrained shearing of the soil with dilatative tendency and the corresponding negative pore, will not be conducive to liquefaction.

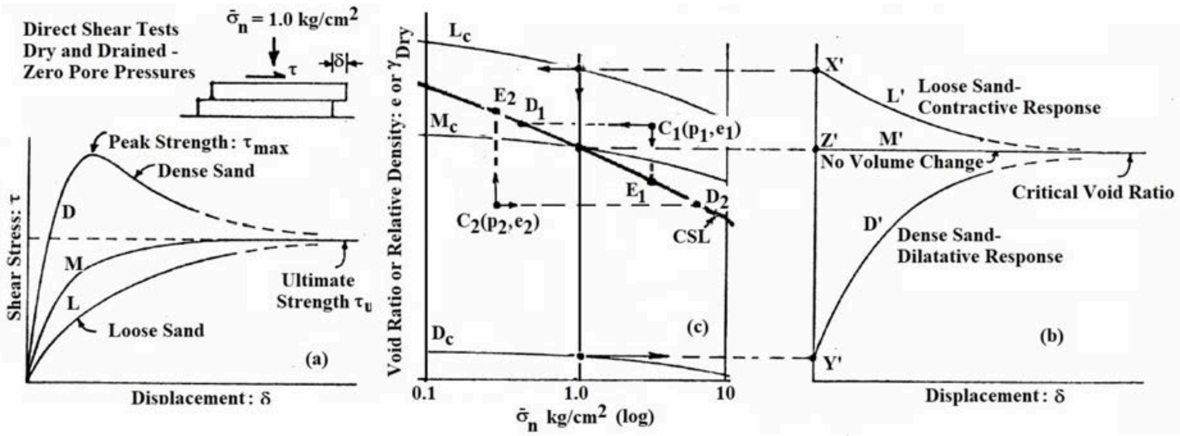


Figure 2: Graphical demonstration of Critical State Line from shear test result (after Casagrande, 1938)

Thus, it is clear that liquefaction is not only a function of the saturation and the plasticity of soil, but also depends on the effective normal stress applied. Casagrande concluded that all combinations of void ratio and effective normal stress located below, or to the left of the CSL in Figure l(c), represent states in which the sand would develop dilative response and thus be safe against liquefaction, while the points to the right or above the CSL would correspond to a contractive response resulting in a slump of limited dimensions, or a flow slide, depending on the resulting drop in effective stress.

History of liquefaction in heap leaching

Although liquefaction flow slides under conventional static loading conditions are well documented for mining wastes (e.g., Davies et al., 2002), these accounts have been invariably in reference to tailings impoundments and coal (fly ash) waste dumps. Most heap leach ores are well drained even after leaching, which makes heaps generally of low susceptibility to liquefaction. The only well documented case of heap liquefaction is for the Cuajone copper mine in Southern Peru, which was triggered by the M_w 8.4 Moquegua, Peru earthquake on June 23, 2001 (Rodriguez-Marek et al., 2004). Although located just 60 kilometres (km) from the epicentre, the failure and the resulting lateral spreading were restricted to the uppermost lift of the heap (Figure 3). Another nearby heap suffered a slope failure but the cause is disputed. Both heaps consisted of low permeability ore with high degrees of saturation.

The liquified lift shown in Figure 3 was under active leaching at the time and the likely cause of liquefaction was determined as the high solution application rate, in conjunction with the relatively fine gradation of the ore and the presence of an underlying inter-lift liner inhibiting pore pressure dissipation. It is worth mentioning, however, that the presence of an inter-lift liner is likely the reason the liquefaction was restricted to only the upper lift.

Figure 3: Liquefaction of the Cuajone Copper Heap, Peru

On the other hand, liquefaction of spent ore (commonly called ripios in South America) dumps is becoming common for Chilean copper mines using dynamic heaps (on/off leach pads). Sulfuric acid leaching of copper ores often results in significant chemical degradation of the ore, producing ripios of very high fines content, low permeability, and low shear strength. Leach cycles for dynamic heaps with poor quality ores can be very long, in part due to the low permeability. For example, at one mine in Northern Chile some of the ore can be irrigated at a maximum of 4 litres per hour per square meter (L/h/m^2), for just 12 hours per day, for an effective irrigation rate of 2 L/h/m^2. The ripios from such heaps is often saturated and very weak. Figure 4 shows ripios at a Chilean mine that has liquefied under its own weight (static liquefaction) during deposition in the ripios dump. In some cases, static liquefaction of the ripios dump has created serious safety risks for operators and traffic at near-by roads. Another copper mine in Chile is currently upgrading ore blending and geotechnical monitoring at its conventional (permanent) heaps to mitigate the risk of liquefaction.

Heap leach projects are getting larger, with heap heights greater than 150 meters (m) becoming common. Mining rates are increasing ten-fold every three decades (Robertson, 2011) and there is now at least one copper mine moving over 1 million tonnes daily. Ore quality is getting worse as miners search for new reserves, and longer leach cycles result in more chemical degradation. Dynamic heaps are increasingly used for poor quality copper ores, and are the prime method considered for nickel ores. Most heap leach projects across the world, including Chile, Peru, Turkey, Nevada, and California, are in seismically active areas. Thiel and Smith (2004) have described in some detail the various reasons for and implications of increased liquefaction susceptibility in heap leaching, including static liquefaction, and earthquake-induced flow slides.

Figure 4: Static liquefaction of ripios, Chile

Triggering mechanisms

Liquefaction triggering is a function of the properties of the soil or leach ore itself, and the mechanism inducing the appropriate loading conditions. The triggering mechanism for liquefaction could be static or dynamic loading. Monotonically increasing shear load imposed by increasing embankment heights, over-steepening the slope, toe erosion, construction equipment loading, reservoir filling, and progressive failure leading to steeper slopes are some of the examples of static loading leading to liquefaction flow (Jefferies and Been, 2016; Sadrekarimi, 2014). In upstream tailings dams, static liquefaction can be triggered if the rate of rise of the crest of the dam is excessive (Davies et al., 2002). As demonstrated by the ripios dump liquified under its own weight in Figure 3, static liquefaction can be a problem with nickel leach heaps or ripios dumps (Smith and Christie, 2015). While seismic shaking, blasting, and pile driving are the most obvious and common examples of dynamic loading that could trigger liquefaction, machine vibrations, effects of water waves, rapid sediment accumulation and groundwater movements are also considered to be potential triggering mechanisms (Owen and Moretti, 2011). In this paper the only dynamic trigger discussed is seismic. Once triggered, the strength of a soil susceptible to flow liquefaction is no longer sufficient to withstand the static stresses that were acting on the soil before the disturbance, and failure ensues.

Based on the flow slides observed in tailings piles and coal waste dumps, Thiel and Smith (2004) gave some indicators of liquefaction and flow slide susceptibility applicable to heap and dump leach piles as well (Table 1). In the years since then, some of the indicators are found to be less relevant and the respective thresholds either too stringent or too liberal. The changed perspective and the considerations leading to changes are listed alongside in the column added to the original table. However, more recent experience with Chilean ripios dumps suggests the height threshold can be as low as a few meters and the foundation slope may not be relevant within the range of heap leach pad geometries.

Table 1: Indicators of flow slide susceptibility (updated from Thiel and Smith, 2004)

Parameter or characteristic	Threshold (approximate)	Changed perspective
Maximum height	≥100 m	CPT work shows the liquefaction triggering below 30 m being hard due to high initial stress and relatively low induced dynamic stress.
Foundation slope	≥15 degrees	May not be relevant within the common range of heap leach geometries, but still relevant because steeper slope increases the runout distance
Location, terrain	Incised valley	Existing heap leach operations with liquefaction issue are not in incised valley and this restriction is also from the runout consideration
Inter-bench slopes	Near angle of repose	–
Heaped moisture content of ore	≥5%	Too low; can be increased to ≥ 10~12% but is very ore dependent
Saturated permeability of ore	≤1 x 10-2 cm/sec	Perhaps too high; <2 to 3 times the irrigation rate may be a better threshold
Saturation (at any point in the heap)	≥85%	–
Other factors:	• No toe support • Finer material near the base • Water, impermeable layer at base	Water on a low permeability layer anywhere in the heap; most of the critical sections have shown high-risk zones well above the base

Dynamic liquefaction hazard assessment

The cyclic stress approach (Seed and Idriss, 1967; 1971), often dubbed as the “simplified approach” or “simplified method,” evaluates the earthquake induced liquefaction susceptibility from estimates of induced shear stresses and the shear stresses required to cause liquefaction expressed by two non-dimensional ratioscyclic stress ratio (CSR) and the cyclic resistance ratio (CRR), respectively. If the CSR is close to or greater than the CRR, liquefaction can occur.

In the simplified method, the CSR is based on the observation that the effect of the non-uniform stress cycles during an earthquake could be equated to that produced by an equivalent number of uniform stress cycles with 65% of the actual peak shear. Thus, the expression for CSR is given as:

$$CSR = 0.65\ (a_{max}/g)\ .\ (\sigma_{v0}/\sigma'_{v0}).\ r_d \qquad (1)$$

Where: a_{max} = Peak horizontal ground surface acceleration during the earthquake (generally determined from deterministic or probabilistic seismic hazard assessment)

g = Gravitational acceleration

σ_{v0} = Total overburden stress

σ'_{v0} = Effective overburden stress, and

r_d = Stress reduction coefficient guided by the flexibility of the soil profile and depth

Peak horizontal acceleration is based on the earthquake under consideration. The stress reduction coefficient, r_d at any depth is known to vary with the flexibility of the soil profile and the range of variation increases with depth. The National Earthquake Engineering Research Council has considered the following empirical bilinear relationship between r_d and depth (Liao and Whitman, 1986) to be suitable for use in routine engineering practice (Youd and Idriss, 2001):

$$r_d = 1.0 - 0.000765\ .\ z \qquad \text{for } z \le 9.15, \text{ and}$$

$$1.174 - 0.0267\ .\ z \qquad \text{for } 9.15 < z \le 23).$$

Where: z = Depth below surface in meters

The soil's cyclic strength, or CRR, can be estimated from either laboratory or field testing, and often both are used. While the classical approach to determining liquefaction susceptibility from laboratory testing is based simply on the moisture content and standard index properties including particle size gradation (viz., Seed et al., 2003; Bray and Sancio, 2006), the critical state approach requires direct measurement of dynamic or cyclic strength. Cyclic triaxial or cyclic direct shear tests are performed over a range of initial in-situ stress conditions to determine the number of loading cycles required to initiate failure under a range of earthquake loads.

The two most common field techniques used to determine CRR are the standard penetration test (SPT) and the cone penetration test (CPT). It is customary to use an earthquake of magnitude M_w=7.5 as the base or reference in such determinations, though a more site-specific event can be substituted. A number of empirical equations to estimate CRR from SPT blow count (N) and CPT tip resistance (q_c) have been proposed in the last forty some years. One relationship widely used to compute CRR from SPT data is (Youd and Idriss, 2001):

$$\mathrm{CRR}_{7.5} = \frac{1}{\{34 - (\mathrm{N}_1)_{60,\mathrm{CS}}\}} + \frac{(\mathrm{N}_1)_{60,\mathrm{CS}}}{135} + \frac{50}{\{10 \,.\, (\mathrm{N}_1)_{60,\mathrm{CS}} + 45)^2\}} - \frac{1}{200}$$

Where:

$(N_1)_{60,CS}$ is the SPT blow count with appropriate corrections for energy, borehole diameter, sample barrel, rod length, and grain characteristics (fines) applied to the raw N-value recorded in the field (Youd and Idriss, 2001).

The equation is considered valid for $(N_1)_{60,cs}<30$ under the assertion that for $(N_1)_{60,cs} \geq 30$ represents soils *too dense to liquify*.

Commonly used expressions for deriving CRR from CPT data, for an earthquake of magnitude $M_w=7.5$, are (Robertson and Wride, 1998),

$$\mathrm{CRR}_{7.5} = 0.833 \left\{\frac{(q_{c1N})_{cs}}{1000}\right\} + 0.05\,; \quad \text{for}, (q_{c1N})_{cs} < 50$$

and,

$$\mathrm{CRR}_{7.5} = 93 \left\{\frac{(q_{c1N})_{cs}}{1000}\right\}^3 + 0.08\,; \quad \text{for}, 50 < (q_{c1N})_{cs} < 160$$

Where:

$(q_{c1N})_{cs}$ is the cone penetration resistance obtained after applying corrections for overburden stress and grain characteristics to raw value q_c as obtained in field.

Once estimates of the earthquake loading, CSR, and the soil's strength, CRR, are obtained, the factor of safety (FOS) against liquefaction is determined in the classical way of dividing the strength by the stress:

$$\mathrm{FOS} = \mathrm{CRR} / \mathrm{CSR}$$

Since the CSR is estimated from the seismic hazard assessment, either deterministic or probabilistic, the uncertainty in that parameter is tied to the hazard assessment and can be quantified accordingly. There is also uncertainty in the determination of CRR using the in-situ test data and, to this end, the Bureau of Reclamation (USBR, 2015) recommends that the CRR obtained using in-situ data is not to be considered a hard lower bound on the cyclic loading that could cause liquefaction; instead, it should be treated as an estimate with a probability of liquefaction of 15 to 30%. For structures such as tailings and water dams, there is a wealth of literature to guide designers in adopting suitable minimum factors of safety. For heap leach facilities (heaps and ripios dumps), this is not the case. Thus, the designer should establish acceptance criteria based on the specific facility's consequences of failure.

Static liquefaction hazard assessment

Static liquefaction can occur when loads are applied too quickly. The most common incidents in the mining sector are upstream raises to tailings dams, where the rate of applied load due to the increasing height of the dam can exceed the strength gain in the underlying tailings. However, this can also occur in ripios dumps, or in waste rock dumps placed over weak, wet soil foundations. Plant residue “dry stack” dumps for nickel processing can also be subject to this mode of failure, as the residue is wet and requires time to consolidate and gain sufficient strength for stable slopes. For leach heaps, static liquefaction should generally not be a significant risk even with very poor-quality ores.

Static liquefaction potential is generally assessed using the critical state approach, where the state parameter (Ψ) is defined as the difference between the current void ratio and the void ratio at critical state ($e_{current}$ - $e_{critical\ state}$), at the same effective stress (Jefferies and Been, 2006). The state parameter can be calculated directly from the CPT data, and for this reason, CPT investigations often include producing profiles of Ψ versus depth for each hole. Davies (1999) and Davies et al. (2002), suggest the limiting value of Ψ to guard against static liquefaction as –0.1, implying that values of Ψ greater than approximately (–0.1) could be subject to liquefaction, even though $\Psi<0$ suggests a dilatant state.

However, the CPT approach only works for existing facilities. For facility planning, the risk of static liquefaction is assessed by investigating pore pressure build up due to rapid stacking of a ripios dump (or, in rare cases, the leach heap) through a combination of laboratory testing and numerical modeling very similar to that used for designing upstream tailings dam raises. Just as with tailings dams, as a ripios dump is raised with sequential lifts of waste, the underlying waste needs to consolidate to dissipate the pore pressures, resulting in an increase in effective stress contributing to strength. The rate of consolidation in turn is controlled by the permeability of the material and the distance to a drain. Because some ripios, especially those from sulfuric acid leaching of copper and nickel ores, can have very low permeabilities, the rate of consolidation and the resulting pore pressure dissipation and strength gain can be very slow. If the rate of rise is too quick, the increasing stresses from the freshly placed material can exceed the strength and a static liquefaction ensues.

