Root cause analysis in geotechnical engineering – an introduction

Author: Prof. Dr. habil. Heinz Konietzky
(TU Bergakademie Freiberg, Geotechnical Institute)

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1 Preface

Root **C**ause **A**nalysis (RCA) is a method to investigate a problem or failure to get the 'route cause' of it. The aim is to learn from mistakes and to avoid the recurrence of such problems / failures in the future. It also aims to regulate customer / ensurance / contractor complains and returns. In some cases it aims also to correct / modify / optimize further / future actions.
RCA is applied in quite different fields, like accident / failure investigation, risk analysis, quality control, management change or auditing.

The primary goal of a RCA is to identify:

- What happened ?
- How does it happened ?
- Why does it happened ?
- How is it possible to prevent such events in future ?

2 Methods

The are quite different methods to perform a RCA depending on the underlying problem. In the following a few common methods are briefly characterized (see also Duphily, 2014; Dogget, 2005).

Barrier analysis: process to identify physical, administrative or procedural barriers or controls that should have prevented the problem / failure.

Change analysis: process to identify how changes of elements have influenced the occurrence of the problem / failure.

Event and causal factor analysis: process to identify the sequence of actions and conditions leading to the occurrence of the problem / failure.

Tab. 2.1: Characterization of RCA methods (LBNL, 2007)

Method	When to Use	Advantages	Disadvantages
Barrier Analysis	Use to identify barrier and equipment failures and procedural or administrative problems.	Provides a systematic approach	Requires familiarity with the process to be effective
Change Analysis	Use when cause is obscure. Useful in evaluating equipment failures.	Simple six-step process	Limited value because of the danger or accepting wrong "obvious" answer(s).
Event and Causal Factors Analysis	Use for multifaceted problems with long or complex causal factor chain.	Provides visual display of analysis process. Identifies probable contributors to the condition.	Time-consuming and requires familiarity with the process to be effective

Fishbone diagram: graphical tool to identify the problem / failure by considering different influencing factors (see Fig. 2.1, please note that additional influencing factors and further subdividing is possible).

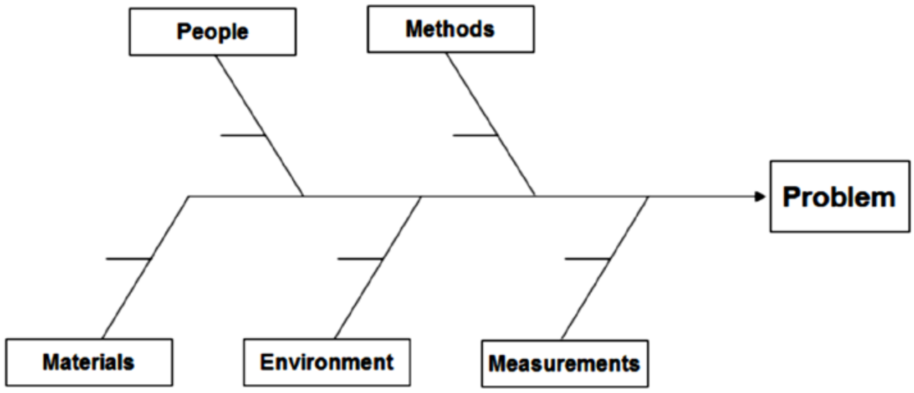

Fig. 2.1: Fishbone diagram for RCA (example)

Five Whys: Procedure based on answering 5 key questions:

- Why do the deficiencies occur ?
- Why are entities not in compliance ?
- Why are risks not being managed or intended results not being realized ?
- Why are strategies not developed ?
- Why is information needed to support decisions not available ?

Fault Tree Analysis (FTA): displays cause-consequence relationships in form of a tree structure to identify failure, undesired or unintended events (e.g. Sharma & Singh, 2015; Wiki, 2021). It is mainly based on Boolean algebra and in some cases including probability theory. It identifies the relevant events and conditions leading to failure. The FTA is described by the standard DIN EN 61025. The FTA is illustrated via symbols as shown in Fig. 2.2. The symbols are connected to create flowcharts. Fig. 2.3 shows a simple example: If G2 and G3 are valid, then G1 is valid; if either X1 or X2 are valid, then G2 is valid; if either X3 or X1 are valid, then G3 is valid.

RCA comprises in general 5 steps:

- Problem definition
- Data collection
- Identification of potential causal factors
- Identification of root causes
- Deduction of recommendations and implementation of solutions

Fig. 2.2: Fault tree symbols with event, gate and transfer symbols (Wiki 2021)

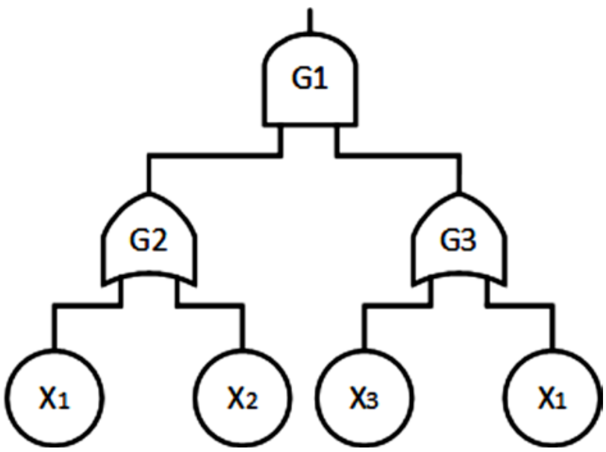

Fig. 2.3: FTA (example)

Numerical backanalysis:

A numerical backanalysis can help to understand the failure mechanisms. Based on observations and measurement results numerical models are set-up duplicating the HMT(C) coupled behaviour on the basis of physical laws and considering the excavation/operation sequence incl. all relevant support/installation measures.

3 Data collection

The fundament of all RCA is the data collection, which comprises the following items:

- Hard- and software related to the problem
- Reports, Maps, Documentations etc.
- Interviews with involved persons / witnesses
- Physical environment ro circumstances
- Relevant regulations / recommendations etc.
- Measurements / monitoring data / observations

4 Applications

There are several journals dedicated to case histories incl. also root cause analysis in respect to events related to natural or artificial impact on engineering projects:

- SSMGE International Journal of Geoengineering Case Histories
- Geoenvironmental disasters

The following sub-chapters provide some examples how RCA is applied in different fields of rock and civil engineering.

4.1 Example: Bridges

Tan et al. (2020) performed a fault tree analysis (FTA) and strategic environmental assessment (SEA) for bridge failure based on data between 2009 and 2019 in China. They also performed a RCA for the collapse of the Zijin Bridge in 2019 Heyuan (Guandong, China).
Fig. 4.1.1 shows the overall results of failure analysis in respect to bridge collapse in China between 2009 and 2018. Fig. 4.1.2 shows further results in respect to life span and construction / service stage.

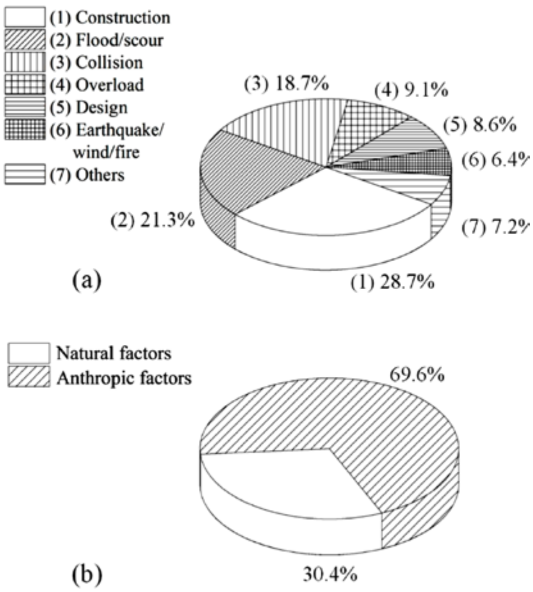

Fig. 4.1.1: Failure causes for bridge collaps (China between 2009 and 2018, Tan et al. 2020)

