HUMAN FACTORS IN DAM FAILURES

Irfan A. Alvi, PE
President & Chief Engineer; Alvi Associates, Inc.; Towson, MD; ialvi@alviassociates.com
Member, ASDSO Dam Failure & Incidents Committee (DFIC)

Introduction: The Essential Role of Human Factors

While relatively uncommon, dam failures continue to occur, sometimes with catastrophic consequences. Investigations of such failures have typically focused on the physical factors involved, which is understandable given the technical orientation and background of engineers. However, the creation and management of dams always involves interacting physical and human factors, and this broader dynamic *system* is responsible for both safety and failure of dams.

Moreover, because physical processes are assumed to deterministically follow physical laws (leaving aside quantum mechanics), with no possibility of physical 'mistakes', we can assert that failure of dams – in the sense of not fulfilling human intentions – is ultimately *always* due to human factors, in other words humans falling short in various ways. These human factors necessarily involve individuals, but they also involve groups of various kinds and scales, including private firms, government agencies, design teams, professional societies, communities, international consortia, etc.

Contributors to Failure

Traditionally, it has commonly been assumed that safety is the default for dams and other systems, and that failures are therefore due to atypical physical factors (eg, 'Acts of God') and/or egregious 'human errors'. However, research over the past few decades suggests that this paradigm should be reversed, with the new default view being that a natural tendency is for systems to move towards disorder and failure (in line with the concept of increasing entropy), and with continual human effort thus being needed to maintain order and prevent failure.

This paradigm reversal leads to the question of why human efforts do sometimes fall short, allowing failure to occur. The most fundamental answer is that we humans, both individually and in groups, are highly fallible and limited. For example, our data and knowledge are incomplete, our models are unavoidably inaccurate to various degrees, our cognitive ability is finite (we have ‘bounded rationality’), we take heuristic shortcuts and settle for ‘satisficing’ rather than optimizing, we’re subject to a host of cognitive biases at individual and group levels, we forget things, and our intuition can be highly unreliable when dealing with unprecedented situations.

Furthermore, despite this fallibility and array of limitations, we often face the challenge of creating and managing complex systems – such as dams, the humans associated with them, and their natural environment – thus further taxing our capabilities. This complexity typically involves interactions among many physical and human factors over the course of time. Examples from dam engineering include interactions between politicians and owners, owners and engineers, owners and contractors, design supervisors and designers, engineers and contract documents, engineers and contractors, contractors and contract documents, contractors and the physical materials and sites of dams, dam operators and dams, dams and their natural environments, dams and their foundations, seepage and structural stresses, seepage and piping, etc.

Moreover, these interactions may be nonlinear and tightly coupled, resulting in phenomena such as feedback loops (eg, the vicious cycle of seepage and piping), large effects from small inputs (eg, major erosion stemming from initially small foundation defects and minor seepage), emergence of qualitative transitions in system behavior (eg, slope failure and dam breach), and formidable uncertainties (eg, seepage paths). In the same vein, there is added complexity due to interfaces with technological systems. For example, use of software obviously confers many benefits, but is also notorious for adverse effects such as causing ‘black box’ cognitive opacity, as well as restriction and distortion of how data is presented (eg, visual computer displays misperceived as being reality).

As if all of this weren’t challenging enough, the norm is that we’re continually faced with finding appropriate tradeoffs between conflicting goals stemming from competing social, economic, political, professional, personal, and other pressures. For example, on one hand, we’re tasked with responsibility for safety, but on the other hand we face pressures to increase system efficiency, productivity, profitability, compliance with deadlines, competitiveness, etc., and indeed engineers routinely feel compelled to reduce cost even without external pressure to do so. These ‘double binds’ (and ‘n-tuple binds’) imposed by the system can powerfully influence how decisions are made by individuals and groups, thus significantly reducing the extent to which we can reasonably assign ‘blame’ for failures and find scapegoats, though it’s also true that there are undeniable cases of gross incompetence, deceit, and corruption which need to be addressed accordingly. In other words, we need to find balance between focusing on the system versus individuals, rather than going to either extreme.

How Failure Generally Unfolds

Studies in a variety of domains within and outside engineering (eg, aviation, medicine, nuclear power, industrial plants, finance, and business) have shown that major failures are usually preceded by a series of steps involving physical and human factors interacting over a relatively long period of time, often years or even decades. Dams are no exception to this general pattern. Each of these steps may be small, often small enough to go undetected or not elicit a response if detected (eg, 'minor' seepage, erosion, or cracking), and with no step or factor sufficient by itself to produce failure. However, when enough factors accumulate and 'line up' appropriately, they can become jointly sufficient to produce observable incidents and failures.

Measures for Preventing Failure

Assessment of the daunting challenges we face due to our limitations in dealing with complexity, uncertainty, and conflicting goals could be cause for pessimism. For example, 'normal accident' theory suggests that a substantial rate of major failures is inevitable for many kinds of complex systems.

Yet, the empirical fact is that modern dam engineering has had a successful track record overall – in the US, there have been hundreds of dam failures among tens of thousands of dams – and the same applies in many other domains involving complex systems, including systems dealing with rapidly evolving adverse situations. Indeed, even in these especially challenging environments, organizations have been identified which have a long track record of success, thus becoming known as 'high-reliability organizations' (HROs). In general, HROs reduce rates of substantial failures by being *preoccupied* with avoiding failure. This 'paranoid' mindset naturally leads to traits such as the following:

- Explicit identification of goal conflicts, so that informed choices regarding goal tradeoffs can be made, thus enabling safety to have sufficient priority

- Continuous monitoring for early indicators of trouble (eg, dam monitoring), and corresponding suspicion of quiet periods

- Prompt response to detected concerns, while still within the 'window of recovery' (eg, immediate correction of problems identified during dam construction, close attention to dam inspection findings, and diligent routine maintenance)

- Conservative safety margins and system ‘slack’, rather than stretching the system to the limit (eg, design conservatism, and reasonable design and construction schedules)

- Redundancy and robustness within organizations and their associated physical systems (eg, independent peer reviews and checks of designs, and redundant measures to limit uplift on dams)

- Design of systems to fail gradually, provide telltale warnings of failure, and incorporate barriers to limit propagation of failure (eg, emergency spillways, fuse plugs, and fuse gates)

- Open sharing of information across and beyond the organization, including reporting of concerns and listening to dissenting voices, so that fragmentary information can be synthesized to connect the dots and understand the ‘big picture’

- Diverse composition of teams (eg, multidisciplinary dam engineering teams, and partnering of engineers and contractors), so that multiple perspectives and models can be brought to bear, thus offsetting biases, reducing oversimplifications, enabling better understanding and prediction of system behavior, and increasing awareness of potential for unintended consequences

- Recognition of personal and organizational limitations in knowledge and skills, resulting in deference to expertise wherever it may be found (eg, consulting with specialized technical experts and listening to people on the front lines), rather than simple authoritarian deference to hierarchy or status

- Sufficient internal diversity and complexity of the system to provide a broad and flexible repertoire of responses to cope with the challenges faced by the system (eg, use of a diverse set of measures to reduce uplift on dams, and emergency response teams comprised of individuals with diverse backgrounds)

- Decision-making authority which is commensurate with responsibilities, with sufficient decentralization to enable safety decisions to be made by those who are best informed and best positioned to implement them

- Organizational culture oriented towards learning from experience, including learning from failures and continuously testing and updating models

- Use of software with care and skepticism

- Use of checklists

- In the context of professions such as engineering and medicine, requiring professional licensing and maintaining high ethical standards

In summary, HROs are mindful, skeptical, cautious, and humble, actively searching for and promptly addressing indicators of trouble before problems grow too large, and making good use of all the information, expertise, and tools available to them to do so. Even with such traits, dam failures may not be entirely preventable, especially if we want continued innovation and progress, but we can still reasonably expect that shifting towards HRO traits – in our personal practices, our organizations, and the broader dam safety community – will significantly help reduce occurrence of failures.

Implications for Dam Failure Investigation

Traditionally, dam failure investigations have focused on providing physical explanations of mechanisms of failure, aiming for objective 'truth' in this regard, and this focus has often been sufficient for the needs of those procuring the investigations. However, in many cases of dam failures, physical and human factors are thoroughly entangled, and/or human factors play a prominent role in the failures, and so telling a useful narrative 'story' of the events leading to failure requires expanding the investigation to include human factors. This has many important implications for dam failure investigations:

- Hindsight bias limits our ability to see why people on the scene made decisions the way they did, and why those decisions would have made sense to them given the circumstances they faced ('local rationality'). As failure investigators, we need to try to put ourselves in their shoes and understand the systemic factors which influenced their decisions, rather than searching for easy scapegoats.

- As we expand failure investigations to include human factors, the extent of human factors we consider becomes a matter of subjective choice, ideally based on pragmatic considerations related to the goals of those procuring the investigation. For example, we could focus on a single individual, a few individuals, one or more departments within an organization, an organization, multiple organizations, the culture of the dam engineering community, or various combinations of these, and we may choose to include regulators as part of the system rather than external to it. And of course legal and liability considerations can strongly influence which and how human factors are investigated.

- Given the complexity of dams, especially when associated human factors are brought into the picture, searching for failure explanations in terms of ‘primary’ or ‘root’ causes can be very misleading and oversimplified. Instead, we need to go into failure investigations with an awareness that the story we end up telling may be a complex one, recognizing that causes can have multiple effects, and effects can have multiple causes, all linked and developing over time. Unfortunately, complexity also means that specific conclusions drawn from a failure investigation may have limited applicability in the future, since the future never exactly repeats the past.

- The evidence we gather during failure investigations is always incomplete and sometimes unreliable (eg, eyewitness testimony), and this is especially the case for human factors. This requires failure investigators to ‘fill in many blanks’ regarding who, what, where, when, why, and how. Doing so brings our own subjectivity into investigations, involving the models we apply, our preconceptions and biases, our limitations in dealing with complexity, etc., which means that different investigators may tell different stories, and often do. Having diversity within investigation teams, and multiple teams investigating the same failure, can help offset the adverse effects of this subjectivity.

- Due to uncertainties and subjectivity, firm failure conclusions may never be reached. In other words, it may not be possible to tell a definitive and final story of why failure occurred – the case may ‘remain open’ indefinitely. Of course, this won’t necessarily prevent litigants in adversarial legal settings from asserting just such definitive stories and attempting to pinpoint blame.

Case Study – Failure of St. Francis Dam

St. Francis Dam was an arched concrete gravity dam located about 40 miles northwest of Los Angeles, designed and constructed by the Los Angeles Bureau of Water Works and Supply under the leadership of General Manager and Chief Engineer William Mulholland. The dam failed catastrophically in 1928, about four years after construction began in 1924, and only days after fully filling the reservoir for the first time, resulting in a flood wave initially well over 100 feet high which killed at least 400 people and caused millions of dollars of property damage, among other losses. This failure is considered by many to be the worst US civil engineering disaster of the 20th century.

The physical factors involved in this failure have been discussed and debated extensively in the literature, and here we instead focus on the human factors which contributed to the failure. Key factors in this regard are as follows:

- Though a respected engineer who was quite accomplished, Mulholland was 'self-taught' from experience and extensive reading, and lacked university education in engineering. Also, while he had supervised the design and construction of 22 dams, this included only one prior concrete gravity dam, the others being embankment dams.

- Despite the limitations of Mulholland's technical background – which were widely known – he resisted scrutiny by his engineering peers or consultation with them during his career, and no one 'above' him at the City of Los Angeles questioned his engineering qualifications either, nor pushed for peer review of his projects. There is no evidence that there was any outside review of the design or plans for the dam.

- During design and construction of the dam, Mulholland's time was largely spent on other projects, and thus he delegated most of his responsibilities related to St. Francis Dam to his subordinates. But they were highly deferential towards him, typically following his general directions without question, and were themselves inexperienced in design of concrete gravity dams. In other words, Mulholland dominated the project, yet his attention was largely elsewhere and most daily work was delegated to underqualified individuals.

- The design of St. Francis Dam was largely adapted from Hollywood Dam designed a few years prior, which saved design time, but with the downside of not giving the attention of developing a truly site-specific design for St. Francis Dam.

- A largely political commitment was made that the reservoir would store one year worth of water supply for Los Angeles. Due to rapid and apparently unpredicted growth of Los Angeles during construction of the dam, the height of the dam was raised twice during construction, each time by 10 feet, without increasing the width of the dam. Compared to redesigning and reproportioning the dam, this action reduced the cost increase of the dam and avoided construction delays, but greatly compromised the stability of the dam.

- Many people associated with the dam, including civic leaders of Los Angeles, had a financial stake related to St. Francis Dam and applied political pressure to keep the project moving forward.

- Subsurface conditions at the dam were quite uncertain because soil/rock mechanics was at an immature stage at the time, limited subsurface exploration and testing of the site was performed, and there was little consultation with geologists during the project. But there were strong indications, both years prior to design of the dam and during the dam's construction, that the schist in the proximity of the east abutment may be unstable. These warning signs were apparently ignored.

- Minimal provisions to reduce uplift were provided, even though such provisions were made for many large concrete gravity dams of the era.

- It was planned that the dam would be substantially trenched into the canyon walls, but only minimal trenching was performed, possibly to reduce cost or expedite construction.

- During the month prior to the failure, travelers on the road along the east shore of the reservoir observed cracks and settlement of the road near the east abutment, but this warning sign was ignored.

- Leaking cracks formed in the dam starting in 1926, and continued to worsen until the dam failure, but these cracks were dismissed by Mulholland and others as being typical for such dams, and were simply sealed to the extent possible, rather than treated as structural warning signs. Mulholland's last such inspection of the dam was only *12 hours* prior to its failure. Moreover, to control cracking, grouted contraction joints were commonly used in concrete dams during that era, but no such joints were used in St. Francis Dam.

- A few hours before the failure, employees drove past the dam and encountered a 1-foot scarp cutting across the road on the east side, raising the possibility of a slope failure near the east abutment, but this warning sign was also ignored.

- After the failure, Mulholland stated that the sole responsibility and blame for the failure was his. While this may sound honorable, it may also be viewed as a further indication that he lacked the humility to recognize that design and construction of a major dam is a complex undertaking which requires collaboration of a diverse team which has ample checks and balances, never a 'one-man show'.

These factors illustrate many ways in which HRO traits were lacking in relation to the planning, design, and construction of St. Francis Dam:

- Safety was repeatedly compromised in order to reduce cost, expedite construction, meet political expectations, and serve the interests of those who had a financial stake in the project.

- There were numerous warning signs over a period of years – such as questionable subsurface conditions, cracking, seepage, and ground movement – which were repeatedly ignored.

- Rather than assembling a diverse team with external reviewers and consultants, great reliance was deferentially placed on Mulholland's expertise, which was limited by both his lack of formal education and his relative inexperience with concrete gravity dams. This lack of collective expertise and lack of open sharing of information contributed to major dam deficiencies such as poor site selection, inadequate measures to control uplift, lack of contraction joints, and insufficient width of the dam relative to its raised height.

- Professional licensing for engineering was not in place in California at the time, and arguably Mulholland and key members of his team would not have qualified as professional engineers. The failure of St. Francis Dam triggered legislation for such licensing in California the following year, and eventually in other states as well.

Conclusions

Fundamentally, all dam failures can be attributed to human factors, at both individual and group levels. Addressing these human factors requires going beyond identifying 'human errors' and assigning blame, instead also carefully considering the systemic complexities, uncertainties, and conflicting pressures which powerfully influence human decisions and drive a 'drift into failure'.

Study of individuals and groups which are continually successful in such challenging environments reveals a shared family of traits, the most central of which is a paranoid preoccupation with avoiding failure. This wary mindset shapes cultures which constantly search for and respond to early indicators of problems, maintain generous safety margins and redundancy, draw on diverse perspectives to better understand the system, use diverse measures to respond to challenges, decentralize decision-making responsibility and authority as appropriate, humbly learn from their experiences, and use tools such as checklists.

By doing our part in implementing high-reliability practices in the dam safety community, all of us involved in dam safety can contribute to reducing the occurrence of dam failures.

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