Learning from Failures: Using Historical Engineering Projects to Teach Better Professional Engineering Skills

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Abstract
The state of the art of engineering knowledge has historically often improved following reviews of major disasters and engineering failures. It is not desirable however for professional engineers to only improve their understanding and skills by "learning from their mistakes". A new final-year engineering course for Civil and Natural Resources Engineering students at the University of Canterbury aims to get students to learn more from other people's past mistakes. A major component of this course is a group project where students investigate notable engineering "failures" from the past century and try to determine the causes behind them. As well as any direct technical reasons for each failure, students are challenged to identify the more "non-technical" issues that contributed to the ultimate denouement, including human errors, ethical shortcomings, and regulatory omissions. Using this exercise, it is hoped that students will learn to recognise common "warning signs" in their future projects that may be pre-cursors to more catastrophic potential outcomes.

1. Introduction

Various commentators have noted that the state of the art of engineering knowledge often tends to make the biggest improvements following reviews of major disasters and engineering failures (e.g. [2], [4]). For example, design standards for buildings in earthquakes were first introduced into New Zealand in 1935 following the 1931 Napier earthquake [1]. Typically the process involves investigating what didn't perform as expected during the event and then devising some new standards or methods to resolve these shortcomings. It is not desirable however for professional engineers to only improve their understanding and skills by "learning from their mistakes".

Also, in many cases, there are a number of intermediate steps that contributed to the ultimate "failure event", many of which are "non-technical". These could include human errors (both individual and collectively via groups and organisations, [6]), ethical shortcomings (e.g. cover-ups, pressure from other parties), and regulatory omissions (e.g. inadequate checks, failing to meet required standards). In hindsight, the identification and elimination of some of these issues may have been sufficient to prevent the final undesirable result.

This paper summarises the development of a new final-year engineering course at the University of Canterbury (UC) that seeks to get students to learn more from other people's past mistakes. A major component of this course is a group project where students investigate notable engineering "failures" from the past century and try to determine the causes behind them, both technical and non-technical.

2. New Professional Engineering Course

In 2013, as part of a review of the undergraduate curriculum, the Department of Civil and Natural Resources Engineering at UC introduced a new compulsory final (4^{th}) year course to their Bachelor of Engineering (BE(Hons)) programme. The course, ENCN470 ("Professional Engineering Development"), had a stated aim to *"further develop and refine students' professional engineering skills, using Civil and Natural Resources Engineering projects and issues for context."* The course included consideration of topics such as risk management, systems thinking, the engineer in society, and engineering ethics, as well as continuing to develop students' skills in teamwork and communications.

IPENZ, in its five-yearly accreditation of UC's engineering programme, had identified the need for these "non-technical" attributes of professional engineering to be better covered in the undergraduate curriculum. Although some of these topics had previously been presented elsewhere in the old curriculum, they tended to be subservient to the technical content of the courses; thus it was possible to pass without demonstrating mastery of them. This new course allowed these topics to be the core component of the final assessment.

An underlying theme for a large part of the ENCN470 course is the concept of "learning from experience". Noting that the students are still relatively limited in their own experience of the engineering industry, the intention is to instead draw on lessons learned from *other* engineers' experiences, via case studies, guest lecturers, and the students' own investigations. Some assignments in the course for example require the students to monitor and comment on engineeringrelated news in mainstream media and to attend and report on a number of industry events (e.g. IPENZ seminars, technical society presentations).

2.1 Teaching about Failure

A lot of engineering education tends to rely on providing students with “recipes” for success; for example, design techniques and calculation methods that have proven to be successful in the past. There is a danger however that such past success may blind professionals from the potential dangers of new projects where the previous circumstances cannot be completely replicated. These dangers may be due to extending the existing engineering knowledge beyond what has been tested, or it may be due to having different personnel, site, and organisational constraints.

