Failures of Tailings Impoundments: Are Attention by Geotechnical Engineers

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ABSTRACT: Are tailings impoundments the most difficult structures that geotechnical engineers will ever work on?

Whether the answer is yes or no, there is no denying the difficulty of these facilities and the limited margin for error in their care. Everywhere additional space has been sought, failures have all too frequently been the outcome. Can these errors be prevented?Mine tailings impoundments are a common area of involvement for geotechnical professionals. These professionals ought to get aware with the vast and regrettably expanding case studies of mine tailings impoundment failure. Geotechnical failure modes, which ought to be less frequent in contemporary geotechnical practise, have been directly responsible for many of the failures in the database. The trends the database indicates have apparent ramifications for geotechnical design practise.

- Cannot be breached upon projectcompletion and must remain struc- turally competent in “perpetuity” (perpetuity is a long time).
- Constantly changing in size and of- ten reaching hundreds of millions of tonnes of material to utilize or store (and occasionally exceeding one bil-lion 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 contami-nants.
- Have no ability to generate revenue for its owner (as opposed to a hy- dro-electric dam, for example) and so generally thought of in less than

Geotechnical engineers and structural engineers are "technical cousins." The two groups are equally qualified to assert that the other "has it easy" during the design process and have received similar instruction in the foundations of mechanics. Yet, there may be communication issues between the two. The structural engineer's insistence that the ground is a linear-elastic material personifies the communication gap, in my opinion. Geotechnical engineers can only be helpful if they acknowledge this fact and supply a reasonable subgrade reaction modulus as soon as possible.

Unfortunately, this is also anticipated when adopting safety factors that are 50% or less of those used for predictable material in addition to steel and concrete.

Consider for a moment that structural engineers decided to give their geotechnical relatives a little more pleasure.

The nature of this fun would take the form of speci- fying the most challenging project con- ditions 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 charac-teristics:

- All of the challenges of water reten-tion dams (e.g. fluid storage with cat-astrophic results if such storage was unintentionally breached). glowing terms as a necessary, but an-noying, cost of doing business.
- Seldom have owners that are familiar with all the key geotechnical issues facing these facilities and thus putt- ing such responsibility on the con- sulting 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 challeng-ing scenario outlined above, geotechnical engineers only has to note that many of us already deal with such challenges on a daily basis – these chal-lenges are called tailings impound- ments.

Tailings impoundments are some of the largest man-made structures. The largest dam ever constructed is a tail-ings dam. Tailings impoundments are also one of the most technically chal-lenging elements in geotechnical prac-tice. 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 en-gineers. Are we listening to the mes- sage?

The Database

Mine tailings impoundment failures are occurring at relatively high rates. Worldwide, the mining industry has ex- perienced several significant impound- ment failures per year over the past 30 years. The rate of failure has actually in- creased 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 approx-imately ten times that for water reten- tion dams.

Conventional water-retention dams continue to be constructed to greater heights with greater storage volumes. However, the safety record for conven-tional dams has been steadily improv- ing 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 in- crease over the past ten years in the number of regulatory agencies involved in setting prescriptive and/or rigid guidelines. The number of mining com-panies with internal programs aimed specifically at assessing current and/or planned tailings dams likely outnum- bers those who do not; at least for me- dium to large sized organizations. An increasing number of undergraduate programs offer at least some form of training in the basics of tailings dam de-sign and the number of graduate theses published on tailings dams has roughly doubled over the past decade. Design professionals have an increasing num- ber 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 de- signed 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 re- view 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 ob- tained from extrapolations and from contributions where relatively good in-ventory 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 refer-enced 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 re- views and similar assignments, has been made aware of a significant num-ber 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 docu-ments are of tremendous value. The point made is that these publications do not offer the entire suite of informationavailable on tailings dam failures. A great many failures (and the valuable lessons associated with them) go un- published 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 aug- mented with largely unpublished infor-mation 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 inci- dents per year. During no year were there less than two events (1970-2001, inclusive). If one assumes a worldwideinventory of 3500 tailings dams, then 2to 5 failures per year equates to an an- nual probability somewhere between 1in 700 to 1 in 1750. This rate of failure does not offer a favourable comparison with the less than 1 in 10,000 that ap- pears representative for conventional dams. The comparison is even more unfavourable if less "spectacular" tail-ings dam failures are considered. Fur- thermore, these failure statistics are for physical failures alone. Tailings im- poundments can have environmental"failure" while maintaining sufficient structural integrity (e.g. impacts to sur-face and ground waters).

