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Tailings Impoundment Failures: Are Geotechnical Engineers Listening?

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Are tailings impoundments the most challenging facilities that geotechnical engineers will encounter during their careers? Whether one answers yes or no, there can be no argument that these facilities are indeed challenging and that there is little room for error in their design and stewardship. Where more room has been sought, failures have been the all too frequent result. Can these failures be avoided?

Many geotechnical practitioners get involved with mine tailings impoundments. These practitioners should make themselves familiar with the extensive and, unfortunately, growing database of mine tailings impoundment failure case histories. Many of the failures in the database have been the direct result of a geotechnical failure mode; failure modes that should be less common in modern geotechnical practice. The implications to geotechnical design practice from the trends indicated by the database are clear.

Structural engineers are "technical cousins" to geotechnical engineers. The two groups have similar training in the fundamentals of mechanics and an equal ability to claim that the other "has it easy" in the design process. There can, however, be communication difficulties between the two. Speaking as an unbiased geotechnical engineer, the communication gap is personified by the structural engineer's insistence that the ground is a linear-elastic material and geotechnical engineers are only useful if they will admit to such fact and provide a suitable subgrade reaction modulus at their earliest convenience. Alas, this is also expected while using factors of safety that are 50%, or lower, of those utilized for predictable materials like steel and concrete.

Now, assume that structural engineers wanted to provide some more good-natured fun for their geotechnical cousins. The nature of this fun would take the form of specifying the most challenging project conditions imaginable for the geotechnical engineer. Soliciting the assistance of learned geotechnical associates not aware of their evil intent, the structural engineers would conjure facilities for the geotechnical engineers to design and steward with the following characteristics:

- All of the challenges of water retention dams (e.g. fluid storage with catastrophic results if such storage was unintentionally breached).
- Cannot be breached upon project completion and must remain structurally competent in "perpetuity" (perpetuity is a long time).
- Constantly changing in size and often reaching hundreds of millions of tonnes of material to utilize or store (and occasionally exceeding one billion tonnes).
- Ever changing states of stress.
- Typically under construction for at least 5 to 10 years but construction can be extended to periods of more than 50 or even 100 years.
- Susceptible to brittle undrained loading response.
- Contain real and perceived contaminants.
- Have no ability to generate revenue for its owner (as opposed to a hydro-electric dam, for example) and so generally thought of in less than glowing terms as a necessary, but annoying, cost of doing business.
- Seldom have owners that are familiar with all the key geotechnical issues facing these facilities and thus putting such responsibility on the consulting designer.

Add to this long list of constraints the additional "just for fun" element that the factors of safety to be used are only marginally greater than unity.

To meet the good-natured challenging scenario outlined above, geotechnical engineers only has to note that many of us already deal with such challenges on a daily basis – these challenges are called tailings impoundments.

Tailings impoundments are some of

the largest man-made structures. The largest dam ever constructed is a tailings dam. Tailings impoundments are also one of the most technically challenging elements in geotechnical practice. At the same time, they have provided some of the biggest "black eyes" to the profession with a number of highly publicized failures occurring in recent years.

The current database of failures is speaking clearly to all geotechnical engineers. Are we listening to the message?

The Database

Mine tailings impoundment failures are occurring at relatively high rates. Worldwide, the mining industry has experienced several significant impoundment failures per year over the past 30 years. The rate of failure has actually increased in recent years since a previous peak that occurred in the early-mid 1930's. Many of these failure events have resulted in massive damage, severe economic impact and, in several cases, loss of life. The rate of failure is approximately ten times that for water retention dams.

Conventional water-retention dams continue to be constructed to greater heights with greater storage volumes. However, the safety record for conventional dams has been steadily improving over the past 40 years to the point that the probability of a conventional dam failure in any given year is less than 1 in 10,000

Tailings dams currently have a higher profile than during any previous period. There has been a dramatic increase over the past ten years in the number of regulatory agencies involved in setting prescriptive and/or rigid guidelines. The number of mining companies with internal programs aimed specifically at assessing current and/or planned tailings dams likely outnumbers those who do not; at least for medium to large sized organizations. An increasing number of undergraduate programs offer at least some form of training in the basics of tailings dam design and the number of graduate theses published on tailings dams has roughly doubled over the past decade. Design

professionals have an increasing number of technical forums to update their skills and compare design competency with their peers.

So why do failures of tailings dams continue to occur? Why is the failure rate increasing in comparison to a few decades ago? These failures are not just for older facilities constructed without formal designs, but include facilities designed and commissioned in the past 5 to 20 years - supposedly the "modern age" of tailings dam engineering. As geotechnical practitioners, it is essential that we understand why these failures occur. To facilitate this understanding, a database of all available case histories for involving failure is required.

Based on an extensive literature review and discussions with regulatory officials worldwide, it is estimated that there are more than 3500 appreciable tailings dams worldwide (Davies and Martin, 2000). This total has been obtained from extrapolations and from contributions where relatively good inventory lists exist: For example, 350 in Western Australia, 65 in Quebec, 130 in British Columbia, 400 in South Africa and 500 in Zimbabwe.

As far as performance of these dams, there are a number of publications that summarize portions of the database for worldwide incidents of tailings dam failure. The four most frequently referenced sources are:

1. 1994 USCOLD database of tailings dam failure incidents,
2. 1996 UNEP database on mine waste incidents,
3. 1997 USEPA summary of relatively recent tailings dam incidents largely focusing on non-compliant events and limited to certain jurisdictions of the United States, and
4. WISE Internet site.

The author, through post-event reviews and similar assignments, has been made aware of a significant number of failure case histories not captured by any of the publications listed above, but which have occurred within similar timeframes and jurisdictions. This is not a criticism of any of the efforts listed above - these summary documents are of tremendous value. The point made is that these publications do

not offer the entire suite of information available on tailings dam failures. A great many failures (and the valuable lessons associated with them) go unpublished due to among other reasons, sensitivity and legal implications.

The complete database includes case histories published as single events or in compilations such as those noted above. The database has been further augmented with largely unpublished information gathered by the author over time. Based on this larger database, it can be concluded that for the past 30 years, there have been approximately 2 to 5 "major" tailings dam failure incidents per year. During no year were there less than two events (1970-2001, inclusive). If one assumes a worldwide inventory of 3500 tailings dams, then 2 to 5 failures per year equates to an annual probability somewhere between 1 in 700 to 1 in 1750. This rate of failure does not offer a favourable comparison with the less than 1 in 10,000 that appears representative for conventional dams. The comparison is even more unfavourable if less "spectacular" tailings dam failures are considered. Furthermore, these failure statistics are for physical failures alone. Tailings impoundments can have environmental "failure" while maintaining sufficient structural integrity (e.g. impacts to surface and ground waters).

Example Case Histories for Tailings Impoundment Failures

To better illustrate the nature of tailings impoundment failures, and hence their impacts, a few examples where Geotechnical failure modes were involved are introduced. In each case, the likely cause of the failure is suggested along with information indicating factual versus perceived impact and lessons that can be learned from the event.

Within the full spectrum of failure modes that have occurred at large tailings impoundments, static liquefaction is likely the most common, and at the same time likely the least understood. As design practice in many mining regions has in fact seemingly discounted the possibility of the mechanisms and conditions for this failure mode, the possibility of its occurrence has often

been overlooked in the search for other causes of failure.

Liquefaction has been well documented in the literature. Liquefaction is a term most often associated with seismic events. However, mine tailings impoundments have demonstrated more static liquefaction events than seismically induced events.

Static liquefaction, and the resulting flowslide of liquefied tailings materials, is indeed a relatively common phenomenon among the more dramatic tailings impoundment failure case histories. Static liquefaction can be a result of slope instability issues alone, or can be triggered as a result of other mechanisms. The fundamentals of static liquefaction are summarized in Davies et al. (2002).

Three static liquefaction case histories are described to demonstrate various ways in which this failure mechanism has manifested itself. Based on an understanding of the fundamentals and the lessons learned from such case histories, general guidelines to minimize the potential for failure in tailings impoundments are presented.

Sullivan Mine, Canada - 1948 and 1991

Davies et al. (1998) describe the static liquefaction event that occurred within the Active Iron Pond tailings impoundment at the Sullivan Mine in August of 1991. The event resulted in a flowslide. Fortunately, a second tailings dyke contained the flow and no off-site impact was experienced. The dam had been built on a foundation of older tailings that were placed as beach below water (BBW) material. The failure occurred to the upstream constructed facility with the initiation of shear stresses in the foundation tailings that exceeded the shear strength. The tailings were loose (generally state parameter, $\Psi > +0.05$), fine-grained silty sand to sandy silt. Pore pressures rose as the material strained and impeded drainage led to a liquefaction event. The downstream slope of the dyke was roughly 3H:1V, The Sullivan tailings facility had been under the design and monitoring stewardship of a recognized consulting organization. This event served to dem-

onstrate that "a well intentioned corporation employing apparently well-qualified consultants is not adequate insurance against serious incidents" (Morgenstern, 1998).

