Failure of Sella Zerbino Secondary Dam in Molare, Italy

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***Abstract* –** Supplementing the Bric Zerbino main dam, the Sella Zerbino secondary dam was a concrete gravity dam about 46’ high and 360’ long, located in Molare, Italy and completed circa 1925. In 1935, the secondary dam failed catastrophically, resulting in at least 111 fatalities. Starting with the planning of the project four decades prior to the failure, a series of human and physical factors interacted and compounded, until a 1000-year storm (more than 15” of rainfall in less than 8 hours) was the final physical trigger for the failure. