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MANAGING CHANGE AND OPTIMISING ASH STORAGE IN AN OPERATIONAL TAILINGS FACILITY

T.A. WILLIAMSON AND M. BARKER
GHD, Brisbane, Queensland, Australia

M. COSTA
CS Energy, Brisbane, Queensland, Australia

ABSTRACT

Changing circumstances at operational tailings facilities often drive the need to adapt existing management plans. Increased requirements for storage of tailings and process water may result in an urgent need to design and build new or higher dams in locations not previously considered. This paper uses the example of an ash storage facility in Australia to discuss important factors to consider when managing change and it illustrates how to "keep the plane flying" whilst designing and building safe and environmentally responsible dams. It considers the necessity for complying with regulatory requirements, company policies, business needs and sound engineering and environmental practices, as well as keepingthe public safe. The ongoing challenge of how to address the potential risk of liquefaction whilst increasing storage capacity is discussed, as well as how to evaluate static liquefaction in these fast-moving and variable sites. Some examples on managing change within this operational site areprovided, including the importance of utilizing skilled operators and qualified engineers,reviewing and updating procedures, and monitoring the dams to ensure their compliance with safety regulations and guidelines.

1. INTRODUCTION AND BACKGROUND

1.1 Arrangement of the Callide power stations and waste containment facility

CS Energy operates the Callide coal-fired power station facility that is located 18km north east of the rural township of Biloela located in the Banana Shire, CentralQueensland in Australia. The site consists of three power stations, Callide A, Callide B and Callide C,and a waste containment facility (WCF), which contains multiple ash storage dams comprising Ash Dam 1 (AD1), Ash Dam 2 (AD2), Ash Dam 3 (AD3) (including a bottom boiler ash storage stockpile known as BS3),Ash Dam 4 (AD4) and Ash Dam B (ADB).The WCF also includes approximately 130 ha of evaporation ponds as part of the facility's water management system. The layout of the power stations, ash dams and evaporation ponds within the WCF is presented in Figure 1.

Callide A is in a 'closed state' as of December 2015 and the site will remain 'dormant' until an economic justification is established to demolish it for scrap value. Callide B was commissioned during 1988/1989 with a nominal 30-year life. Callide C was commissioned in 2001 with an expected operational life of approximately 35 years. Callide C is owned through a 50-50 joint venture between CS Energy and InterGen, and operated by CS Energy.

The dams in the WCF store the fly ash, bottom boiler ash (BBA) and process waste water produced from the power stations.These waste products are mostly conveyed to the storage areas as a 'lean or dense phase slurry'(a mix of ash and water with dense phase having a higher solids content than lean phase) by pumped pipelines. This process is often referred to as 'ash slurry deposition'. Some of the BBA is transported to the WCF as a 'dry material' by trucks, and some of the fly ash is sold to the cement industry.

AD1, AD2 and AD3 received ash from Callide A and have been filled. AD2 has been rehabilitated by conversion into a wetlands area. AD4 was commissioned in the early 1980s and similarly received ash from Callide A, prior to its closure. At the time of writing, AD4 periodically receives BBA from Callide C and occasionally some lean phase ash from Callide B.

Figure 1 : Layout of Callide power stations and WCF.

The design of the Callide B and C ashing systems was based on the conveyance of both fly ash and bottom ash to ADB via a dense phase slurry system. This was aimed at improving ash storage efficiency within the WCF resulting from the higher in-situ dry density and greater stacking height achieved by this ash delivery method.

1.2 Operational challenges

Operational problems with the dense phase slurry system have persisted since its original commissioning and the system has rarely performed as designed. Particularly for Callide C, thishas resulted in operating the system effectively as a medium phase slurrywith only the flyash component conveyed to the WCF. Originally the BBA component was dewatered,trucked and stored on the surface of the decommissioned AD3 and this area became known as BS3 (refer to Figure 1). BS3storage area has reached its final landform height and BBA is now trucked to an area within the AD4catchment known as the 'night dump' and other stockpile areas within the WCF.Stockpiles of BBA are primarily used for constructingash disposal cell bunds within the WCF.

