Root Cause Analysis (RCA) in Dam Design

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This paper will present the use of Root Cause Analysis (RCA) as a means of evaluating the causes for failure modes and is based on work completed for an upstream tailings storage facility (TSF) raise where significant transverse and longitudinal cracking was observed.

The design of the TSF was based on the use of a starter wall with perimeter discharge from spigots spaced at about 25 m centres along the upstream crest. The TSF was raised using an upstream design and during routine inspections two years after completion of the raise, transverse cracks of up to 30 mm were noted on the crest and longitudinal cracks up to 40 mm width were noted on the downstream slope of the raised embankments. Concerns were raised over the extent and depth of the transverse cracking and the risks they pose to piping, seepage and containment.

Field investigations including test pitting and material testing were completed to evaluate the depth and extent of the cracking. The findings from field investigations, together with a review of the historical aerial photographs and superposition of the cracks and the locations of the spigots were then used in a Root Cause Analysis workshop.

Discussions on all causes for the cracking, asking the question "why did the problem occur?", and then continuing to ask "why that happened?" until the fundamental process element that failed was reached"

During the workshop, the most significant contributors for the transverse and longitudinal cracking and the likely location, extent and size of the cracks were evaluated. This identified the potential for traditional structural hog and sag bending moments causing the transverse crest cracking with the potential for transverse cracking at the interface of the raise and the original tailings. This was not previously identified as a potential piping location. The longitudinal cracking was considered to be mainly owing to settlement of the upstream tailings.

Keywords: *Root Cause Analysis, cracking, upstream raise.*

Introduction

It is critical that everyone take a personal and active role in improving quality in design, construction, operation and maintenance. The failure modes associated with piping through embankments and foundation have been documented in some detail in the Piping Toolbox (USBR et al, 2008), however, the Root Cause Analysis of failure initiating events can provide additional information to be used for design, construction and operational changes in the construction of dams (http://www.isixsigma.com/tools-templates/cause-effect/determine-root-cause-5-whys/).

Asking "Why?" is a favorite technique of a three year old child in finding out more and the "5 Whys" is a technique used to get to the root of a problem that does not involve data segmentation, hypothesis testing, regression or other advanced statistical tools, and in many cases can be completed without a data collection plan.

By repeatedly asking the question "Why" (five is a good rule of thumb), you can peel away the layers of symptoms which can lead to the root cause of a problem, however, you may find that you will need to ask the question fewer or more times than five before you find the issue related to a problem.

The "5 Whys" can be used individually or as a part of the fishbone (also known as the cause and effect or Ishikawa) diagram. The fishbone diagram helps the analyst to explore all potential or real causes that result in a single defect or failure. Once all inputs are established on the fishbone, the analyst can use the 5 Whys technique to drill down to the root causes.

It is important to note that the purpose of the 5 whys isn't to place blame, but rather to uncover the root cause of why something unexpected occurred. Additionally, it helps a team create small, incremental steps so that the same issue doesn't happen again (to anyone).

This paper will provide a methodology that can be simply applied for dealing with a variety of potential or actual failure modes in dam design and construction.

Philosophy for Root Cause Analysis (RCA)

The philosophy behind a RCA is as follows:

- When defects or problems occur, they present a golden opportunity because they can tell a story about why and how they occurred.
- When dealing with a problem, it is essential that the "true" problem is understood before action is taken.