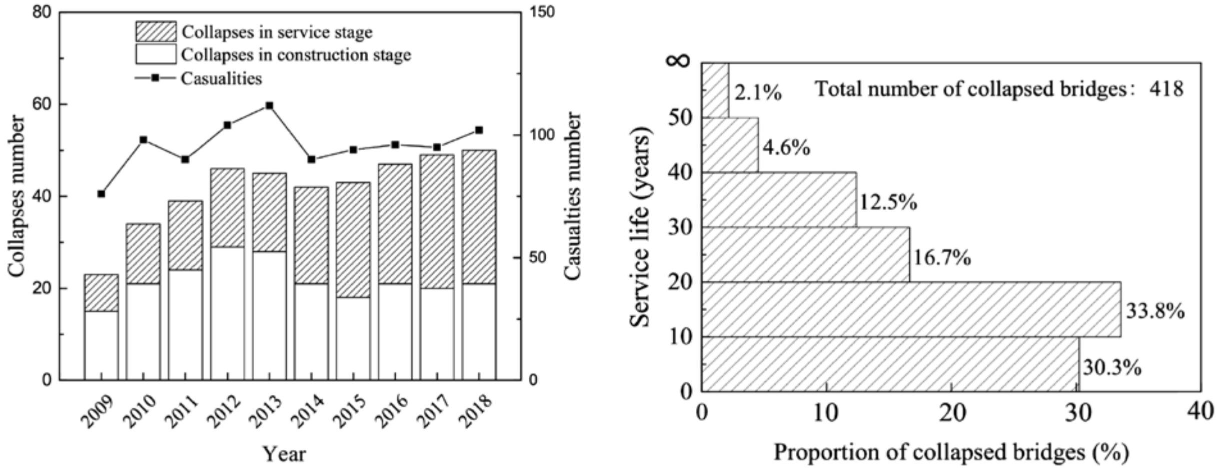

Fig. 4.1.2: Results of failure analysis for bridge collaps (China between 2009 and 2018, Tan et al. 2020)

In Tan et al. (2020) a RCA is documented in detail for the Zijin Bridge (see Fig. 4.1.3)

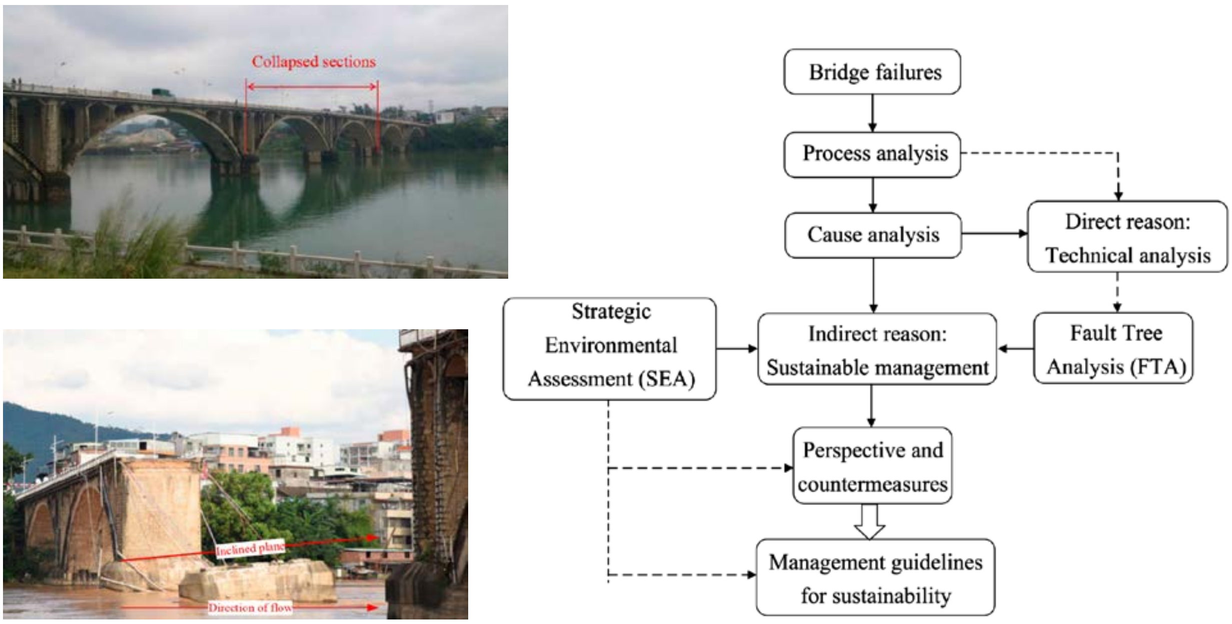

Fig. 4.1.3: Flow chart for RCA for Zijin Bridge (Tan et al. 2020)

Detailed numerical analysis in combination with FTA revealed the failure evolution as illustrated in Fig. 4.1.4. Increasing traffic flow and loads as well as increasing water flow in combination with unsufficient monitoring have caused the collapse. Aggravated river scouring and inadequate reinforcement of pier 3 have initiated the collapse process.

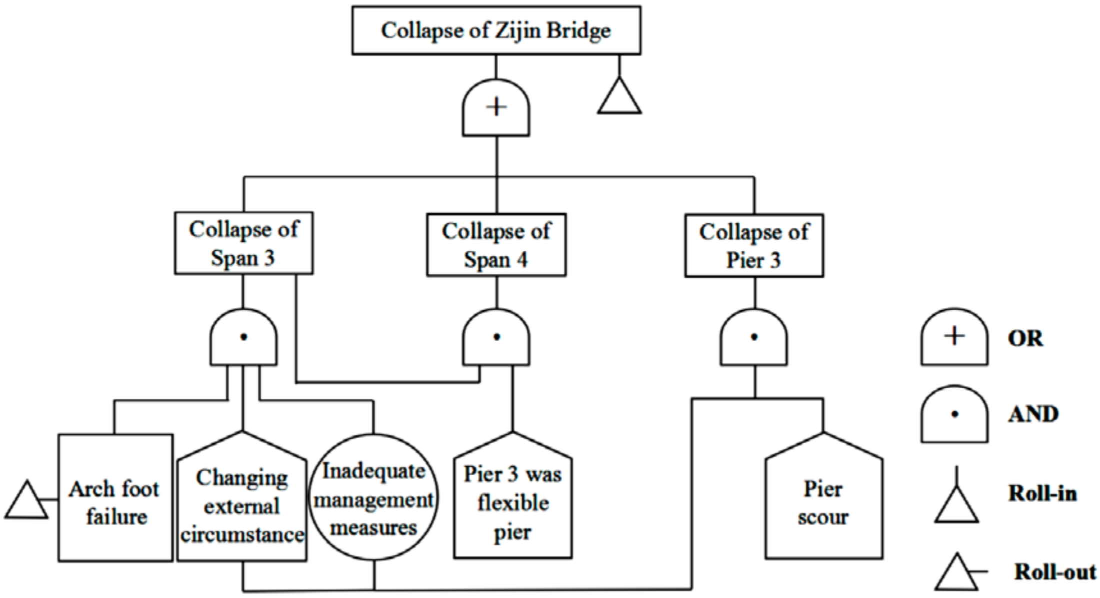

Fig. 4.1.4: Main fault tree of Zijin Bridge collapse (Tan et al. 2020)

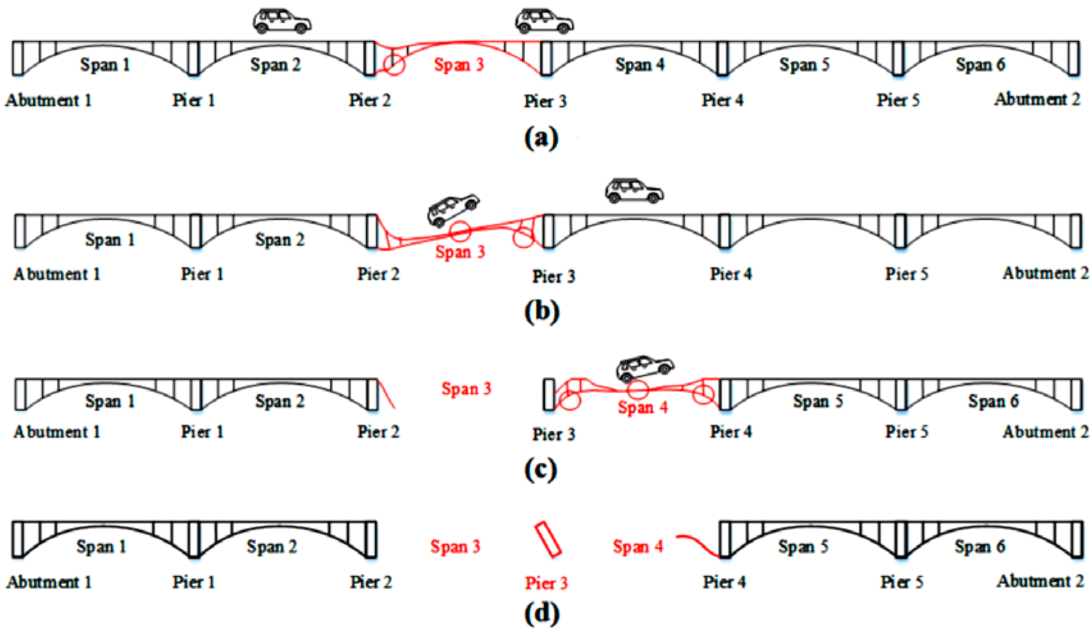

Fig. 4.1.5: Collapse sequence of Zijin Bridge (Tan et al. 2020)

Chowdhury et al. (2012) have analyzed the reasons for potential bridge failure of the J.B. Edwards Bridge using FTA (see Fig. 4.1.6) subdivided into superstructure and substructure components.