These ongoing issues had resulted in considerable additional operational effort and expenditure to control placement of the ash (e.g. construction of low height BBA bunds to form ash deposition cells) in the attempt to achieve the short- and long-term objectives of the WCF Ash Management Plan. It wasrecognised that whilst these sub-optimal conditions persist, operational expenditure would continueto be elevated and the ability to achieve the final landformheight documented in the WCF Ash Management Plan may become challenging, particularly with respect to stability and potential liquefaction issues of the ash and ash cell containment bunds.

2. "FIX THE PLANE WHILE FLYING IT"

In 2018/2019,CS Energy recognised that ash disposal storage capacity within the WCF using existing planning, design, construction processes and procedureswas rapidly diminishing. These matters and persisting issues with the dense phase ash slurry systems prompted CS Energy to develop and implement a revised strategy to improve the WCF asset integrity.The lessons learnt following the recent tailings dam failures were considered, including theBrazilian Brumadinhotailings dam failureon 25 January 2019,and a Master Plan was developed for the WCF Life of Facility (LoF). The strategy included engaging specialist engineering service providers to carry out the following four key tasks for the WCF:

1. High level overview of previously carried out studies on embankment dam stability and potential liquefaction engineering investigations.
2. Audit of outstanding historical report recommendations with the aim to identify and attempt to close out any outstanding recommendations.
3, Asset Integrity and Operations Review, which included a review of the following key areas:
   (a) Engineering techniques used in relation to the design and construction of the dams,including a gap analysis of previously analysed failure modes for ADB andanalysis of identified failure mode gaps.
   (b) Regulatory compliance and alignment with the Australian Environmental Authority statutory obligations.
   (c) Operationalmethods and alignment with the Australian National Committee of Large Dams (ANCOLD) guidelines and other international good practice.
4. LoF Master Plan, which included a facility wide review and master planning. The key focus for the Plan included the determination and analysis of the ash disposal requirements and capacity of the WCF, including:
   (a) Detailed planning and designs for a forward 6-month outlook.
   (b) Preliminary planning and concepts for the future 6-month to 18-month outlook.
   (c) Concept planning and sketches for the future 18-month tothe power stations' end of life.
   (d) Alternative ash disposal options.

The engagement of GHD, a multidisciplinary specialist engineering services provider was identified to be key to the successful delivery of the strategyto safely "fix the plane while flying it".

This was a challenging situation, as GHDneeded to endeavour to design short-term options, which were aligned with the long-term strategy before the master plan was fully developed. An example of this was when a 'borrow area' nearly extended beneath a proposed short-term dam embankment, which was planned for construction later in the developing schedule. This would have required the area to be re-filled, causing the additional unnecessary cost of double-handling material. Within the first few months, many decisions and changes were made to keep the site operational, and this required frequent contact and communications between members of the design and client teams. It was important that key contactsin these teams had an overview of the whole program and coordinated activities, whilst keeping others fully informed on any decisions, which may impact on designs and operational activities. These strong communication links helped to reduce the number of issues and conflicts.

During the short-term options design stage, many important factors required consideration, often with conflicting interests, and the time constraint around the immediate need for storage only compounded this challenge.

One important factor was the need to maintain high quality standards.All teams were fully aware of the need to maintain high standards of structural safety and environmental compliance. Despite the pressing time constraint, the dam operator and consultant team undertook to plan, design and build engineered dams in accordance with modern water and tailings dam guidelinesin order to avoid liquefaction issues and the resulting limitations that this posed on the construction of the cells for ash deposition.This required an element of conservatism when designing the dam profiles. It also required close collaboration between the designers, the client's engineering and operations teams, and the construction contractor. Often, the designers travelled five hours to site at short notice to check and advise on site queries so they could fully understand the situation. However, as the partnership developed and familiarity of the site grew, the designers were able to communicate remotely. This was greatly aided by the operations team sending drone-flown aerial and traditional photographs on a daily basis.

Another factor to consider was cost. With the lack of knowledge, the designers began with specifying a conservative downstream slope ratio of 1 vertical (V) to 2.5 horizontal (H), i.e. 1V:2.5H. However, as ground investigations were completed and results provided on foundation properties, the designers were able to refine the slopes to a steeper ratio of 1V:2.0H.A cost saving was found by incorporating a steeper downstream raise of 1V:2.0Hover an earlier built embankment, which had a 1V:2.5H slope (see Figure 2).