Ironically, the 1991 event was similar in nature to a dyke failure that occurred in 1948. The passage of more than forty years should not have been enough to induce Tailings Dam Amnesia, TDA. TDA refers to a state of tailings dam design or stewardship where lessons available at that very site are ignored in spite of ample available information on-site, visual evidence of previous event occurrence and/or published accounts of incidents on a given project.

Merriespruit, South Africa – 1994

The Harmony Gold Mine in South Africa utilized a "paddock" system for tailings management. Paddock systems are relatively common in South Africa and are essentially upstream constructed tailings impoundments with little freeboard and relatively saturated BBW dam shells. The mine was located

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near the town of Merriespruit. The Merriespruit failure occurred on February 22, 1994 in the evening. A massive failure of the north wall occurred following a heavy rainstorm. Overtopping due to inadequate freeboard was ample trigger for static liquefaction once enough toe material was eroded away. More than 600,000 m^3 of tailings and 90,000 m^3 of water were released. The slurry traveled about 2 km covering

nearly 500,000 m^2. Given the downstream population, it is fortunate that not more than 17 people lost their lives in this tragedy.

The Harmony tailings were quite fine-graded with more than 60% finer than 74 µm. However, these fines were also essentially cohesionless and once an area of the dam toe was eroded and local slopes were increased to the range of 2H:1V, static liquefaction and the massive flowslide was initiated soon after. Fourie et al. (2001) stated that a large portion on the tailings had $\Psi > 0.1$.

Essentially all of the post-failure laboratory testing exhibited dilatant behavior, leading a number of well-published engineers to suggest that the failure mode was uncertain. The fact that contractant behavior could not be easily coaxed from the tailings in a laboratory setting yielded the flawed conclusion that they must then be dilatant in both the laboratory and field settings. This conclusion was reached even in light of in-situ piezocone data that clearly indicated the potential for an in-situ contractant response to rapid transient loading. Terzaghi noted, *"nature has no contract with mathematics – she has even less of an obligation to laboratory test procedures and results"*. The author has encountered too many geotechnical projects in general, and tailings dam projects in particular, in which distrust and skepticism were regarded toward anything that could not be demonstrated by laboratory testing. This is a very curious attitude and has not helped understand/prevent a number of tailings impoundment failures. For the Merriespruit failure, in the giant stress-controlled test represented by the dam itself, contractant, undrained behavior clearly resulted.

Stava, Italy – 1985

Perhaps the most tragic tailings impoundment failure to date occurred on July 19, 1985. A flourite mine, located near Stava in Northern Italy, had both of its tailings dams fail suddenly in "domino" fashion and release approximately 240,000 m^3 of liquefied tailings. The liquefied mass moved up to speeds of 60 km/h obliterating everything in its

path for a stretch of some 4-km. The flowslide destroyed the village of Stava and also caused considerable damage at Tesero, at the junction of Stava Creek and the Avisio River at the 4 km point from the mine.

Both tailings dams were nearly 25 m high with one constructed directly upstream of the other. The failure mechanism began with failure of the upper dam that in turn overtopped and caused failure of the lower dam. The dams were upstream constructed with outer slopes ranging between 1.2 to 1.5 horizontal and 1 vertical. Based upon the likely state of the in-situ tailings, the soil mechanics curiosity with this failure is that the dams could attain such a height prior to failure. There is no question that the design of these dams was not consistent with even the most elementary engineering principals available at the time. There are a number of "rules" for upstream tailings dam engineering (summarized recently by Davies and Martin, 2000) that were understood for many years prior to the Stava failure. The Stava dams both broke far more of these rules than they followed.

One of the earliest descriptions of a liquefaction failure is that given by Hazen (1920), in his paper on the failure of the Calaveras Dam during its construction by hydraulic methods. In the tendency to over-complicate the practice of soil mechanics over the last few decades, wisdom contained in the key literature of the past appears to have gone forgotten. Static liquefaction was understood to be a potential threat to the safety of tailings impoundments well before complex laboratory testing, stress paths, critical state soil mechanics and limit equilibrium and stress-deformation computer power became popular and available. For example, Casagrande and MacIvor (1970) stated, "the loose and saturated granular or chemical wastes deposited behind a relatively thin shell of supporting material could cause failure of the tailings dam. While undisturbed tailings may adequately contribute to the stability of the dam, the strength of such a "shell" cannot possibly withstand liquefied tailings". This quotation is not offered for its novelty or profundity but for the reason that, by its very self-evident simplicity, it is difficult to believe that it has been ignored repeatedly in the past 30 plus years. The Stava failure clearly failed per the predicted scenario noted by Casagrande and MacIvor.

Los Frailes, Spain – 1998

Possibly the most publicized tailings dam failure to date was the April 1998 Aznalcollar (Los Frailes) event in Spain. A shallow foundation failure led to the release more than 5×10^6 m^3 of process water and tailings from one of two adjacent ponds within an overall impoundment. For this failure, a lack of understanding of the prevailing foundation conditions was directly attributable to a design that was contraindicated by site conditions. Rapid foundation movements created shear strains that triggered static liquefaction of impounded tailings exacerbating the flow volumes.

The Los Frailes incident, besides demonstrating the immense power of the media to bring tailings dam failure events to a worldwide audience in a matter of hours, allowed a candid assessment of how such incidents can have immediate, and dramatic, impact on a mining company's finances. While other events were certainly at play in 1998, the failure triggered an immediate negative stock market response. The event occurred at only one of a number of mines for a relatively major mining company. The dramatic share devaluation of the parent company in 1998 demonstrated the collective impact a single tailings failure event can have on the medium-term investment confidence in a given corporation. The implicit geotechnical responsibility that goes with designing tailings impoundments was emphasized by the Aznalcollar failure.

Other Considerations

The education being received by engineers involved in tailings impoundment design is obviously highly influential to their design abilities. This is particularly the case with static liquefaction, which is a key contributor to the tailings dam failure database. Classical soil mechanics as found in many textbooks still being used today presents a simplistic and erroneous view for the loading of saturated cohesionless granular particles (usually lumped together as "sands") and water systems – that is for example, most tailings. The simplistic view is that by defining the friction angle and pore pressure of the sand we can predict the strength of that sand, the drained strength. The exception these references allow for sands is during an earthquake when the sand may become 'liquefied'. Clays on the other-hand are deemed to be cohesive and have an undrained strength. Those readers who have benefited from a more enlightened education during their geotechnical careers may not find this a credible proposition. However, even into the 21st century, a range of educators, regulatory and quasi-governmental groups, and an alarming number of geotechnical practitioners still have not un-learned their first series of lectures in soil mechanics based on textbooks expounding the views noted above. Until these simplistic models have been un-learned by all involved with the design, licensing, and construction of tailings impoundments, a major contributor to failures, i.e. inappropriate and incorrect designs based upon a lack of understanding of the tailings strength, will likely continue.

There is a wide range of specialized literature on the subject of the strength of cohesionless soils and their interactions with shear-induced pore pressures. However, little of this is to be found in textbooks, it is mostly in technical journals and specialized publications. Recent useful discussions can be found, for example, in Martin and McRoberts (1998), Carrier (1991), and Been (1999). These are written from the perspective of geotechnical engineers with a thorough understanding of tailings materials and provide a starting point for newcomers to the considerable volume of literature that exists.

The most fundamental of the "new" lessons on cohesionless soil (sand and most silts) strength is that like a clay, rapidly loaded saturated cohesionless soils can have an undrained strength, and like clay this strength can be stress

and strain path dependent. Loose sands/silts such as those deposited in many tailings beaches can have a very low strength; they contract during shear just like a sensitive clay. However, unlike clays that have a unique void ratio compression state, sand has wide ranges in its void ratio compression state. The wide ranges in the initial void ratio of sands, and of the fabric of field-scale deposits of these sands, means that predictions of the in-situ undrained strength for these materials is challenging to the design professional.

If a proper understanding of undrained strength of tailings had been available to many designs, the failure database would be much smaller.

Omai, Guyana – 1994

A non-liquefaction case is noted to demonstrate that other geotechnical issues are of concern with tailings impoundments. Another highly publicized event, the internal erosion failure of the Omai mine tailings dam, involved a dam breach and the release of cyanide-laden water to the Omai River and then to the much larger Essequibo River. This event caused debatable environmental damage with reports of downstream devastation far outstripping the ability of the dilute contamination to ever accomplish.