Example Case Histories for Tailings Impoundment Failures To better illustrate the nature of tailingsimpoundment failures, and hence theirimpacts, a few examples where Geotechnical failure modes were in-volved are introduced. In each case, thelikely cause of the failure is suggestedalong with information indicating fac-tual versus perceived impact and les-sons that can be learned from the event.

Within the full spectrum of failure modes that have occurred at large tail- ings impoundments, static liquefaction is likely the most common, and at the same time likely the least understood. As design practice in many mining re- gions has in fact seemingly discountedthe possibility of the mechanisms and conditions for this failure mode, thepossibility of its occurrence has often been overlooked in the search for othercauses of failure.

Liquefaction has been well docu-mented in the literature. Liquefaction isa term most often associated with seis-mic events. However, mine tailings im-poundments have demonstrated more static liquefaction events than seismi- cally induced events.

Static liquefaction, and the resultingflowslide of liquefied tailings materials,is indeed a relatively common phenom-enon among the more dramatic tailingsimpoundment failure case histories. Static liquefaction can be a result ofslope instability issues alone, or can betriggered as a result of other mecha-nisms. The fundamentals of static liq-uefaction are summarized in Davies etal. (2002).

Three static liquefaction case histo- ries are described to demonstrate vari- ous ways in which this failure mechanism has manifested itself. Based on an understanding of the fundamen- tals and the lessons learned from such case histories, general guidelines to minimize the potential for failure in tail-ings impoundments are presented.
onstrate that "a well intentioned corporation employing apparently well-qualified consultants is not ade- quate insurance against serious inci-dents" (Morgenstern, 1998).

Ironically, the 1991 event was simi-lar in nature to a dyke failure that oc- curred in 1948. The passage of more than forty years should not have been enough to induce Tailings Dam Amne-sia, TDA. TDA refers to a state of tail-ings dam design or stewardship where lessons available at that very site are ig- nored in spite of ample available infor- mation on-site, visual evidence ofprevious event occurrence and/or pub- lished accounts of incidents on a givenproject.

Merriespruit, South Africa –1994

The Harmony Gold Mine in South Af-
rica utilized a "paddock" system for tailings management. Paddock systems are relatively common in South Africa and are essentially upstream con- structed tailings impoundments with lit-tle freeboard and relatively saturated BBW dam shells. The mine was located nearly 500,000 m^2. Given the down- stream population, it is fortunate that not more than 17 people lost their livesin 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 oncean area of the dam toe was eroded andlocal slopes were increased to the rangeof 2H:1V, static liquefaction and themassive flowslide was initiated soon af-ter. Fourie et al. (2001) stated that alarge portion on the tailings had $\Psi > 0.1$. Essentially all of the post-failure laboratory testing exhibited dilatant be- havior, leading a number of well-pub-lished engineers to suggest that thefailure mode was uncertain. The factthat contractant behavior could not be easily coaxed from the tailings in a labo-ratory setting yielded the flawed con-clusion that they must then be dilatant inboth the laboratory and field settings. This conclusion was reached even inlight of in-situ piezocone data thatclearly indicated the potential for anin-situ contractant response to rapidtransient loading. Terzaghi noted, *"na-
ture has no contract with mathematics –*

Sullivan Mine, Canada - 1948 and 1991

Davies et al. (1998) describe the static

she has even less of an obligation to lab-oratory test procedures and results". The author has encountered too many
liquefaction event that occurred within
the Active Iron Pond tailings impound- ment at the Sullivan Mine in August of 1991. The event resulted in a flowslide. Fortunately, a second tailings dyke con-tained 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 stew- ardship of a recognized consulting or- ganization. This event served to dem-**"a well intentioned corporation employing apparently well-qualified consultants is not adequate insurance against serious incidents"(Morgenstern, 1998)**

near the town of Merriespruit. TheMerriespruit failure occurred on Febru-ary 22, 1994 in the evening. A massivefailure of the north wall occurred fol- lowing 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. Theslurry traveled about 2 km covering

geotechnical projects in general, and tailings dam projects in particular, in which distrust and skepticism were re- garded toward anything that could not be demonstrated by laboratory testing. This is a very curious attitude and has not helped understand/prevent a num- ber of tailings impoundment failures. For the Merriespruit failure, in the giantstress-controlled test represented by thedam itself, contractant, undrained be- havior clearly resulted.

Stava, Italy – 1985

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

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

Both tailings dams were nearly 25 mhigh with one constructed directly up- stream of the other. The failure mecha- nism 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 hori-zontal and 1 vertical. Based upon the likely state of the in-situ tailings, the soil mechanics curiosity with this fail- ure is that the dams could attain such aheight prior to failure. There is no ques-tion that the design of these dams was not consistent with even the most ele- mentary engineering principals avail- able at the time. There are a number of"rules" for upstream tailings dam engi-neering (summarized recently byDavies and Martin, 2000) that were un-derstood for many years prior to the Stava failure. The Stava dams both broke far more of these rules than theyfollowed.

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 con- struction by hydraulic methods. In the tendency to over-complicate the prac- tice of soil mechanics over the last fewdecades, 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 mechan- ics and limit equilibrium and stress-de- formation computer power became popular and available. For example, Casagrande and MacIvor (1970) stated,"the loose and saturated granular orchemical wastes deposited behind a rel-atively thin shell of supporting materialcould cause failure of the tailings dam.While undisturbed tailings may ade-quately contribute to the stability of thedam, the strength of such a "shell" can-not possibly withstand liquefied tail-ings". This quotation is not offered forits novelty or profundity but for the rea-son that, by its very self-evident sim- plicity, it is difficult to believe that it hasbeen 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 tailingsdam failure to date was the April 1998Aznalcollar (Los Frailes) event inSpain. A shallow foundation failure ledto the release more than 5 x 10^6 m^3 ofprocess water and tailings from one oftwo adjacent ponds within an overallimpoundment. For this failure, a lackof understanding of the prevailing foun- dation conditions was directly attribut-able to a design that was contraindi-cated by site conditions. Rapid foundation movements created shearstrains that triggered static liquefactionof impounded tailings exacerbating theflow 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 as- sessment 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 immediatenegative stock market response. The event occurred at only one of a numberof mines for a relatively major mining company. The dramatic share devalua-tion of the parent company in 1998demonstrated the collective impact a single tailings failure event can have on the medium-term investment confi- dence in a given corporation. The im- plicit geotechnical responsibility thatgoes with designing tailings impound- ments was emphasized by the Aznalcollar failure.

Other Considerations

The education being received by engi- neers involved in tailings impoundment design is obviously highly influential to their design abilities. This is particu- larly the case with static liquefaction, which is a key contributor to the tailings dam failure database. Classical soil mechanics as found in many textbooks stillbeing used today presents a simplistic and erroneous view for the loading of saturated cohesionless granular parti- cles (usually lumped together as“sands”) and water systems – that is forexample, most tailings. The simplisticview is that by defining the friction an-gle and pore pressure of the sand we canpredict 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 un- drained strength. Those readers who have benefited from a more enlightened education during their geotechnical ca- reers may not find this a credible propo- sition. However, even into the 21st cen- tury, 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 me- chanics based on textbooks expound- ing the views noted above. Until thesesimplistic models have been un-learned by all involved with the de- sign, licensing, and construction of tailings impoundments, a major con- tributor 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 interac- tions with shear-induced pore pres- sures. However, little of this is to be found in textbooks, it is mostly in tech-nical journals and specialized publica- tions. Recent useful discussions can be found, for example, in Martin and McRoberts (1998), Carrier (1991), andBeen (1999). These are written from the perspective of geotechnical engi- neers with a thorough understanding of tailings materials and provide a startingpoint for newcomers to the considerablevolume 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. Loosesands/silts such as those deposited inmany tailings beaches can have a verylow strength; they contract during shearjust like a sensitive clay. However, un-like clays that have a unique void ratiocompression state, sand has wideranges in its void ratio compressionstate. The wide ranges in the initial voidratio of sands, and of the fabric offield-scale deposits of these sands,means that predictions of the in-situ un-drained strength for these materials is challenging to the design professional. If a proper understanding of un- drained strength of tailings had beenavailable to many designs, the failure database would be much smaller.