The ENCN470 curriculum includes a series of topics designed to help students appreciate the value in learning about engineering failures and to give them the necessary investigative tools:

- Generic types of failure (e.g. objectives not met, undesirable side-effects); Effects of failures on different entities (people, property, level of service, etc).
- Reasons for investigating failures (punitive measures, avoid future failures); Issues with formal Inquiries.
- General causes of failures (due to aims, organisations, methods, people); Human errors (skills/rules/knowledge-based); Organisational and group behaviour (e.g. “groupthink”).
- Systems representations of complex engineering concepts (entities, relationships); Characteristics of good systems descriptions (completeness, discrimination, naming, etc).
- Models for failure investigation (“Swiss Cheese” model, spray diagrams, multiple cause diagrams); Formal Systems Model concept.
- Risk management strategies for projects/ activities (avoid, reduce, mitigate, etc); Use of design standards and awareness of their limitations.
- Legislation affecting engineers; Liabilities under law; Environmental planning & legislation (RMA, Environment Court, town planning).
- Ethics vs morality and the law; Schools of ethical thought (teleology/deontology, utilitarianism); Tests for ethical decision-making; Professional engineering codes of ethics.

The ENCN470 course also notes that one problem in industry can be a loss over time of “institutional memory”, as new generations of engineers come in. Petroski [5] identified an interesting sequence of new types of bridge failures approximately 30 years apart since the 1840s, and hypothesised that this time gap may represent the point at which the next generation forgets about the lessons learned from the (now retired) previous generation when testing the bounds of new designs.

Some other courses within this programme and at other universities with engineering degrees do present case studies of notable failures as part of their content. However, these courses tend to focus on the technical aspects of the failures (as a way of illustrating the technical theory being introduced) and overlook the more complex nature of human failings, and the constant tension of costs and benefits (i.e. risk vs reward) on many projects.

Many other undergraduate engineering programmes cover professional engineering topics (e.g. the University of Auckland’s Faculty of Engineering has a compulsory final-year course called “Professional and Sustainability Issues”). However, to the best of our knowledge, the author is not aware of any other engineering programmes in Australasia that cover failure investigation in a broad-based manner as this new curriculum does. Elsewhere however, a growing number of engineering faculties are offering courses in “forensic engineering” (e.g. Columbia, New York; Cleveland State University), using case studies such as those studied here to teach students about multi-disciplinary failure analysis.

2.2 Engineering Failure Case Study Project

A major component of the ENCN470 course is a group project where students investigate a notable engineering “failure” from the past century and try to determine the causes behind it. As well as any direct technical reasons for each failure (e.g. structural failure of a beam), students are challenged to identify the more “non-technical” issues that contributed to the ultimate denouement, including aspects of human error and failings in ethical behaviour, risk management, and regulatory obligations. Using this exercise, it is hoped that students will learn to recognise common “warning signs” in their future projects that may be pre-cursors to more catastrophic potential outcomes.

The students work in groups of four or five, allocated to projects on the basis of their submitted “top five” preferences. It should be noted that, by this stage of their studies, students are able to choose elective courses in their sub-disciplines of interest (e.g. structural, geotechnical, fluids, environmental, transport). Therefore the aim is to allow them to investigate a project of particular technical interest to them. Table 1 provides a list of some (not all) of the projects that have been offered to students to date; as well as spanning both New Zealand and international contexts, and over a broad range of eras, they encompass a range of different technical fields. There were 26 case studies investigated in 2013, and 32 in 2014, with more than half being investigated in both years.

The project is also designed to test students' general engineering skills in a variety of ways. Each group is required to produce a final written report and deliver an oral presentation, both to a high standard. They are also required to initially prepare a detailed project plan, outlining the tasks, roles, timelines, quality controls, etc necessary to complete the project, and later to formally peer review a draft of another group's outputs.