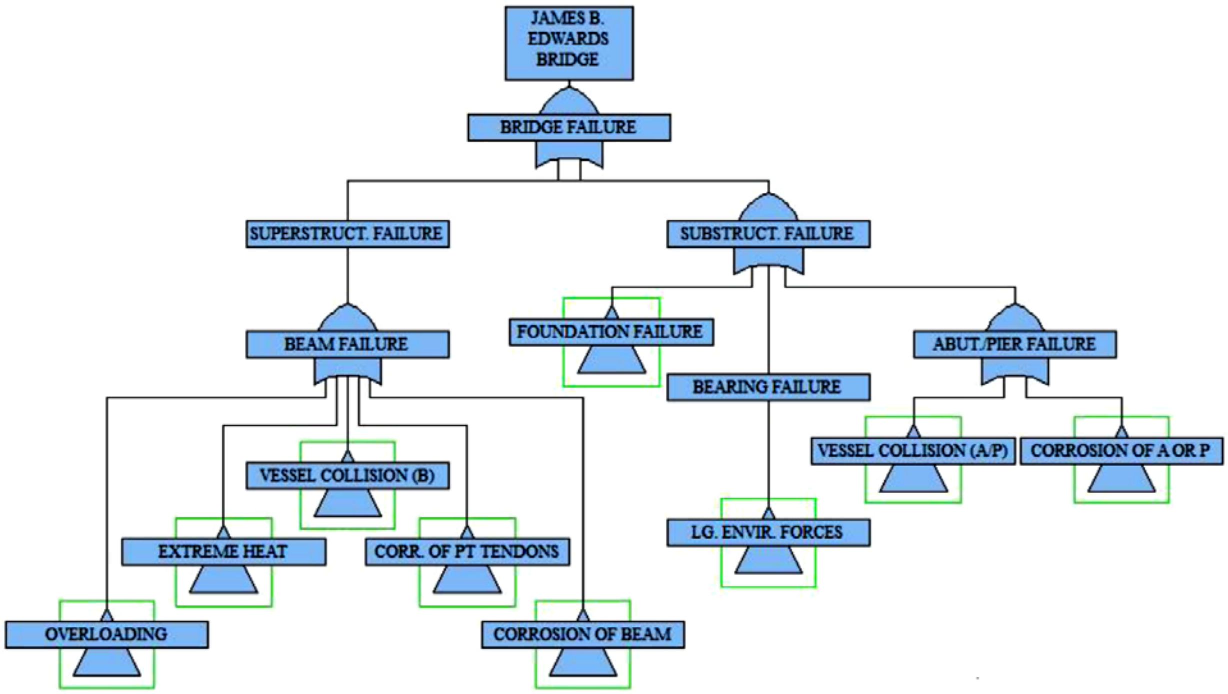

Fig. 4.1.6: FTA for J.B. Edwards Bridge (Chowdhury et al. 2012)

4.2 Example: Underground Coal Mining

Roof fall events in a coal mine were investigated (see Fig. 4.2.1). The following causes for roof fall were detected:

- rock type
- thickness of roof layer
- diagonal dimension of intersection
- presence of faults
- water flow / moisture

Based on the RCA a roof support design scheme was developed using a geomechanical classification scheme considering the important factors revealed by the RCA.

Direk (2015) used the FTA to analyse roof and rib fall events. Van der Merwe et al. (2001) have documented and analyzed rock fall events in coal mines in South Africa. A summary of identified causes is shown in Fig. 4.2.2.