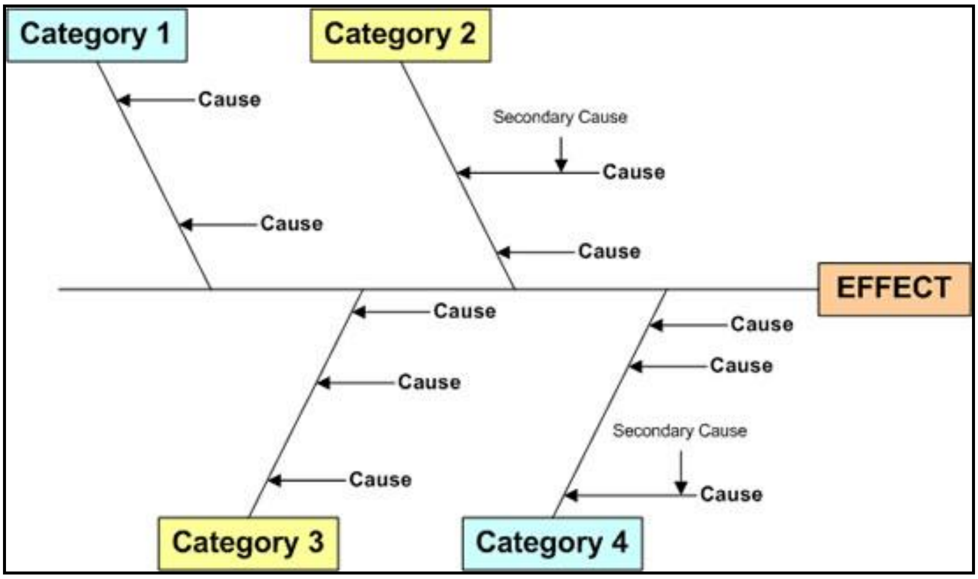
- Problems are often masked for a variety of reasons including lack of information, operation or design rules that are applied without a complete understanding of the effects or limitations on the design, construction or maintenance of the facility.
- When completing a root cause analysis well, it is important for the work to be completed by a team of people who must be:
    - Focused and open-minded
    - Patient and quick
    - Relentless

If we do a poor job of identifying the root causes of our problems, we will waste time and resources putting band aids on the symptoms of the problem.

Fishbone or Cause Effect Diagram

When utilizing a team approach to problem solving, there are often many opinions as to the problem's root cause. One way to capture these different ideas and stimulate the team's brainstorming on root causes is the cause and effect diagram, commonly called a fishbone. The fishbone as shown on Figure 1 helps to visually display the many potential causes for a specific problem or effect. It is particularly useful in a group/workshop setting and for situations in which little quantitative data is available for analysis.

Figure 1 – Example Fishbone or Cause Effect diagram



The fishbone has an ancillary benefit because people by nature often like to get right to determining what to do about a problem before understanding the problem fully. The fishbone or RCA approach can help bring out a more thorough exploration of the issues behind the problem, which will lead to a more robust solution.

Methodology

The method for constructing a Cause Effect diagram is as follows.

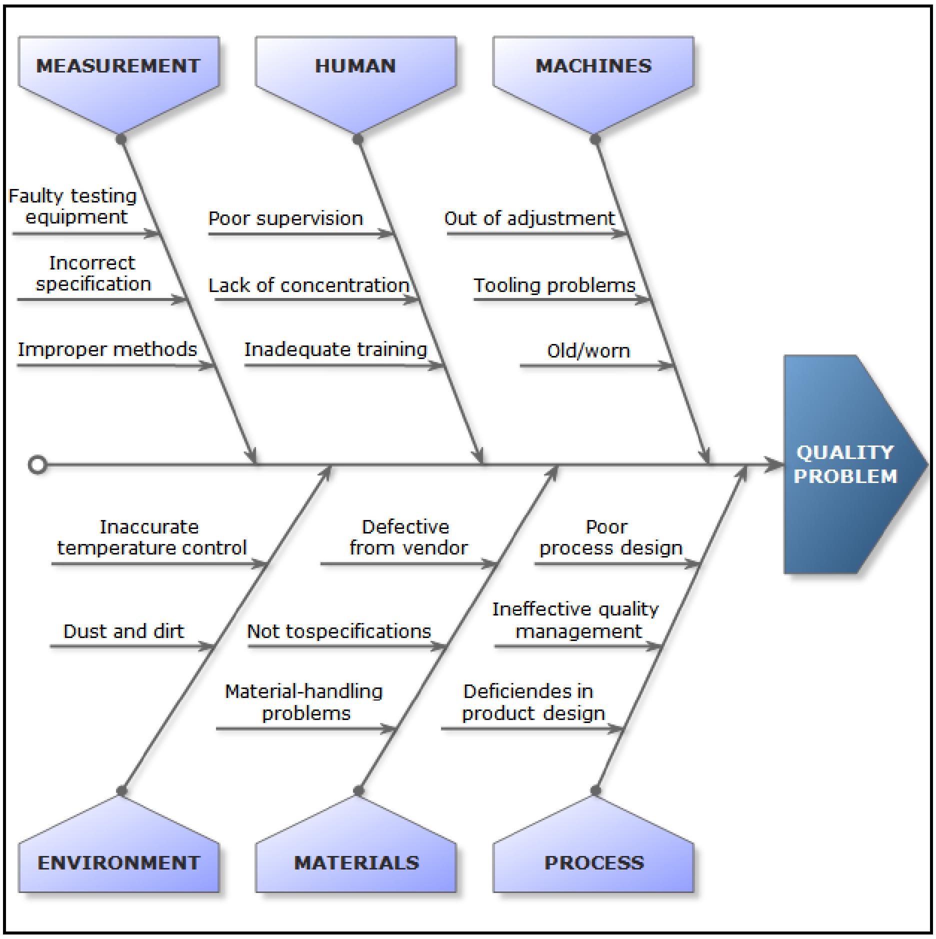
Materials needed: flipchart or whiteboard with marking pens. Some may prefer to utilize an Excel spreadsheet or word document for capturing ideas.

1. Agree on a single problem or opportunity statement (effect). The problem or opportunity that is selected for analysis is documented by a key word description or short narrative description placed in a rectangle or box, generally on the right side of the diagram. Draw a box around it and draw a horizontal arrow running to it. When analyzing more than one problem or opportunity, a different cause and- effect diagram is used for each problem or opportunity.
2. Brainstorm the major categories of causes of the problem. If this is difficult use generic headings for example:
    - Measurement
    - Human (manpower)
    - Machines (equipment)
    - Environment

- Materials
- Methods/Process

An example of using these categories to identify a Quality Problem is shown on Figure 2.

Figure 2 – Quality Problem Example Fishbone



These categories are not exhaustive and will depend on the problem or opportunity under consideration and as illustrated in the RCA for the Tailings Storage Facility presented below.

3. Write the categories of causes as branches from the main arrow.
4. Brainstorm all the possible causes of the problem. Ask: "Why does this happen?" As each idea is given, the facilitator writes it as a branch from the appropriate category. Causes can be written in several places if they relate to several categories.
5. Again ask "why does this happen?" about each cause. Write sub–causes branching off the causes. Continue to ask "Why?" and generate deeper levels of causes. Layers of branches indicate causal relationships.
6. When the group runs out of ideas, focus attention to places on the chart where ideas are few.

Brainstorming

What is it?

Brainstorming is a process in which a group quickly generates as many ideas as it can on a particular problem and/or subject and is also used for risk analysis.

How is it done?

- Identify a topic, problem or issue and make sure there is mutual understanding of the task and objective. Write the topic on a flip chart, whiteboard, spreadsheet or word document being used for the workshop
- Each person presents one idea going in sequence (Round Robin). If a person doesn't have an idea, pass and move on to the next person. This is not always practiced in risk analysis workshops but can be a subtle and yet significant change in the approach for eliciting information from the participants.
- All ideas are recorded.

- There is no evaluation or discussion during the session.
- Focus is on quantity of ideas, not the quality.
- When all ideas are exhausted, take a break. When you come back, people may have more ideas to add to the list.
- Keep the idea generation separate from the evaluation or analysis of ideas.

Analysis

Analyse the ideas (causes) and eliminate trivial and/or frivolous ideas.

Rank causes and circle the most likely ones for further consideration and study.

Investigate the circled causes. Use other techniques to gather data and prioritize findings.

Brainstorming guidelines:

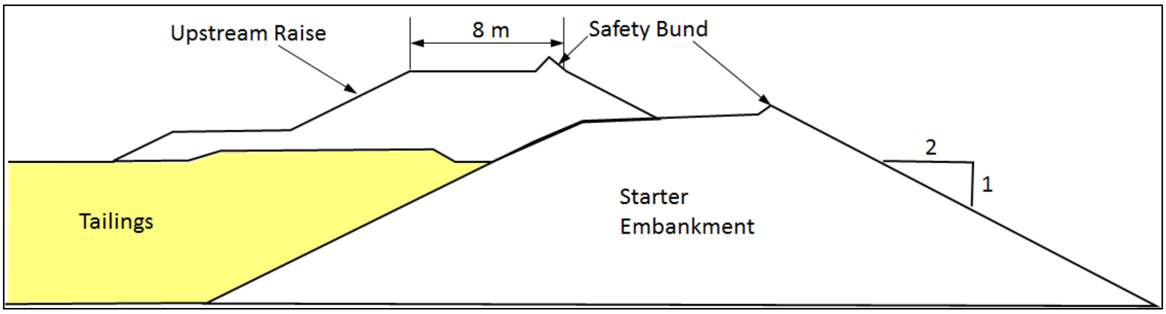
- Generate as many ideas as possible.
- Encourage free-wheeling.
- No criticism is allowed, either positive or negative.
- Equal opportunity to participate.
- Record all ideas.
- Let the ideas incubate.

Root Cause Analysis Application

The problem

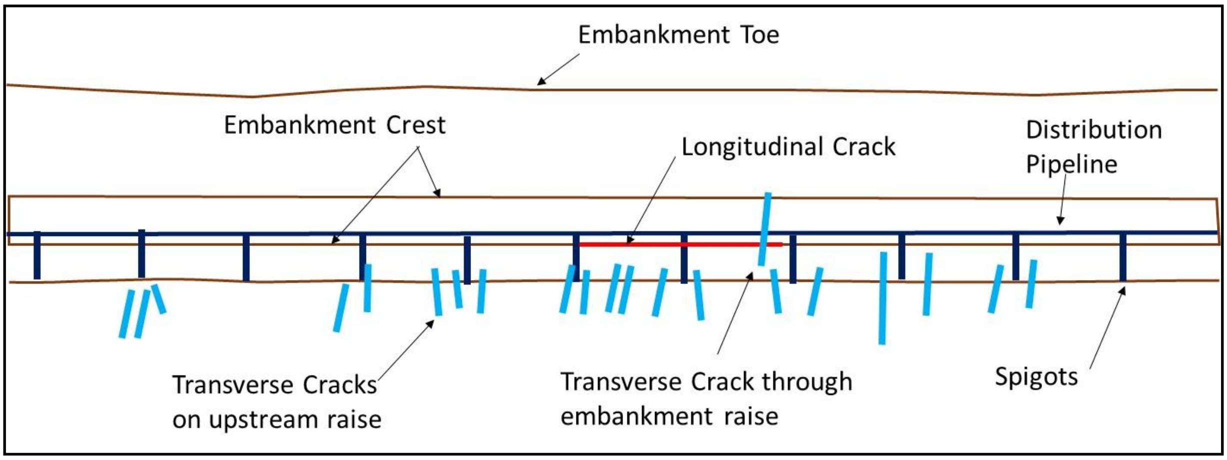
A Tailings Storage Facility (TSF) was being raised for a second time using an upstream raise methodology. The stage 1 comprised a homogeneous starter embankment of height varying from about 2 m to 12 m with upstream and downstream slopes of 2H:1V and a crest width of 8 m. The first raise was 2.6 m, as shown on Figure 3.

Figure 3 – Transverse and longitudinal cracking observed on upstream raise



The deposition into the storage facility was by means of spigots spaced at about 25 m centres along the upstream crest. During routine inspections two years after completion of the raise, transverse cracks of up to 30 mm were noted on the crest and longitudinal cracks up to 40 mm width were noted on the downstream slope of the raised embankments, with a typical pattern shown on Figure 4.

Figure 4– Cracking observed on TSF upstream raise



Geotechnical Investigations

Detailed logging of the observed cracks, test pitting on the embankment crest and materials testing was completed to investigate the cause of the cracking. The crack depths and widths for the most significant crack locations shown on Table 1.

Table 1 – Geotechnical Investigation test pit data

Test Pit	Test Pit Depth (m)	Crack Depth (m)	Crack Width (mm)
01	1.3	1.3	2
02	1.5	1.3	2
03	1.0	0.8	1
04 – 1/3	1.4	1.4	3
04 – 3/3	1.6	1.6	5

Photographs of typical transverse cracks and a test pit are shown on Figure 5. The transverse and longitudinal cracks were found to intersect at some locations, as shown on Figure 6.