Table 1: Examples of Projects investigated (not all)

Mapua Contaminated Site Clean-up, Nelson (1990's)
Levin Landfill project, Horowhenua (1950's-2000's)
Lake Manapouri Power Scheme (1960's-70's)
Project Aqua hydro scheme, North Otago (2003-04)
Opuha Dam Breach, South Canterbury (1997)
Whaeo Canal Failure, Bay of Plenty (1982)
Matahina Dam, Bay of Plenty (1967-87)
Malpasset Arch Dam, France (1959)
Abbotsford Slip, Dunedin (1979)
Eschede Hi-Speed Train Disaster, Germany (1998)
Sydney Cross City Tunnel Toll Road, NSW (2000's)
New Orleans levee failures (2005)
Central Artery/Tunnel Project, Boston (1991-2007)
Ballantyne's Fire, Christchurch (1947)
Napier Earthquake Fire (1931)
South Rangitikei Rail Bridge Collapse (1975)
West Gate Bridge, Melbourne (1970)
Quebec Bridge, Quebec City, Canada (1907/1916)
Kaimai Tunnel collapse, Bay of Plenty (1970)
Stadium Southland collapse, Invercargill (2010)
Cave Creek platform, West Coast (1995)
Hyatt Regency Walkway, Kansas City (1981)
World Trade Center, New York (2001)
Hartford Civic Center, Connecticut (1978)
I-35W Mississippi Bridge, Minneapolis (2007)
Charles de Gaulle Airport Terminal 2E, Paris (2004)
King Dome Failure, Seattle (1994)
Silver Bridge collapse, Point Pleasant, Ohio (1967)
Love Canal contamination, Niagara Falls (1953-78)
Southerner level crossing collision, Rolleston (1993)

2.2.1 Project Tasks and Questions

The following tasks and questions need to be resolved as part of each group's investigations:

- Concisely describe the entity/project in question and the circumstances leading to the failure(s).
- Prepare at least one **systems model** of the entity/project, making it clear whose perspective/ world-view is being presented (and why). Compare the systems model against an ideal Formal System Model, as described in [7] and discussed further below in Section 2.2.2.
- Prepare a **risk management matrix** of potential risks/hazards prior to the failure(s), indicating the relative likelihood and consequences of each risk/hazard. How did the actual risks/hazards contributing to the failure compare with other risks/hazards that didn't eventuate?
- Identify any potential **ethical issues** that may have arisen before, during or after the failure(s). How might events have been different if certain ethical decisions had been made differently? (e.g. if participants had followed IPENZ's Code of Ethics)
- Consider the **regulatory environment** that was present before or during the failure(s). How might events have been different if the entity/project was operating under present-day legislation/regulations in New Zealand?
- From the above analysis, determine what were the **underlying causes or contributory factors** behind the failure(s).
- If you were undertaking a formal Inquiry into this failure, what would you be **recommending** (both technical and non-technical) to try to prevent a similar type of failure from happening again? What lessons are there to learn for engineering entities/projects in general? How do these recommendations compare with what actually happened after the failure(s)?
- What were the likely effects/implications of this failure and its subsequent aftermath **on society in general**? For example, changes in our daily lives, or changes to perceptions of engineers and engineering projects.

Students are able to source whatever material they can find to help their understanding and to derive their conclusions, via online or Library resources. At the end, each group is expected to have a comprehensive overview of the factors that led to the failure being studied, and how a failure of this nature could have been prevented.

2.2.2 Formal Systems Model

Fortune and Peters [3] outlined a technique for investigating failures in projects that compared the actual events and entities involved against an "ideal" state of affairs. A visual model is created to represent the project itself (the "system"), surrounded by the other aspects of the organisation(s) undertaking the project (the "wider system"), which in turn is surrounded by other physical and social factors external to the organisation (the "environment"). This so-called "ideal" Formal Systems Model (FSM, shown in Figure 1) aimed to represent all of the necessary components for successfully completing a project, e.g. having a suitable sub-system monitoring the project's performance.

