Big Dams & Bad Choices: Two Case Studies in Human Factors and Dam Failure

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Introduction: Human Factors & Industrial Accidents

Human choices, behaviors, and errors (collectively "Human Factors") have been a critical contributing factor in historic dam failures.

Presumably, no dam builder ever builds a dam with the intention that it will rupture. Likewise, refineries are not engineered to burn, bridges to collapse, ships to sink, pipelines to burst, strategies to be defeated, security perimeters to be breached, networks to disintegrate, or airplanes to crash. Such failures may occur for technical or environmental reasons that are at best peripherally related to bad decisions, but in major accidents it is often at least abetted by our choices.

Many large industrial systems, from dams to nuclear reactors to aircraft carriers, are operated with excellent safety records. Major failures are extremely uncommon in most of these systems. When major failures do occur, the human element often plays an important - if not pivotal - role, and has the troubling ability to circumvent technical defenses.

However, that doesn't mean that such failures should simply be credited to "human error." Humans are a vital control component of most large systems, and are often called upon to perform the most complex and error-prone functions, like reconciling conflicting and ambiguous data, or making high-speed judgement calls based on scant information. The challenges human operators face may be intrinsic to the situation, and in many cases are inadvertently exacerbated the system design itself. Although it is sometimes very easy to blame the operator in hindsight, that does not necessarily make in meaningful. "Human error" often doesn't consist of clear "wrong choices" but instead of choices that were clearly bad *in hindsight*, and perhaps made with poor information or flawed assumptions, but *seemed* good at the time.

These decision-making failures have many contributing factors, like risk-taking philosophies, engineering miscalculation, mentally filtering data to fit our expectations, "groupthink," social dynamics, political pressure, and the natural difficulty humans have recognizing and responding to non-linear systems. A salient example of the latter is our difficulty recognizing and responding to geometric growth patterns, such as leaks constantly doubling in size and frequency, or wildfires growing (as they often do) at a geometric rate.

Unfortunately, it appears that no engineering specification or assurance can be totally proofed against bad data, ordinary human mistakes, or system failures - and it can be very difficult if not impossible to fully protect large projects and complicated systems against actively "bad choices".

The role of human factors in dam failure has strong implications for dam development, particularly tailings dams, where there is or may someday be intense economic pressure to cut costs and meet production goals. In the following two cases, possible "poor choices" are clearly labelled as *human factors*.

Teton Dam, Idaho, 1976

Teton Dam was a 305-foot tall earth-filled dam which catastrophically breached during initial reservoir filling, and is one of the most famous dam failures in the United States. The human error dimension of this was extensively explored by systems-failure expert Charles Perrow in the 1984 classic *Normal Accidents*, and this account is largely a synopsis of his work:

Early in construction, a team of USGS geologists became very concerned that the dam would be in danger of imminent seismic collapse, and drafted a warning memo. USGS supervisors objected to the "emotion" in the memo, and it was redrafted multiple times, until the memo was void of urgency and perhaps downright unclear (Human Factor 1, diluting communications content for social reasons). It had no apparent impact on the Bureau of Reclamation (BoR), which was building the dam.

A surviving marginal note by BoR geologist indicates the only recorded reaction of the BoR to the USGS memo: the intention to prepare some "constructive criticism" (Human Factor 2, dismissing contradicting opinions & evidence). At the time, the BoR had already invested $4.6 million in the project (it would eventually costs roughly $100 million to build, and the collapse may have cost the government $2 billion). The BoR was probably loathe to move or heavily alter the project, due to this large investment (Human

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Factor 3, reluctance to abandon sunk costs).

Earthquakes, however, did not end Teton Dam: cracks in the ground did. During construction, cracks in a rock abutment which were initially characterized as less than 2” in size were found to be caves large enough to walk into (Human Factor 4, investigation appears to have been incomplete and made inapproriate assumptions). Use of grout (cement to fill cracks) was twice what was estimated.

After grouting and construction were complete, engineers began to fill the reservoir, and doubled the rate of filling twice (Human Factors 5 & 6). Between the two doublings, a BoC memo indicates the functioning water flow monitors (14 of 17 total) indicated a groundwater flow 1,000 times what was expected. The memo concluded that the monitoring system was faulty (Human Factor 7, wrongheaded conclusion which fits expectations, not evidence. Nonetheless, maybe the monitors really *were* faulty).

Two months later, three leaks appeared over two days; the project engineer is on record as being unworried, since some degree of leaking is normal for such dams (Human Factor 8, reasonable-seeming general interpretation but perhaps out-of-sync with the specific situation). Being fair to the project engineer, this is certainly true, although in the comfort of hindsight one begins to worry about groundwater flows being 1,000 times normal at quadruple the design-specified filling rate.

The increased fill rate had in fact been partly justified as a way to "test" the grouting. Perrow observes that it's unclear what the engineers planned to do if the grouting failed under this "test." This author adds that it's unclear what the engineers would have considered an adequate but recoverable negative result, if the alarming data of 14 out of 17 waterflow monitors, and increasing visible seepage, were not adequate - or if they believed the waterflow monitors *were* faulty, why they proceeded with a deliberate stress-test in absence of working waterflow monitors.

Three more leaks, appeared in rapid succession the next day, and the final leak swallowed earth-moving equipment which was dispatched to fill it. Perrow wryly notes: “[the project engineer], one assumes, was now worried.”

The dam then breached and released 80 billion gallons of water.

As described by Perrow, none of the numbered items above would be addressed by actual engineering improvements to dam specifications. They appear to result from such elements as faulty investigation, disregarding of conflicting information, assumptions about evidence, and the pressures of financial commitment.