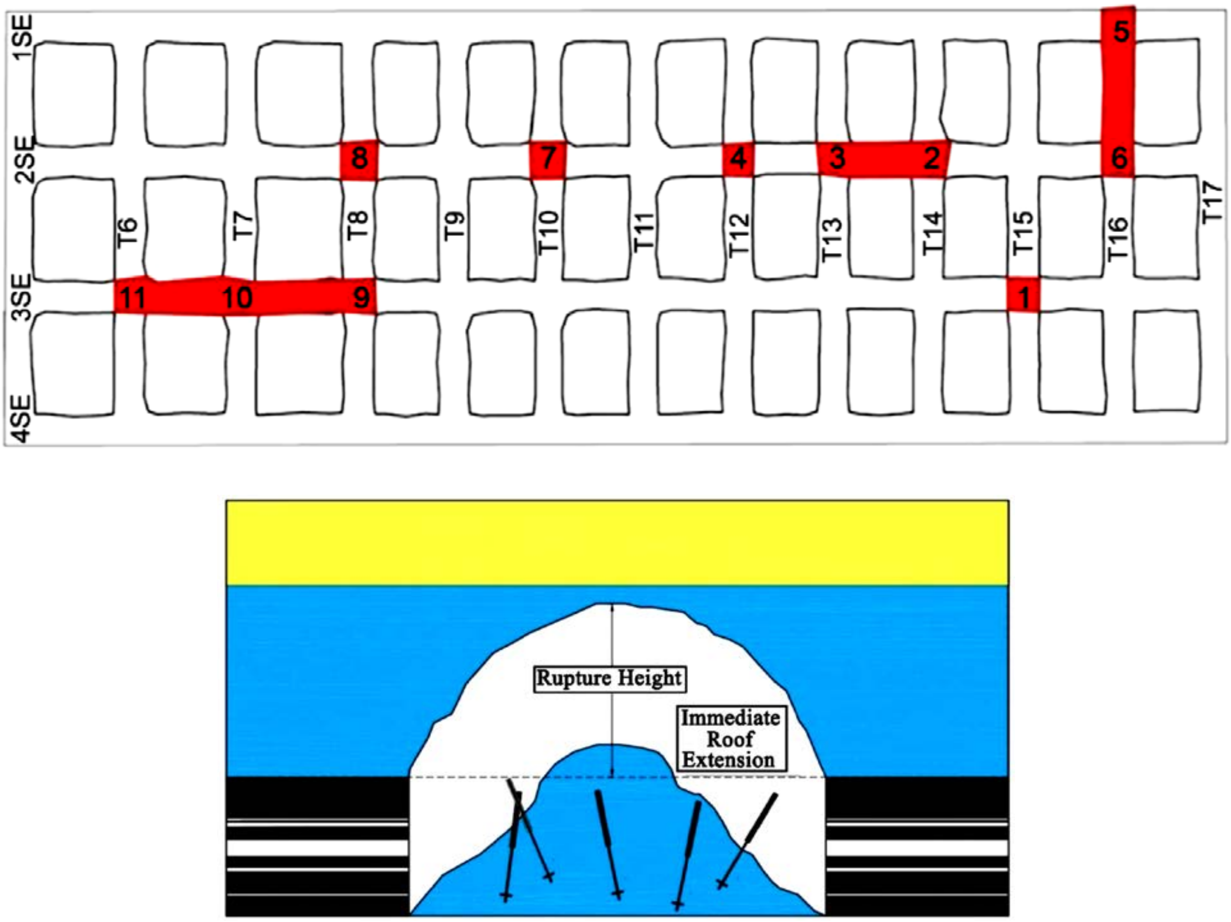

Fig. 4.2.1: Roof fall events a coal mine (Zingano & Andrade, 2021)

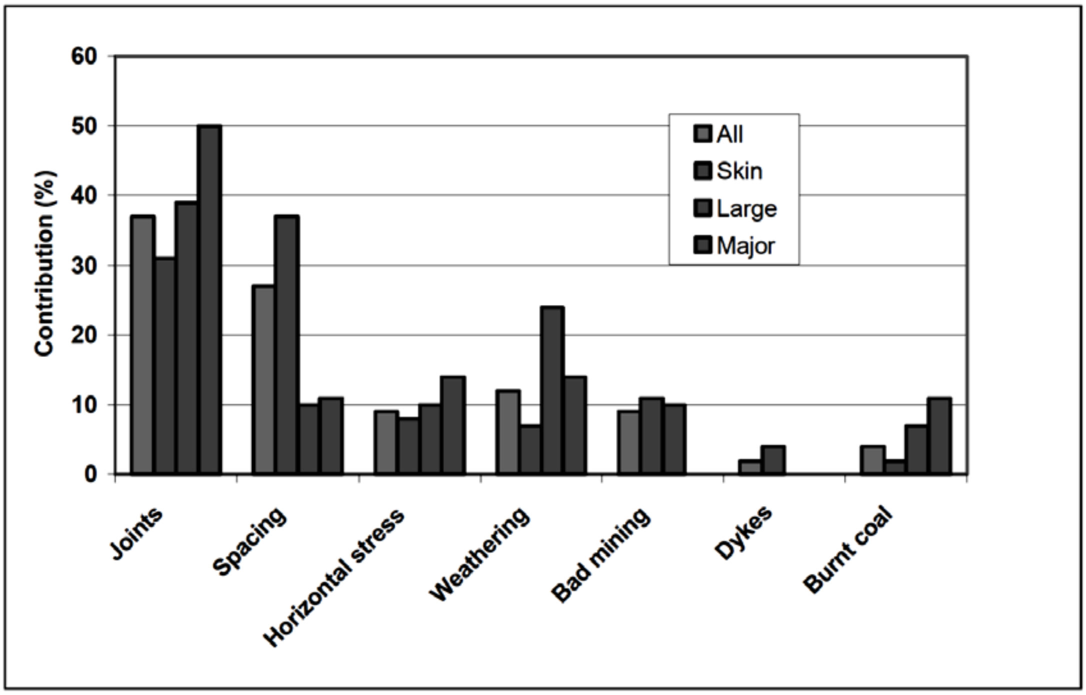

Fig. 4.2.2: Summary of RCA for rock fall events in coal mines in South Africa (van der Merwe et al., 2001)