Omai, Guyana – 1994

A non-liquefaction case is noted to demonstrate that other geotechnical is-sues are of concern with tailings im- poundments. Another highly publicized

Geotechnical Issues andTrends Apparent in The Database

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

- Active impoundments are more sus-ceptible to tailings dam failure - thistrend may diminish over time if the current trend advocated by some to flood all tailings impoundmentsupon closure gains momentum
- Upstream constructed dams = moreincidents. This statement is not quitefair since there are more upstream dams than other geometries, how- ever upstream dams are more sus- ceptible to liquefaction flow events and are solely responsible for all ma-jor static liquefaction eventsthe past by many others. However, re-viewers of the case histories seldom make the most important conclusion; that is that there have been no unex- plained failure events. If one becomes a student of tailings dam failure case his-tories, and all designers and regulators should indeed do just that, a single con-clusion arises. These failures, each and every one, were entirely predictable in hindsight. There are no unknown load-ing causes, no mysterious soil mechan-ics, 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 acombination of the two, in each and ev-ery case history. If basic design and con-struction requirements are ignored, a

event, the internal erosion failure of the Omai mine tailings dam, involved a tailings dam's candidacy as a potentialfailure case history is immediate.
dam breach and the release of cyanide-laden water to the Omai River andthen to the much larger Essequibo River. This event caused debatable en-vironmental damage with reports of downstream devastation far outstrip-ping the ability of the dilute contamina-tion to ever accomplish.

The failure was likely the first tail- ings incident to provoke worldwide out-rage. 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 theThere was a lack of designability, poor stewardship (construction, operating orclosure) or a combination of the two, in each and every case history. If basicdesign and construction requirements are

ignored, a tailings dam'scandidacy as a potentialfailure case history is immediate.

The failure database summarizes themain contributory failure mode(s) fromthe tailings dam failures that have oc- curred. In each case, elementary engi- neering issues and/or basic operating issues have been involved. There is no need for exotic explanations for the fail-ures and no need to question the funda-mental principles of engineering geomechanics. The latter have governedin each failure case but unfortunately were seemingly lost along the way.

Minimum Requirements for the

actual damage to the environment. Fol- lowing extensive post-failure investiga-

Geotechnical Engineer Involved with TailingsImpoundments

tions, representatives of the original
design consultant and the post-incidentDam Review Team strongly disagreedon relatively basic engineering issues involved in both the original design andthe ultimate failure mechanism(s). Thisdisagreement was quite visible in Geotechnical News (Haile, 1997 and Vick, 1997, respectively). It is difficultto learn from case histories when thereis as much controversy over simple engineering principles supposedly avail- able at the undergraduate level.

- Seepage related phenomena (e.g. piping due to poor filter design and/or construction such as was evi-dent in the Omai dam failure) are themain failure mode for non-upstreamtailings dams
- Earthquakes are of little conse- quence for most non-upstream dams
- For inactive impoundments, over-topping is cited as the primary failuremode in nearly 1/2 of the incidents

The list of trends from the database canbe continued and has been presented in

The failure database, if we wish to lis- ten, is speaking very clearly to Geotechnical Engineers with respect to our minimum technical responsibilitieswhen dealing with tailings impound- ments. The list of lessons being noted,if not shouted, by the database includes:

- Understanding that any tailings im- poundment that derives some or all of its structural support from the tail- ings themselves needs to ensure thatthose tailings are not contractant un-der any conceivable shear loading
- Drained loading factors of safety are of little relevance to the potential structural calamity a tailings im- poundment 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 tail- ings are to be avoided. Impound- ments with excessive seepage or impoundments without appropriate spillways are often destined to be more temporary than intended by thedesigner (and certainly by the owner)
- Past designs should not be reliedupon for a new project – no two siteshave identical foundation, tectonic, hydrogeological, tailings character-istics, operating criteria etc. etc.. – avoid an "off the shelf" design men-tality – tailings impoundments are not automobiles and cannot be massproduced
- Filter designs are not optional and ig-noring 1 or 2 out of the ten golden rules is not "a good score for getting80 or 90%", it is increased candidacyfor the failure database
- Welcome independent peer review - do not view such as an attack on your design and/or professional compe- tency but a benefit to you as much asyour client

Summary and Conclusions Consider the following Tailings DamFailure Axiom - Tailings dam failuresare a result of design, constructionand/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 po-tential to essentially eliminate such events with an industry-wide commit- ment to correct design and stewardship practices. The necessary knowledge forsuch a scenario exists; the knowledge just has to be used.

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

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