Teton Dam Breaches

A major piping leak along the right abutment propagates headward, cutting through the crust of the dam and leading to a total breach. In the last image a tongue of "blue water" reaches through the gap.
source: Public Domain

The Teton Failure in Photos

The Teton Failure was captured in photographs. This **website** features a full **time-series gallery** .

Vajont Dam, Italy, 1963

The Vajont Dam Disaster is one of the world’s great examples of failure at the cutting edge, and has the distinction of being both the worst dam failure and the most deadly landslide in Europe’s recorded history. This account draws very heavily on Genevois & Ghirotti's **“The 1963 Vajont Landslide”** and Marco's **“Decision-Making Errors and Socio-Political Disputes over the Vajont Dam Disaster"** , and lightly from the history presented in **Risky Ground.**

Construction of Vajont Dam, a concrete thin-arch dam high in the Italian Alps, began in 1957. The Italian government promptly mandated the project add 66 meters to the height of the dam, which nearly doubled the reservoir volume. This new, much more aggressive specification came after much of the engineering and geology had been done (Human Factor 1 – changing the dam in a more ambitious and risky way without thorough technical groundwork). This choice made Vajont the tallest dam of its type in the world, and may have been a prestige-driven choice (Human Factor 2).

Vajont Dam after the Landslide

Vajont's reservoir was mostly displaced by a massive landslide, creating a wave that crested 500 feet over the dam's rim. The dam still stands, but the event permanently removed it from service.

source: Public Domain

One expert warned the designer that this modification might cause serious geological problems, but the authorities refused to conduct an expert review. In 1957 three independent experts also separately concluded the mountainside was dangerously unstable. Their reports were ignored (Human Factors 3 & 4 – avoiding critical inquiry and disregarding conflicting information). Vajont proceeded to an advanced stage of construction without further slope assessment.

Another human factor may also be "hiding" here: the non-linear multiplication of stresses resulting from a higher dam. Changing from 196 m to 262 meters might seem like increasing project scale by only 1/3 to a non-technical observer, but it doubled the reservoir volume. Additionally, all of this water mass is added in the upper 25% of the dam height, which would have moved center-of-stress considerably higher on the dam. Although subsequent events proved the extraordinary strength of the dam, the fact that the political authorities don't seem to have appreciated this qualifies as Human Factor 5.

In 1960, a landslide in another Alps reservoir at Pontesei, created a tsunami which overtopped that dam by several meters. Subsequently, a study was commissioned at Vajont. As a result of the Pontesei event, Vajont became politically controversial. In 1959, a journalist who predicted the future disaster was publicly denounced. Decision-makers asserted that the geology and stability of the region was understood with certainty (Human Factor 6 & 7: "shooting the messenger", overestimating one's own knowledge).

Later in 1960, a geologist investigating the mountain slopes in the wake of the Pontesei tsunami identified a massive prehistoric landslide on the slopes extending into Vajont's reservoir, which he believed could re-activate. This very large landslide looked, on its surface, as if it was composed of intact and in-place geological layers, which gave the superficial illusion that there was no slide. Other consulting experts on the project and the general scientific community did not accept the geologist's theory that the landslide existed.

Nonetheless, the possible landslide was observed as the reservoir was filled, beginning in 1960. Small movements were subsequently detected over several months. Eventually, a small section collapsed into the growing lake, generating ~100 foot waves.

After a 50 meter reservoir drawdown, the slide stopped moving. Filling was resumed late in 1961. By late 1962, the slide had again began to move slowly – and the lake was lowered by 50 meters again. The movement stopped. Project geologists now believed that slide motion was due only to the rocks becoming quickly saturated with water, and that the slope would remain stable if the reservoir was gradually filled. The accepted consensus on the project was that the landslide could generate slow motion, and was not at risk of rapid failure under gradual filling (Human Factor 8 – optimistic misunderstanding of the risk).

Gradual filling resumed. At a new-high water level, the slide began to move for the third time and the reservoir was dropped (this time by only 10 meters, perhaps due to time constraints). Slide motion accelerated as the reservoir dropped. After roughly a month of increasing slide motion, the entire prehistoric landslide suddenly failed. A 2-km wide, 250-meter thick mass of rock plunged into the reservoir at speeds that may have exceeded 100 mph, and generated the giant wave that swept over the dam and killed 2,000 people downstream in 7 minutes.

The aftermath of the Vajont disaster became highly politicized and ideological. This politicization penetrated into the investigative, legal, and political aftermath, as well as into the public narratives. The Vajont Project was "permeated by the modernist quest to tame, to control and to discipline nature," in **Marco**'s words.

The dam was at the time extraordinarily prestigious and a masterpiece on the world engineering stage. By the time of reservoir filling, the project had amassed huge financial investment (and presumably professional and political investment as well). This was likely a major factor in the project's continuation: it can be extremely difficult to abandon a project of national significance partway through, and to publicly admit or even personally accept that a critical risk was not discovered earlier – and the pressure to hope that risks or poor-choices-already-made turn out well may become overwhelming.

In 2008, UNESCO identified the Vajont Dam – which was intended to stand as a symbol of humanity's engineering achievements – as one of the great world lessons in "the failure of engineers and geologists."

UNESCO's finding may be a final and ironic human factor: misconstruing human failures as technical ones.

Some geologists *did* identify the slide and expressed concern, and their concerns made it as far as the newspapers. The engineering of the dam itself was expert: the structure itself withstood extraordinary forces, and still stands – albeit inoperable – today.

Arguably, Vajont was actually a triumph of engineering - and although there appears to have been legitimate scientific disagreement and misinterpretation, multiple geologists *did* identify the risk.

However, Vajont was an epic failure of human choices and scientific judgement. Human factors trumped engineering and at least some of the hard science, at the end of the day. The result was disaster.

*For more on dam failure, see **Understanding Dam Failure.***

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