Figure 2 shows a section through the first dam known as Creek Dam 1 (CD1), which was planned to address the immediate ash storage issue. It was designed as a zoned earthfill embankment comprising the following zones and drainage:

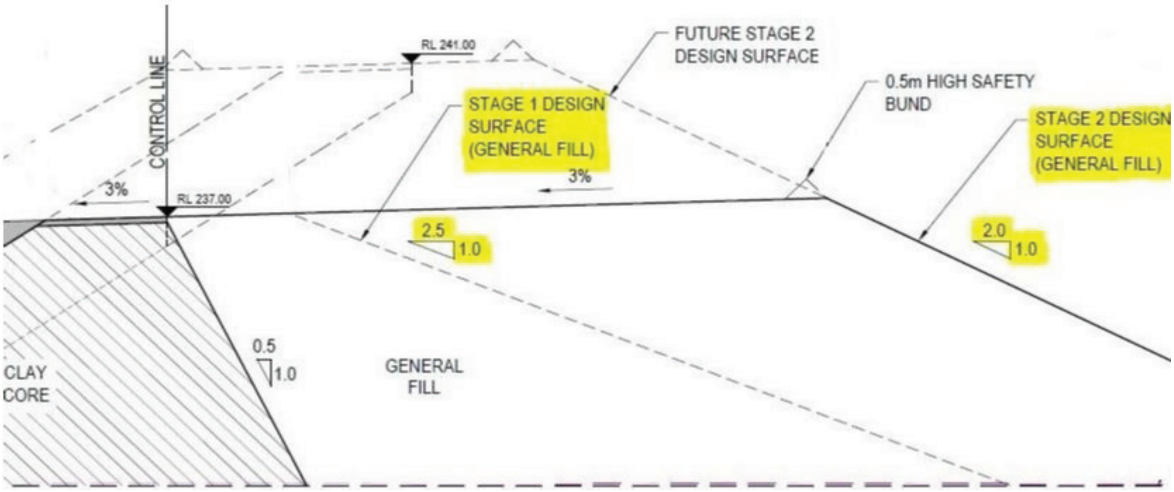

Figure 2 : Optimizing the profile of the embankment dams.

- An upstream BBA zone with a permeability of 1E-4m/s to 1E-5m/s, designed to provide a high permeability layer to drain the water from any fresh ash deposition near the upstream face with the aim to lower the pore water pressure within the embankment and increase the overall stability. This was sourced from available stockpiles on site.
- A central clay core zone was designed to reduce the seepage to lower the phreatic surface within the downstream shoulder and increase the embankment stability. The clay material was sourced from available residual soils on site.
- The downstream shoulder comprised general fill, a gravelly clay to clayey gravel material, which was sourced from available weathered rocks on site.
- Water collected in the upstream BBA zone was designed to be removed using a Megaflo® drain in the lower part of the BBA connected to a 100 mm Class 18 PVC drainage pipe leading to the downstream side of the dam via an excavated channel through the foundation of the wall. The PVC pipe was fully encased within the core zone and part of the fill zone using flowable fill (cement stabilised sand) with a BBA zone downstream of the flowable fill for seepage and piping control along the flowable fill/foundation interface.

Some of the reasons for selecting the design profile and location of CD1 dam included:

- Test pit laboratory results, Field Vane Shear Testing (FVST) and Dynamic Cone Penetrometer (DCP) testing in the proposed borrow areas and foundation location of CD1 dam demonstrated the suitability of the materials to be used and showed the foundations were generally weathered to extremely weathered rock to firm residual soils. The strength parameters adopted for the stability assessments of the foundation materials included an undrained shear strength of 45 kPa for the residual soil and an undrained strength of 150 kPa for extremely weathered rock.
- The CD1 dam wall spanned a relatively narrow remnant water course 'valley' and could be abutted on both sides to existing ash storage walls (refer to Fig. 3).
- DCP testing of the BBA bund wall on the left abutment showed refusal at almost 2 m depth, indicating CD1 could be keyed in to this compacted BBA surface, which had an estimated downstream batter of1V:1.7H.
- The upstream BBA zone of the CD1 embankment would act as a crack filler for potential internal erosion through the wall, in the event that cracks develop on the abutments from differential movement of the CD1 embankment against the BBA on the left abutment and the ash on the right abutment.
- The BBA would lower the phreatic surface on the upstream side as opposed to the internal filter lowering the phreatic surface downstream of the core zone.
- The BBA was quicker and easier to place on the upstream face rather than as a narrower filter zone within the embankment, which helped to speed up the construction programme.
- The embankment would form part of the final landform and would be fully encapsulated with ash deposition on the downstream side within approximately 2 to 3 years.
- The relatively short length of dam could be built in approximately 6 weeks and provided storage for approximately 7 weeks, providing time to plan and build the next dam.
- A berm was incorporated downstream of the CD1 embankment toe in preparation for a future 4 m raise of the dam using a downstream raise with extension of the BBA, clay and general fill zones.

- The ‘safety in design’ risk assessment identified 18 risks across the system components, all of which were managed within acceptable thresholds.

At suitable points in the program, safety in design and lessons learnt workshops were held with the client-consultant-contractor team. This led to a better understanding of each party’s challenges and helped to refine the designs and optimize the plant requirements onsite. One example was the contractor advice that a minimum widthof 5 m was required for embankment construction owing to the size of the compactor and this needed to be incorporated within the design workfor this embankment and future designs.

Another key learning point was the ongoing requirement for utilizing skilled operators and qualified engineers, who were experienced in earthworks and dam engineering.‘Hold points’ were specified for certain higher risk activities, which required supervision onsite by registered engineers such as keying into the BBA bund wall on the left abutment.

As part of the suite of improvement works, a review was undertaken on the dam safety management program. The *Queensland dam safety management guidelines*(Queensland Government 2002) describes this as a system that incorporates dam safety values as part of the culture of the organization and the day-to-day operation of a dam. A dam safety management program comprises policies, procedures and investigations, which minimize the risk of dam failure. Following a gap analysis and a series of interviews with CS Energy staff, a maturity assessment of CS Energy’s approach to dam safety management was undertaken and an improvement plan was developed.

The Ash Management Plan, which comprises a suite of five documents, is a statutory requirement of the WCF and must be updated every three years. The next review and update will include the work carried out as part of the strategy to improve the WCF asset integrity, as described below:

1. Operation and Maintenance Manual: The 2018 Manual will be updated with the revised day-to-day operating and maintenance procedures to ensure the safety of the dams within the WCF, including updated methodologies for discharging ash to the storage areas and monitoring of the dams. It will include a description of the frequency and methodology for undertaking routine surveillance inspections and reading instrumentation in accordance with good practice guidelines such as the *Queensland dam safety management guidelines* (Queensland Government 2002).
2. Corrective Action Plan: The 2018 Plan will be reviewed and updated to assist with the evaluation of options to reduce the water level in ADB should it reach any of the required regulatory freeboard trigger levels.
3. Spill Management Plan: In the event that the water level in ADB continues to rise above the regulatory freeboard trigger levels and threatens to overflow the ADB spill weir, this Plan contains a procedure for taking further risk mitigating actions, including sampling and notification requirements.
4. Emergency Action Plan: This Plan will be updated in accordance with the *Emergency action plan for referable dam guideline* (Queensland Government 2017) to cover preparedness in relation to the occurrence of an emergency condition at ADB and will provide information necessary for emergency agencies to manage a downstream evacuation in the case of a potential dam failure. A Safety Review and Comprehensive Risk Assessment are prerequisite tasks for updating the Emergency Action Plan.
5. Ash Management Plan: The 2018Plan will be updated to include amendments to the strategy for the design, construction and operation of the ash storage within the Callide WCF, as well as an update to the final ash landform plan. It will include an assessment of the water management infrastructure and will discuss salt management and impacts on groundwater.A key feature of the revised Plan will be discussion on the geotechnical investigations undertaken in 2019 and the additional investigations, field trials and laboratory testing planned in early 2020. It will discuss the strategic change from BBA bund construction to zoned earthfill embankments, which resulted following a review of an ash bund slippage incident that occurred at the WCF in 2017. Two root causes for this slip were considered to be (1) slope failure through the weak foundation silt layer; and (2) liquefaction of the tailings. This incident and a discussion on liquefaction is considered further in section 3.