4.3 Example: Ground control in underground hardrock mining

Dey & Barclay (2018) presented a comprehensive RCA for ground control failures in underground hardrock mining. They used fishbone diagrams to identify causal factors. They identified 10 primary causal factors out of 40 in total:

- Lack of burst-prone ground support
- Lack of understanding of geology and stress conditions
- Lack of management commitment to safety
- Ineffective risk management process
- Improper mine plan
- Lack of understanding of seismic hazards
- Dysfunctional IRS
- Installation of ground support by workers using handheld support
- Lack of understanding of structural geology
- Lack of specialized resources (industry/consultants/regulators)

Lack of rock burst-prone ground control was identified as most important factor. The following recommendations are deduced for prevention:

- Improve cost effectiveness, efficiency
- Excavation Design for potential installation of burst prone support
- Understand lifecycle of excavation
- Be proactive in your mining planning to accommodate future burst prone GS design
- Anticipation process for installation of burst prone support
- Improve installation equipment availability
- Predetermine areas for burst prone support (pre-hab)
- Operations acceptance of ground control recommendations for burst prone support
- Incorporate burst prone support into the cycle (consider it single pass installation – not primary/secondary)
- Prioritize secondary support. Link to mining plan schedule
- Improve the ability to measure the residual capacity of the support
- Equal importance to production bonus system for pre-hab and rehab
- Quality control of surface support (need for continuous improvement)
- Continuous improvement of the design of the composite burst prone support system
- Better clarity on the specs of the various dynamic supports
- Better understanding of the interaction between individual components of burst prone system (e.g. not always numerically driven)

The developed fishbone diagram considering the geomechanical conditions is shown in Fig. 4.3.1.

Fig. 4.3.1: Fishbone diagram for analyzing the detailed failure causes in respect to the geomechanical environment (Dey & Barclay, 2018)

4.4 Example: Storage salt cavern wells

Berest at al. (2019) studied several casing and cement leaks in the salt storage industry worldwide. The origin of the leakage was in moset cases due to poor welding/screwing conditions and corrosion, but also strong deformation of the rock mass. Based on the RCA several conclusions were drawn to minimize failure and to give warnings:

- Carefull longterm monitoring of wellhead pressure
- High quality wellbore completion
- Performing of mechanical integrity tests

4.5 Example: Water dams

Anderson et al. (1998) analysed several dam failures by using the backanalysis method. Different reasons for dam failure were detected, like:

- erosion of the abutment
- unstable reservoir banks
- underestimation of effective stress effects
- joints with clay fillings in the abutment
- earthquake excitation

Miwa & Kurashima (2003) performed a RCA of diversion dam failures in Japan.

Barker (2016) describes the general RCA approach for dams and explains it by using an example. He gives an example for a cause-effect diagram (fishbone diagram) in respect to quality (see Fig. 4.5.1).