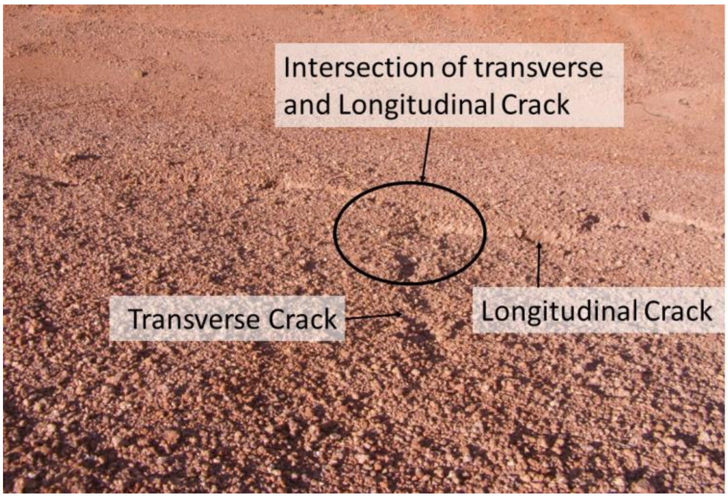
Figure 5 – Transverse and longitudinal cracking observed on the Stage 1 upstream raise

Transverse Crack on Crest

Test pit for transverse crack

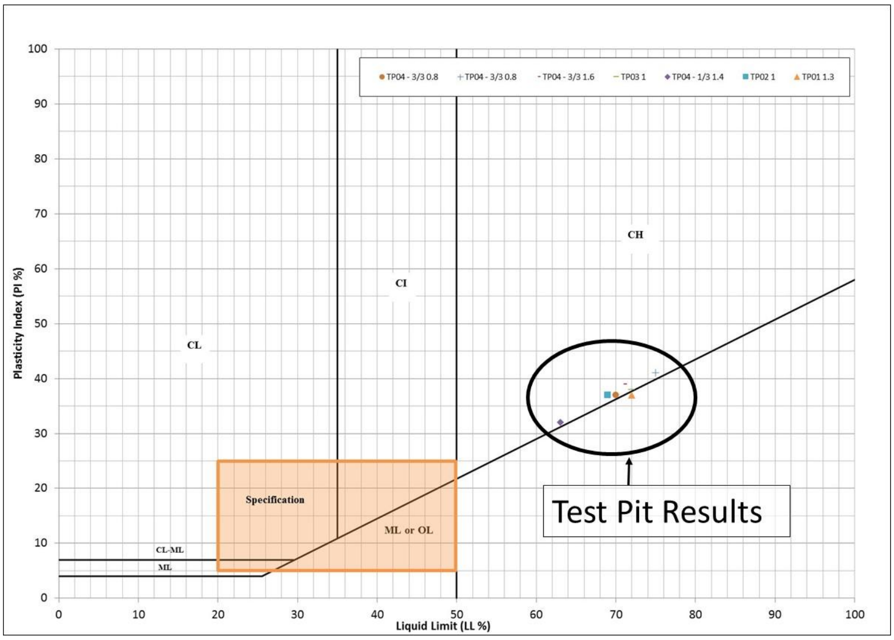
Longitudinal crack at downstream side of raise

Figure 6 – Transverse and longitudinal cracking observed on upstream raise



The materials testing showed that the material was generally more plastic than the specifications, as shown on Figure 7.

Figure 7 – Plasticity Chart for test results on crack investigation test pits



The concern over the cracking was the increased risk of piping both for the current design height and the increased raise height. Consequently, a Root Cause Analysis (RCA) was completed to evaluate what actions were required for treatment of the cracking.

Root Cause Analysis (RCA) Objectives

The RCA for the Tailings Storage Facility was completed with the following objectives.

- To gain an understanding of the primary cause/s for the problem as to the reason for the transverse and longitudinal cracking observed in the TSF
- To use the results of a risk analysis used to evaluate the potential probability of piping through the cracks.
- Define trigger levels for monitoring and taking action when decant levels rise
- Determine any immediate and long term remedial actions to be taken for treatment of the cracks.

Methodology

The Root Cause Analysis was completed in a workshop using the following process:

Presentation of the field investigations.