3. LIQUEFACTION CONSIDERATIONS

3.1 Tailings dam failures by liquefaction flowsliding

It is recognised that tailings dams are dynamic structures with continual changes and complexity owing to the ongoing requirement for increased storage of tailings. There are primarily three construction methods for tailings dams; namely, a traditional downstream raise, a centre line raise and an upstream raise where tails are stored above a main starter wall. The cost of upstream raised facilities is generally the lowest and requires the least land footprint, which together makes this dam construction method attractive.

The International Committee of Large Dams (ICOLD) Bulletin 121 (ICOLD2001) states that upstream raise construction accounts for more than six times the number of failures than downstream and centre line raises. Furthermore, the November 2015Fundão(Morgenstern et al.2016)and the January 2019 Brumadinho(Robertson et al. 2019) tailings dam failuresin Brazil clearly demonstrated the significant risks associated with not having a full understanding of the effects of changes during the design, construction and operation of upstream raise tailings facilities. As a result of these failures, some countries,including Brazil (Mining Journal 2019), have openly discouraged the upstream construction method.

The investigations into theFundãoand Brumadinhotailings dam failures by liquefaction flowsliding show that these were the consequence of a chain of events and conditions. The trigger for liquefaction of ash is shearing, requiring stresses to be applied, either by earthquake shaking (seismic liquefaction) or static liquefaction. There is a significant body of knowledge available in relation toliquefaction caused by seismic loading. However, the catastrophic static liquefaction triggered at Fundão was reportedly the result of a particular mechanism, not typically identified as applying to, nor associated with, dam failures.

3.2 Liquefaction incident in the Callide WCF

Since the start of operation, the construction method for the tailings storage facilities at Callide had been upstream raises using BBA for the embankments, with peripheral decant using 150 mm diameter slotted PVC pipes. The system operated as required until 22 May 2017, when a static liquefaction failure occurred during construction of a 2 m upstream raise. The liquefaction resulted in release of tailings for a distance of 500 m that was contained within the WCF with no loss of life or damage to the environment.

- Typical static liquefaction trigger mechanisms are depicted on Figure 3, include the following:
- Overtopping of the embankment leading to breach and release of the tailings through the breach, which increases shear stresses on the potentially liquefiable material.
- High or excess pore pressures within the liquefiable material.
- Creep, which is not commonly considered as a trigger for liquefaction.
- A failure elsewhere in the ash mass, which may cause a rapid transfer of shear stresses to the loose ash.
- Overstress of the liquefiable material owing to over-steepening of the bund slopes, increasing the shear stresses.
- Rapid toe erosion of the ash beach causing lack of support.
- Squeezing mechanism postulated to be a trigger for the Fundão failure.
- An increase in the rate of loading through either constriction of internal bunds, an increase in ash production or rapid changes in water level in the ash deposit.
- Progressive failure/load shedding owing to differential movement within the foundation weak zone and the contractive brittle tailings.
- Ash slurry lean density and flushing cycles leading to excess free water and a high phreatic surface.