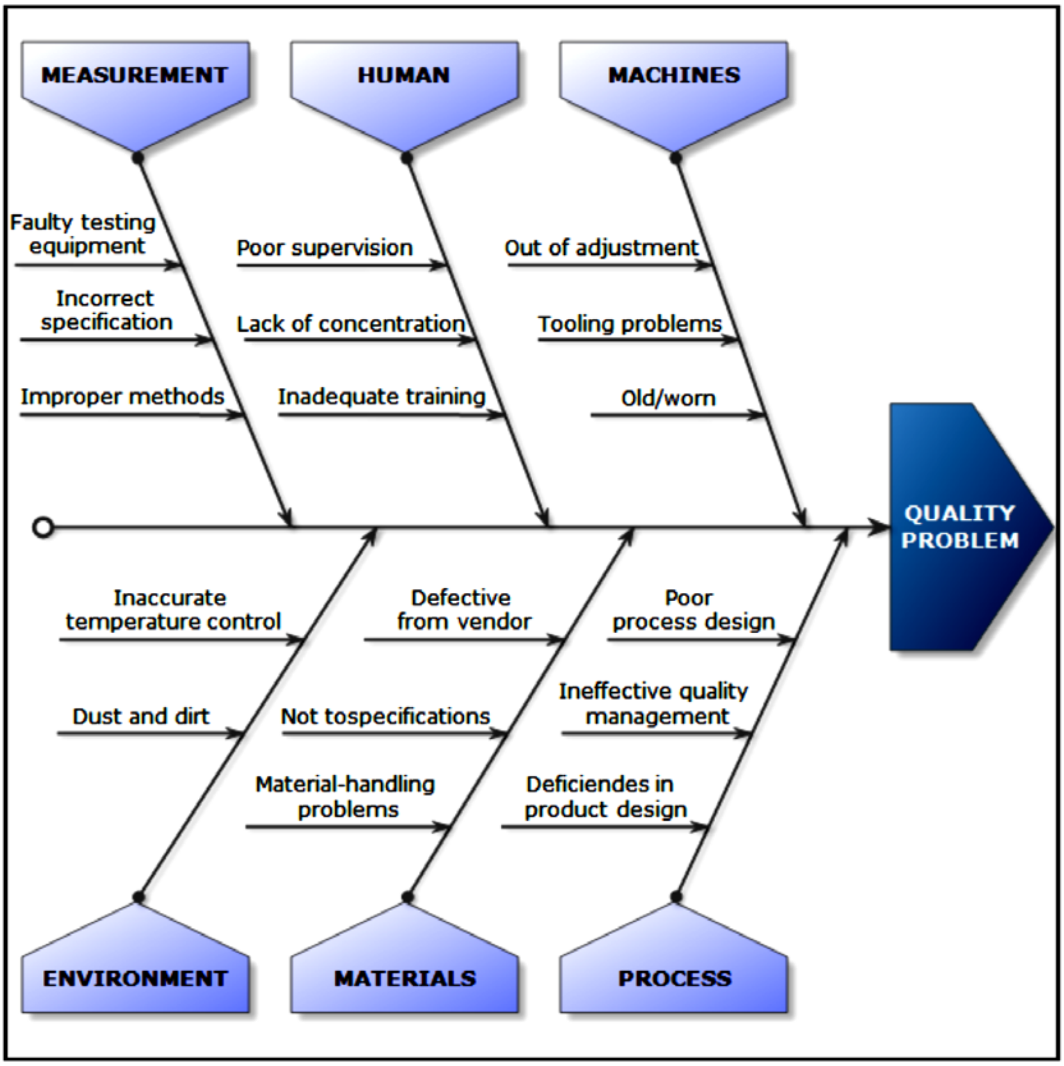

Fig. 4.5.1: Fishbone diagram for the quality problem (Barker, 2016)

Barker (2016) provides a RCA example for a tailing storage facility (dam) which failed by several cracks (piping failure). After detailed crack analysis was performed a fishbone diagram was used to detect potential failure causes (see fig. 4.5.2).

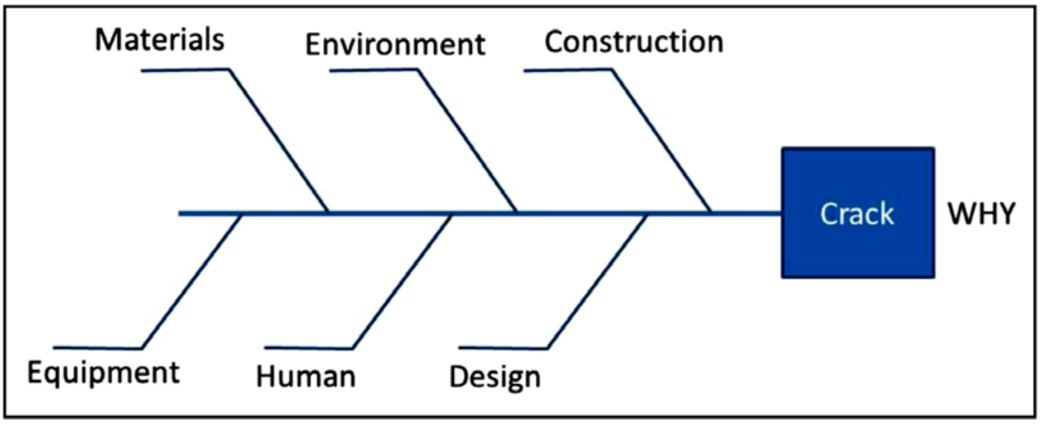

Fig. 4.5.2: General fishbone diagram for the quality problem (Barker, 2016)

Based on the detailed analysis 4 significant contributors for transverse cracking were detected:

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

For longitudinal cracking the following main causes were identified:

- Soft tailings along the wall causing differential settlement
- Raise height too high for the foundation material
- Rapid construction period

Finally, several mitigation measures were deduced.

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