The major observations from the investigations, which comprised visual observations, test pitting and materials testing were as follows:

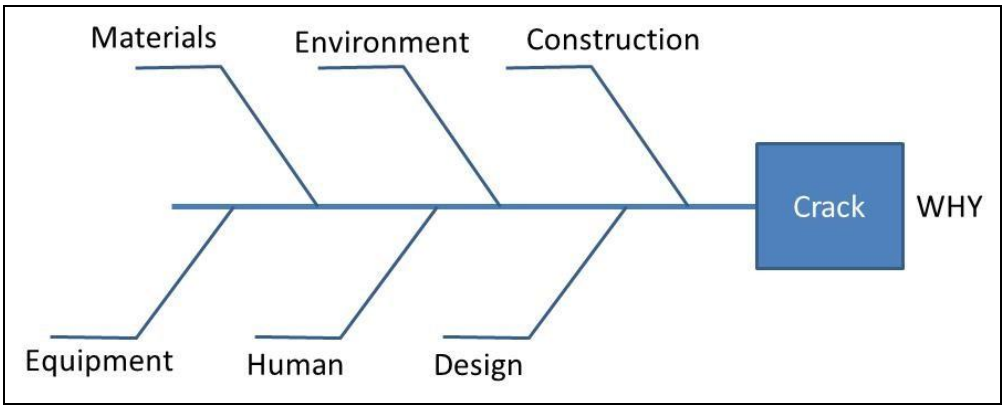
- Longitudinal cracking is extensive
- Transverse cracks are visible on the embankment crest and are generally located at the previous raise spigot positions
- The most significant longitudinal and transverse cracking was observed in an area where a lot of soft tailings were deposited in the past owing to difficulties with deposition and water recovery in the cell.
- The depth of cracking was observed in one test pit on the crest to extend down to about 1.6 m with the crack remaining open with a width of about 3 mm. The depth of cracks in the remainder of the test pits ranged from about 1 m to 1.3 m.
- Some of the cracks were found to have closed up following rainfall.
- The Plasticity Index and the Liquid Limit for the tested samples were well in excess of the design specifications.
- The rainfall data showed the following
    - The construction period extended into the wet season.
    - Following completion of the embankment, there was a period of 6 months during which there was very little or no rainfall, at the end of which, the cracking was first observed.

Root Cause Analysis

Discussions on all causes for the cracking, asking the question "why did the problem occur, and then continuing to ask why that happened until we reach the fundamental process element that failed".

The following categories were used for the interrogation of the root cause for the longitudinal and transverse cracks, the results for which are shown below.

Figure 8 – Root Cause Analysis Categories and Effect



Transverse Cracking Root Cause Analysis results

The causes for transverse cracking were evaluated for each of the categories in Figure 8. The most significant root causes were determined by consensus of the participants during discussions in the meeting, as shown on Table 2.

Table 2 – Root Cause Analysis for Transverse Cracks

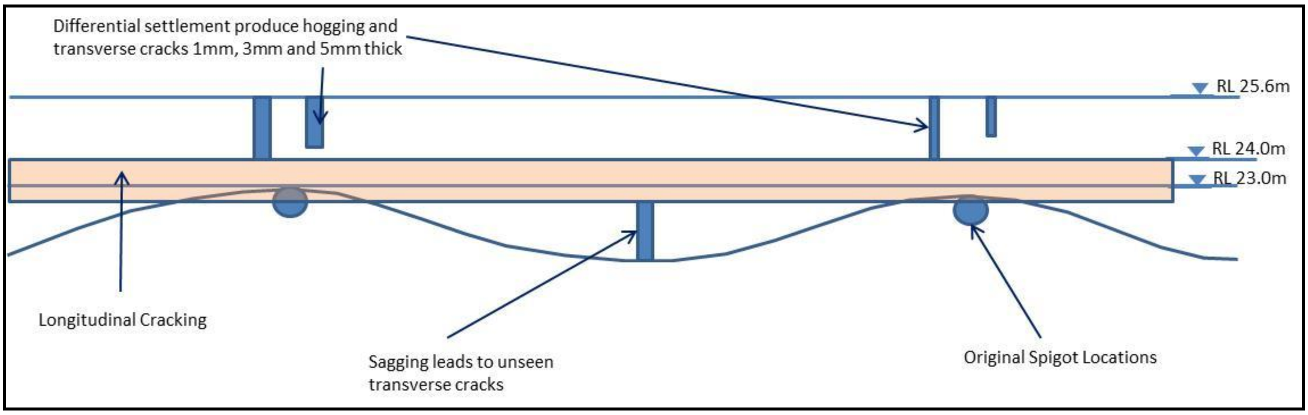
Root Cause	**Significance**
Materials	
Spigot locations and material deposition gives foundation soft and hard variability along the wall – differential settlement (Figure 9)	1
Borrow materials plastic causing drying shrinkage of the material, which is more brittle than design leading to concentrated cracks and not distributed cracks	3
Specification Moisture content may have been lower than the actual required to compact the material leading to increased potential for drying shrinkage cracking	
Environment	
Wet season timing (Moisture Content of placed material)	
Dry period following construction	
Construction	
Zone 3C key trench wheel rolled and not roller compacted to Specification – placed to give bearing for upper material	
Material borrowing changes in lot parameters	
Rapid construction period	4
Equipment	
Use of spigots for material deposition – normal practice	
Design	
Specification of materials outside of the available parameters	
Consolidation not accounted for adequately	
Raise height too high for the foundation material	2
Inadequate testing of the foundation material during the raise	
Human	
No issues identified	