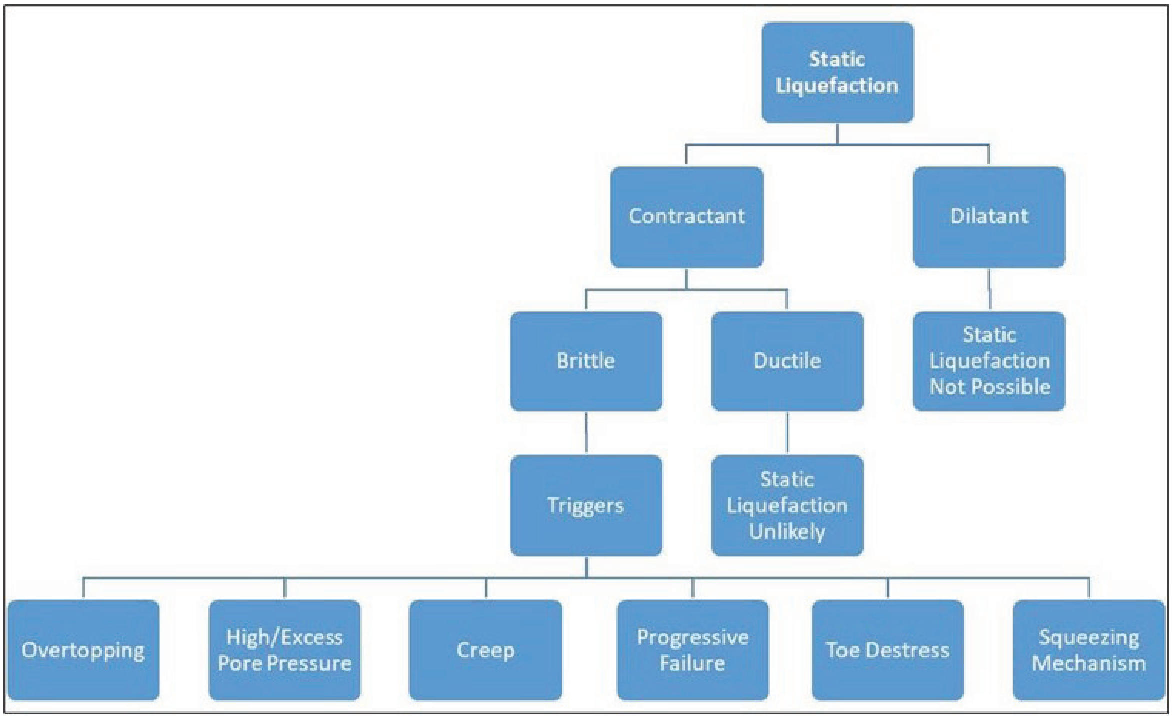

Figure 3 : Triggers for static liquefaction of a tailings storage facility (Barker et al. 2019).

A number of these trigger mechanisms were present at Callide WCF prior to the liquefaction incident. There was, therefore, concern by CS Energy as to whether a similar event could occur with the ongoing operation of the facility using the upstream raising construction method comprising BBA. As a result, the decision was made to change the design and construction method to incorporate a downstream conventional fill embankment with upstream BBA for drainage. Furthermore, the deposition strategy was changed to provide a central decant system to limit the potential for saturation of the perimeter embankment. This method of construction provided greater certainty regarding the potential for slope failure and subsequent liquefaction. It had the additional benefit of allowing an increase in the height of the starter embankment, which provided additional storage and an increase in the ash to fill ratio.

The liquefaction incident highlighted the following practices that needed to be in place to minimise the potential for static liquefaction of tailings:

- Good understanding of the foundations: In situ vane shear testing, sampling and testing of undisturbed samples is recommended where possible and characterisation of the foundation material by an experienced engineering geologist.
- Good understanding the ash properties: Understanding material characterization at the in situ density and stress levels is key to understanding liquefaction potential of the ash. Material characterisation using in situ CPTu and vane shear testing as well as critical state soil testing is recommended.
- Designing stable slopes: Design to be undertaken using well understood material parameters.
- Developing a sound slurry discharge plan: Measures to be included to avoid saturation of the outer wall.
- Acceptance of ash slurry lean density and flushing cycles leading to excess free water and a high phreatic surface as part of the design.

In addition to the above practices, a number of tools can be used to evaluate the causes and likelihood potential for liquefaction, including root cause analysis and fault tree analysis methods.

3.3 Root cause analysis

The root cause analysis process involves holding discussions on all possible causes of the problem, asking questions to find out why the problem occurred, and then continuing to ask why that happened, until reaching the fundamental process element that failed. A typical root cause analysis is shown in Figure 4.

When completed, the root cause analysis identifies the most significant contributors for the problem being evaluated and provides the analysts a way forward to evaluate the problem using detailed analysis, including the use of fault tree analysis for bringing the various components of the root cause into a qualitative and potentially quantitative probability for the liquefaction to occur.