Modeling and software for liquefaction analysis

A variety of constitutive models like UBCSAND, Hypoplastic, and CASM (Zardari, 2011) have been implemented in commercially available finite element or finite difference computer software to analyze static as well as dynamic liquefaction. Castillo et al. (2005) have demonstrated the use of UBCSAND coupled with the finite difference software FLAC to predict dynamic liquefaction potentials during an earthquake for heap leach pads. Computer analysis using these models and software allow the designer to both estimate the risk of static liquefaction and design effective counter measures. Such measures may include the use of vertical or horizontal drains to speed consolidation and thereby strength gain, buttressing the high-risk areas with better quality material such as waste rock, slowing the rate of rise by constructing a larger area for disposal, or mixing the ripios with better quality material (this is currently being used at one Chilean copper heap leach project, and was previously used at a gold valley fill heap leach project in Peru).

Heap leach analogues

Since there have been no major liquefaction failures in heaps, and only a few in ripios dumps, analogues become important. Dawson et al. (2011) mention a number of flow slide failures over the past quarter century in Rocky Mountain coal mine waste dumps with heights of 100 to 400 m. These dumps were constructed by end-dumping and stabilized at their natural angle of repose of approximately 38°. Initial collapse of structure in some nearly saturated sandy gravel layers within many of these dumps are believed to have caused high pore pressure build up and liquefaction in spite of safe designs produced by conventional static slope stability analyses.

Among the breaches in coal ash ponds, the infamous dyke failure at Tennessee Valley Authority's (TVA) Kingston plant in 2008 is considered as one of the most expensive environmental and industrial disasters. The Kingston failure was the first tailings-like failure to exceed $1 billion in remediation costs. Kingston is an important reference for designing dumps of wet, lower permeability material such as heap leach ripios. Irrespective of whether or not the TVA disaster and other coal ash failures could be decisively attributed to liquefaction, for the dykes being constructed of coal ash, often in the near-saturated state, the liquefaction susceptibility is certainly a reality and is drawing attention. The analogy to heap leaching or building a ripios dump of saturated, weak material such as acid leached copper or nickel ore is self-evident.

Finally, tailings facilities are good analogues, if not at face value, certainly from consideration of the fundamental soil mechanics. The failure of tailings deposits due to liquefaction has been observed for at least sixty years (WISE, 2020). One of the most talked about tailings dam failures due to liquefaction is the El Cobre copper mine dam slide in Chile, triggered by a strong earthquake in 1965 and resulting in more than 200 deaths with 2.25 million cubic meters (m^3) tailings released and travelling 12 km downstream. In 1966 at the Merthyr Vale Colliery-owned coal mine in Wales, UK, a liquefaction-induced dam failure following a heavy rain caused the release of 162,000 m^3 of tailings, killing 144 people. In 1994 the Merriespruit gold tailings dam in South Africa failed, causing 17 deaths and considerable damage. Forensics established that a good percentage of the material in the failed area was of a contracting nature, in a metastable state and the overtopping in conjunction with the erosion of the impoundment wall resulted in static liquefaction of the tailings and a consequent flow failure. The 2015 static liquefaction failure of the Fundão tailings dam at Germano mine in Brazil killed at least 19 people, flooded the town of Bento Rodrigues with polluted slurry which travelled 663 km to the Atlantic Ocean, and caused some $5 billion in damages. This failure was also attributed to inadequate drainage leading to liquefaction. Still fresh in our memories is the January 2019 devastating failure of the tailings dam B-1 at Vale S.A.'s Córrego do Feijáo

Iron Ore Mine in the state of Minas Gerais, Brazil that released 12 million m^3 of tailings flowing down 7 km and killing at least 259 people. The expert panel investigating the case released its final report in December 2019, which declared the failure and the resulting flow slide to be caused by static liquefaction within the tailings body in the dam itself and linked it to a history of marginal designs, inadequate water management, poorly understood tailings characteristics, and excessive rain in the region.