As shown on Table 2, the most significant contributors for the root cause of the transverse cracking were as follows.

1. Spigot locations and material deposition gives foundation soft and hard variability along the wall – differential settlement
2. Raise height too high for the foundation material
3. Drying shrinkage of the material, which is more brittle than design leading to concentrated cracks and not distributed cracks
4. Rapid construction period

The transverse cracking caused by the variability of the material deposition along the wall had not previously been identified as a potential pathway for piping failure in the areas of sagging shown on Figure 9 and this, combined with the longitudinal cracking was a cause for concern.

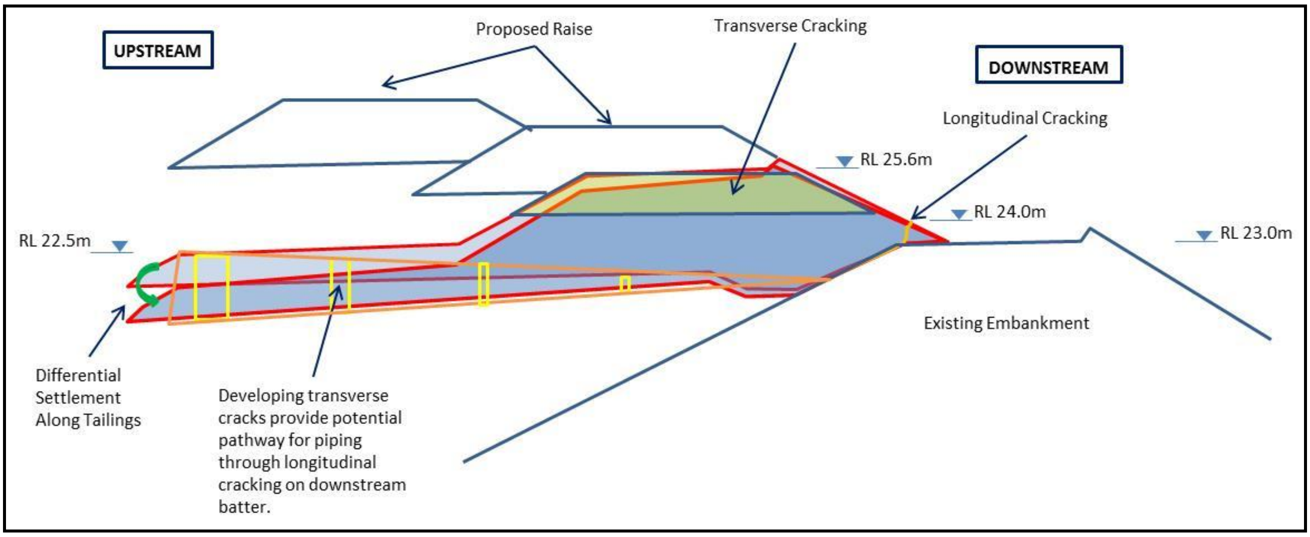
Figure 9 – Variable deposition along cell wall leading to differential settlement and transverse cracking (Longitudinal crack area also shown)



Longitudinal Cracking Root Cause Analysis results

The causes for longitudinal cracking were evaluated for each of the categories in Figure 8. The typical Stage 1 cross section showing the formation of the longitudinal and transverse cracking is presented on Figure 10.

Figure 10 – Settlement of tailings leading to longitudinal cracking and transverse cracking at sagging between spigot pipes



The most significant root causes for the longitudinal cracking were determined by consensus of the participants during discussions in the meeting, as shown on Table 3.

Table 3 – Root Cause Analysis for Longitudinal Cracks

Root Cause	Significance
Materials	
Soft tailings along the wall – differential settlement (Figure 6**Figure**)	1
Borrow materials plastic causing drying shrinkage of the material, which is more brittle than design	

Root Cause	Significance
leading to concentrated cracks and not distributed cracks	
Specification Moisture content may have been lower than the actual required to compact the material leading to increased potential for drying shrinkage cracking	
Environment	
Wet season timing (MC of placed material)	
Dry period following construction	
Construction	
Zone 3C key trench wheel rolled and not roller compacted to Specification – placed to give bearing for upper material	
Material borrowing changes in lot parameters	
Rapid construction period	3
Equipment	
Use of spigots for material deposition – normal practice	
Design	
Specification of materials outside of the available parameters	
Consolidation not accounted for adequately	
Raise height too high for the foundation material	2
Inadequate testing of the foundation material during the raise	
Human	
No issues identified (See comment below)	

Comment: The Client also developed the root cause analysis further where the effect of management decisions on the root cause for the cracking was evaluated but are not reported on here.

As shown on Table 3, the most significant contributors for the root cause of the longitudinal cracking were as follows.

1. Soft tailings along the wall causing differential settlement
2. Raise height too high for the foundation material
3. Rapid construction period

Immediate mitigation Measures

A significant issue with respect to the cracking is that the cracks cannot be observed in the sag areas of the embankment as they are most likely to be below the berm level of RL 23 m, as shown schematically in Figure 10.

The following immediate measures for mitigation of the cracking and failure potential were identified in the workshop.

- Tailings deposition along the wall in areas where cracks are present in order to seal open cracks where possible
- In the event of excess water being stored on the cells, use the gravity decant and pump the water away to lower the cell water levels.
- Increase surveillance during rain periods to look for seepage and commence with Emergency Actions where appropriate, taking note of the Trigger Levels.

Long term Mitigation Measures

The following long term measures for mitigation of the cracking and failure potential were identified in the workshop.

- Better control on material parameters with reduced plasticity from borrow areas
- Modification of tailings in situ to provide a firmer foundation and reduce upstream settlement. This is important for the long term operation and upstream raises shown on Figure 6
- Reduce the height of future raises to about 1 m
- Account for existing cracks (Transverse and longitudinal) in the future design by provision of an upstream sealing zone or downstream seepage collection drain. Other design measures may be evident during the future detailed design.

- Construction lot management to stagger layers in the embankment (brick formation)
- Longer construction period – improved consolidation of the foundation tailings leading to reduced differential settlement.
- Improved QA procedures for index testing of “as placed” materials and grading specifications.

Conclusions

The root cause analysis for the cracking observed at the Tailings Storage facility identified the transverse cracking caused by the variability of the material deposition along the wall that had not previously been identified as a potential pathway for piping failure in the areas of sagging shown on Figure 9. This, combined with the longitudinal cracking along the downstream side of the Stage 1 raise was a cause for concern and resulted in a number of mitigation actions being developed for the raise design and management of the facility.

When dealing with a problem, it is essential that the “true” problem is understood before action is taken. Problems are often masked for a variety of reasons including lack of information, operation or design rules that are applied without a complete understanding of the effects or limitations on the design, construction or maintenance of the facility.

The use of Root Cause Analysis is similar in many respects to a detailed Failure Modes Analysis and is a valuable tool for evaluating the many categories and their causes that can be identified to determine the real cause of the potential failure end evaluate appropriate mitigation measures

Acknowledgements

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List of references

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