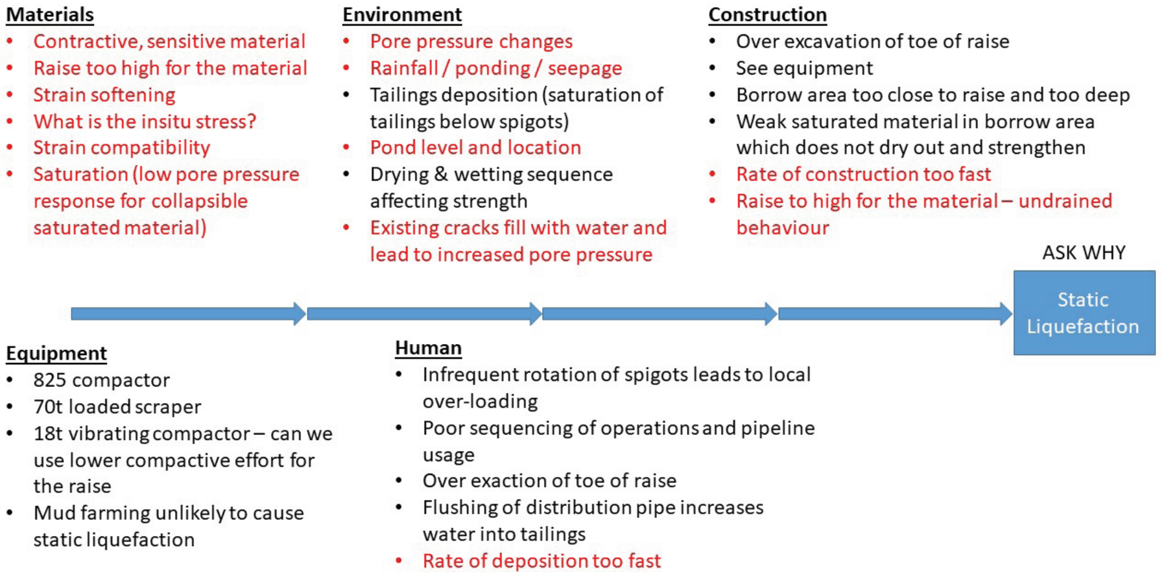

Figure 4 : Root cause analysis for static liquefaction of an upstream raise tailings storage facility (Barker et al. 2019)

3.4 Fault tree analysis

A fault tree is a logical graphic model of the various parallel and sequential combinations of faults that will result in the occurrence of the predefined undesired event. The faults can be events that are associated with component hardware failures, human errors or any other pertinent events, which can lead to the undesired event. A fault tree is not a model of all possible system failures or all possible causes for system failure. Rather, it is tailored to its top event, which corresponds to some particular system failure mode and, therefore, includes only those faults that contribute to this top event. Moreover, these faults are not exhaustive. They cover only the most credible faults as assessed by the analyst.

The trigger mechanisms in the root cause analysis can be combined using the fault tree approach in order to gain an understanding of the combination of events required to lead to the flow liquefaction. A portion of a simplified fault tree is shown in Figure 5.

The use of the fault tree allows for details of the intermediate and basic events to be described and subsequently quantified in order to evaluate the likelihood of a particular top event occurring.