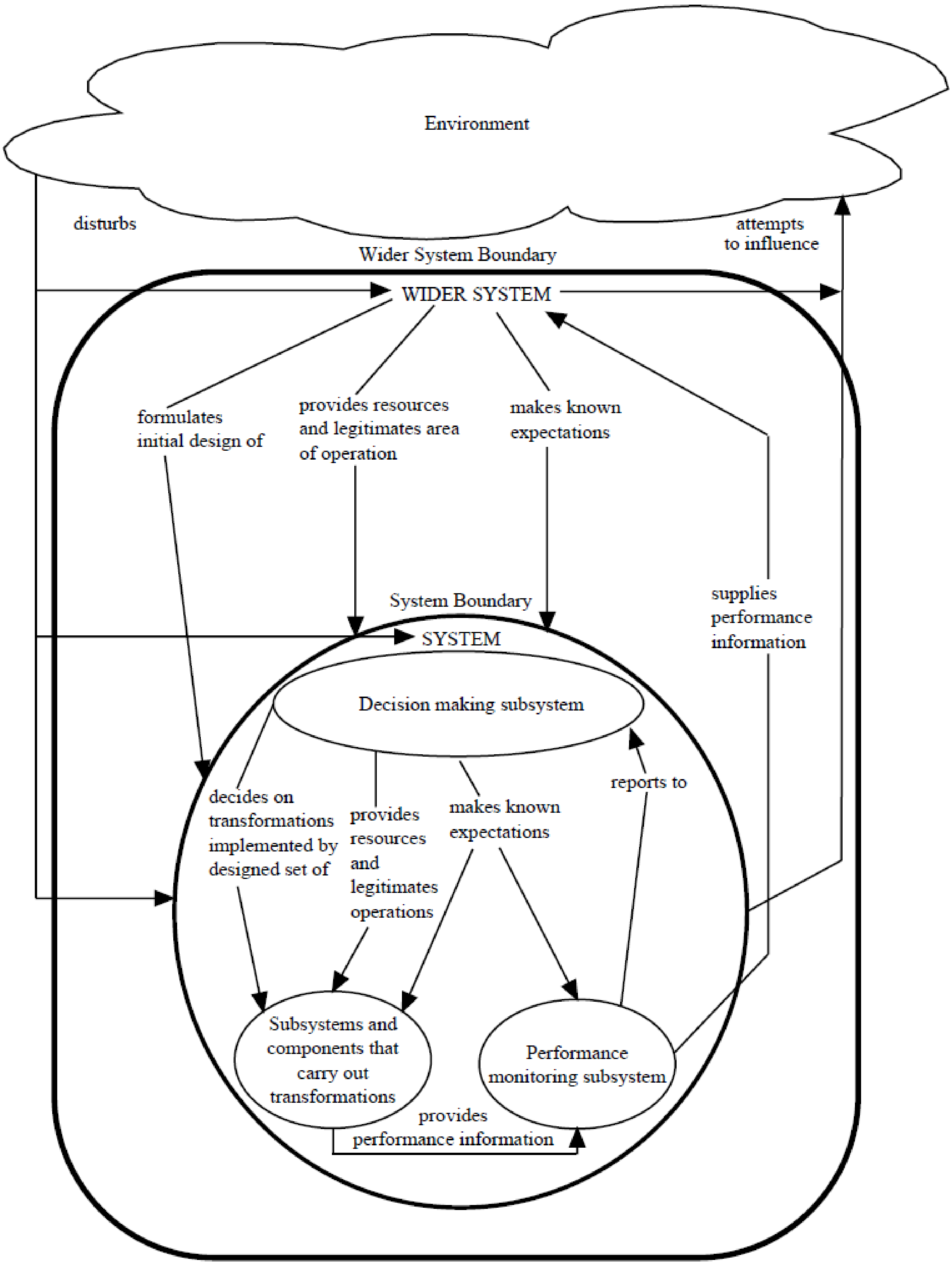

Figure 1: General Structure of an “ideal” Formal Systems Model for a successful project/entity (from [3])

A key part of the assignment requires students to construct a systems representation of their project in the FSM format. For their identified failure(s), they could then determine what deficiencies were present in their systems model relative to the ideal FSM. For example, they might have noted that the governing organisation (the "wider system") did not make available sufficient resources to complete some aspect of the project.

The FSM approach provides a useful systematic method for identifying the likely non-technical reasons for the project failure. It offers a consistent framework with which to test the quite varying circumstances affecting the many different projects being studied (32 in 2014).