Summary and lessons to be learned

Increasing heights of the heaps and ripios dumps, in conjunction with many drastic failures in the sibling arenas attributed to liquefaction, demand a full understanding of and greater attention to this phenomenon by heap leaching sector professionals. The general principles and the susceptibility criteria for static as well as dynamic liquefaction remain the same as adopted in the sibling arenas of tailings dam, described above, and the failures have a lesson for the heap leach industry. They strongly point to the need for proper consideration of liquefaction susceptibility for ores and ripios of relatively low quality, especially for acid leach operations such as copper, nickel, and uranium. For most operations that have liquefaction susceptible materials serious problems can be avoided if recognized in the design. However, when this is neglected, the problem is much harder to mitigate once in operations and risk to property, the environment and human health can be significant. Operational changes required to circumvent the liquefaction potential, where possible, may even have drastic financial consequences. Some tools helpful to identify and mitigate liquefaction risk are given below:

Ore and ripios characterization: Laboratory testing for grain size analysis with focus on percentage fines, plasticity characteristics, unit weight, permeability and shear strengths of the ore forming the heap, are components of standard testing currently practiced, and must be continued. However, while degradation of both the physical and mechanical properties of the ore upon leaching is a well-known phenomenon, by and large, leach ore tests are generally performed on fresh or slightly aged ore. Such tests can be misleading, and this is one of the reasons that several Chilean heap leach operations are now spending hundreds of millions of dollars to retrofit their facilities. It is recommended that these tests be performed on aged (leached) as well as fresh ore samples.

Additional laboratory testing: Cyclic triaxial or direct shear testing are not part of routine testing for heap leach piles. Understandably, these are more difficult as well as expensive tests. The sample size restrictions and the elaborate setup to get meaningful results from these tests impose additional constraints and not every testing laboratory is equipped to perform these. Nevertheless, these tests should be considered essential for any project with liquefaction-susceptible ore and ripios and the industry must work to eliminate the constraints in conducting these tests and getting meaningful results. As with the other testing, it is important that these tests be performed on properly aged samples to simulate the long-term performance in the heap or ripios dump.

Heap design: Designing heaps and ripios dumps for free draining slopes is a practice that at least one major mining company have adopted, and is best practice for any heap that may have limited long-term permeability. Drained slopes can be achieved by selectively stacking the best quality ore in these areas, by constructing drains similar to a chimney drain in a dam, or by installing vertical drains such as wick drains as the heap is raised (these approaches are in use in two and several mines, respectively).

Operational checks: Once in operation, the heaps and ripios dumps should be evaluated at some routine frequency, ideally using cone penetrometer tests in conjunction with geophysical surveys to detect high saturation zones. Installing an array of piezometers in the heap and regular monitoring to keep track of the phreatic surface is also a good practice and is now being followed in some heap leach facilities. Also, any increase in the irrigation rate during the operation, perhaps for improved kinetics or other metallurgical needs, must be evaluated for the geotechnical impacts and potential contribution to liquefaction risk.

Additional analysis: Considering the large distances to which the liquefied materials have flown in various flow slides, for risk assessment and potential risk management, a run-out analysis should be considered an integral part of operational control as the leach pile height rises. Since the first of its kind analysis method was developed by Lucia (1981), a number of empirical-statistical and analytical models for two and three-dimensional run-out analysis have been developed, viz. Dan-W (Hungr Geotechnical Research, Inc.) and Flo-2 D (Flo-2 D Software, Inc.).

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