The failure was likely the first tailings incident to provoke worldwide outrage. However, the technical debate that was part of the aftermath of this failure was as unique as the degree of public outcry in comparison with the actual damage to the environment. Following extensive post-failure investigations, representatives of the original design consultant and the post-incident Dam Review Team strongly disagreed on relatively basic engineering issues involved in both the original design and the ultimate failure mechanism(s). This disagreement was quite visible in Geotechnical News (Haile, 1997 and Vick, 1997, respectively). It is difficult to learn from case histories when there is as much controversy over simple engineering principles supposedly available at the undergraduate level.

Geotechnical Issues and Trends Apparent in The Database

By combining published accounts of failures and those available through reviews, industry contacts and similar sources, several trends from the tailings impoundment failure database are evident. These are outlined below.

- Active impoundments are more susceptible to tailings dam failure - this trend may diminish over time if the current trend advocated by some to flood all tailings impoundments upon closure gains momentum
- Upstream constructed dams = more incidents. This statement is not quite fair since there are more upstream dams than other geometries, however upstream dams are more susceptible to liquefaction flow events and are solely responsible for all major static liquefaction events

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There was a lack of design ability, poor stewardship (construction, operating or closure) or a combination of the two, in each and every case history. If basic design and construction requirements are ignored, a tailings dam's candidacy as a potential failure case history is immediate.

- Seepage related phenomena (e.g. piping due to poor filter design and/or construction such as was evident in the Omai dam failure) are the main failure mode for non-upstream tailings dams
- Earthquakes are of little consequence for most non-upstream dams
- For inactive impoundments, overtopping is cited as the primary failure mode in nearly 1/2 of the incidents

The list of trends from the database can be continued and has been presented in the past by many others. However, reviewers of the case histories seldom make the most important conclusion; that is that there have been no unexplained failure events. If one becomes a student of tailings dam failure case histories, and all designers and regulators should indeed do just that, a single conclusion arises. These failures, each and every one, were entirely predictable in hindsight. There are no unknown loading causes, no mysterious soil mechanics, no "substantially different material behaviour" and definitely no acceptable failures. In all of the cases over the past thirty years, the necessary geomechanical knowledge existed to prevent the failure either at the design and/or operating stage. There was lack of design ability, poor stewardship (construction, operating or closure) or a combination of the two, in each and every case history. If basic design and construction requirements are ignored, a tailings dam's candidacy as a potential failure case history is immediate.

The failure database summarizes the main contributory failure mode(s) from the tailings dam failures that have occurred. In each case, elementary engineering issues and/or basic operating issues have been involved. There is no need for exotic explanations for the failures and no need to question the fundamental principles of engineering geomechanics. The latter have governed in each failure case but unfortunately were seemingly lost along the way.

Minimum Requirements for the Geotechnical Engineer Involved with Tailings Impoundments

The failure database, if we wish to listen, is speaking very clearly to Geotechnical Engineers with respect to our minimum technical responsibilities when dealing with tailings impoundments. The list of lessons being noted, if not shouted, by the database includes:

- Understanding that any tailings impoundment that derives some or all of its structural support from the tailings themselves needs to ensure that those tailings are not contractant under any conceivable shear loading
- Drained loading factors of safety are

of little relevance to the potential structural calamity a tailings impoundment can represent – if you have any upstream-constructed and/or BBW tailings, you need an undrained evaluation

- Tailings are very erosive and piping works that are placed through tailings are to be avoided. Impoundments with excessive seepage or impoundments without appropriate spillways are often destined to be more temporary than intended by the designer (and certainly by the owner)

- Past designs should not be relied upon for a new project – no two sites have identical foundation, tectonic, hydrogeological, tailings characteristics, operating criteria etc. etc.. – avoid an "off the shelf" design mentality – tailings impoundments are not automobiles and cannot be mass produced

- Filter designs are not optional and ignoring 1 or 2 out of the ten golden rules is not "a good score for getting 80 or 90%", it is increased candidacy for the failure database

- Welcome independent peer review - do not view such as an attack on your design and/or professional competency but a benefit to you as much as your client

Summary and Conclusions

Consider the following Tailings Dam Failure Axiom - Tailings dam failures are a result of design, construction and/or operational management flaws - not "acts of god".

As a positive corollary to the axiom, if the reasons for tailings dam failures are readily identifiable, there is the potential to essentially eliminate such events with an industry-wide commitment to correct design and stewardship practices. The necessary knowledge for such a scenario exists; the knowledge just has to be used.

From the design perspective, the impoundments have, and continue to, speak to us. Are we listening?

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