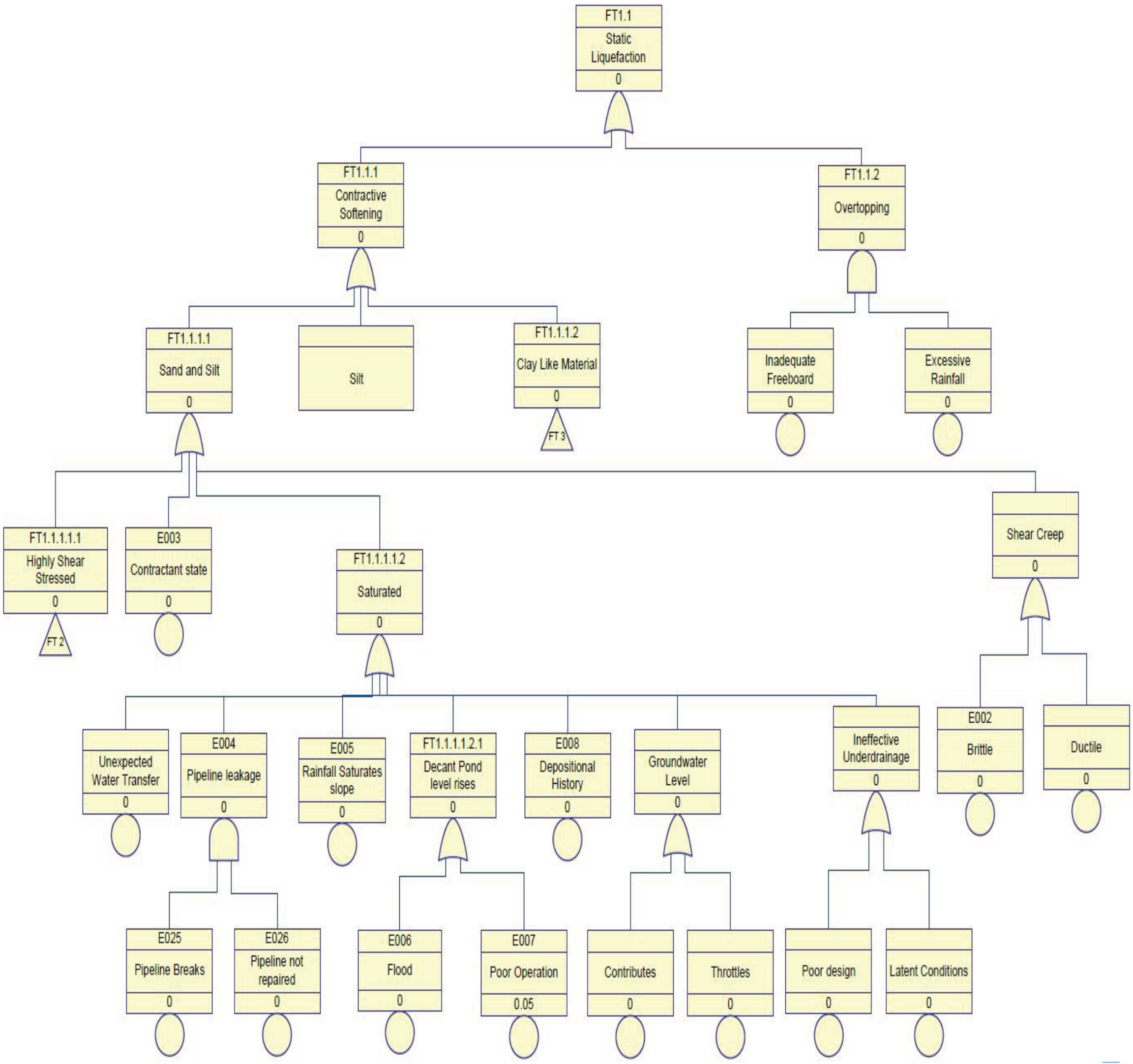

Figure 5 : Liquefaction fault tree (in part) (Barker et al. 2019)

4. CONCLUSIONS

Managing change and implementing safety improvement measures within a fast-moving operational tailings facility is challenging. It is understandable that operators at power stations want the waste products to be removed as efficiently as possible and want to minimize the time and effort on this process.

One of the main reasons for the success of the upgrade at the Callide WCF was the partnership approach of the client-consultant-contractor team and the willingness of the operators to change existing practices and look for continual improvement. Ultimately, this collaborative and positive approach led to a safer (in terms of operational safety as well as dam safety) and more environmentally compliant site.

Key to this process was the good communication between all parties, whichsupported the decision-making process and prevented wastage such as the example provided in this paper with regard to double-handling of material.

Another important point that came out of this project was utilizing skilled operators and qualified engineers. The contractor was very experienced in earthworks, however, it was vital that qualified dam engineers provided guidance during critical points in the program, and were on hand to provide advice on site when needed.

The paper finalizes with a discussion about the ongoing challenge of how to address the potential risk of liquefaction whilst increasing storage capacity and how to evaluate static liquefaction in these fast-moving and variable sites. The main points of this section were having a sound understanding of the trigger mechanisms for liquefaction and using a design and construction method appropriate for the available materials.

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