3. Issues Identified with the Group Project

An interesting challenge for some groups is to first identify what exactly the "failure" was in their project. While some projects (e.g. Opuha Dam breach) have a fairly obvious physical failure, others involve a series of ongoing events that could be considered failures (e.g. Boston "Big Dig", featuring accidents, cost over-runs, etc). Still others seem even less obvious whether any notable failure had occurred at all; e.g. the Chesapeake Bay Bridge-Tunnel (Virginia) stumped one group because the facility is still operating today (despite a few major ship collisions). A useful idea suggested to some groups is to identify what would have been the likely project objectives at the start of the venture and then consider whether those objectives had been successfully met. For example, some of the aims of the Chesapeake Bay Bridge-Tunnel were to open up development of the Delmarva Peninsula, and to operate an economically sustainable toll operation, neither of which has been fully achieved.

Some groups encounter difficulties discovering the regulatory and engineering environments of their projects, due to their considerable distance in time and space from present-day New Zealand. Where these information gaps cannot be resolved, the students are asked to focus on how the project would have fared in present-day New Zealand, taking into account current legislation, IPENZ requirements, and so on.

Although students are encouraged to concentrate on the non-technical aspects of their projects, many still focus too much on the technical reasons for the failures. Given the predominant emphasis in their studies on technical subjects, such as load capacities and material properties (and their likely greater comfort with these topics), this is perhaps not surprising. In many cases, students may have also been influenced by an official "Commission of Inquiry" report obtained for their project, most of which have historically been limited in scope to technical aspects of the failure.

Some of the projects investigated have considerable similarities between them, both in terms of the facilities involved and the failure mechanisms. It is pertinent to note that clearly the lessons of past failures have not always been heeded. For example, one group presenting on the Hartford Civic Center collapse (due to snow in 1978) concluded that the findings from this investigation should *"prevent a reoccurrence in the future".* However another group had just presented on the Stadium Southland collapse in 2010, a similar publicly-owned sports facility also damaged by snow loads!

In fact, a common theme identified was the role that many public agencies like Councils played as both owner/developer and regulator for many of the projects studied. Clearly there were often difficulties prescribing the same level of independent scrutiny to their own projects as is done for private ventures. This point has subsequently been picked up for highlighting in more detail in the ENCN470 curriculum.

It is interesting to note that most of the projects studied were subsequently repaired or a revised version completed, rather than being abandoned. This suggests that there was merit in the original objectives of the facility, rather than it being "doomed from the start". Many of the projects were however the catalyst for improvements to regulatory requirements or engineering best practice. For example, the similar failures of the Ruahihi Canal (1981) and the Wheao Canal (1982) were instrumental in the formation of the New Zealand Society of Large Dams (NZSOLD).

Some other aspects of the ENCN470 course experienced "teething troubles" in its first year (2013), partly due to a reluctance by students to spend time on "non-technical" topics deemed less important to their careers. However, feedback on the failure case study project was generally positive from the students. A couple of quotes from the student course evaluation illustrate this:

"The group project was good; it was quite fun to learn about a failure while my peers were learning about something completely different and then we could come together to share it with each other in the presentations."

"The failure project was a good learning tool. Before starting the project, many concepts were just vague things that one ought to do. The project was a framework to see them in action."

The project also provides a practical way to introduce aspects of engineering heritage to the students without it coming across as a "dry" history lecture. Many of the projects studied are considered touchstones of modern engineering practice (i.e. when existing practices were questioned or new practices introduced), and it is useful for students to appreciate the context of why it is that modern professional engineers "do the things they do" in current engineering.

4. Conclusion

The new ENCN470 course has enabled a number of "non-technical" professional engineering skills to be assessed in a more direct (yet still contextually relevant) manner. By focusing on how engineering projects can fail in a variety of ways, students gain a set of skills to help them identify how things can go wrong, for both technical and non-technical reasons. Using the historical case study project, it is hoped that students will learn to recognise common "warning signs" in their own future projects that may be pre-cursors to more catastrophic potential outcomes. At a time when major events like the Canterbury Earthquakes have raised public awareness of engineering practices, this seems like an important skill for our future students to have.

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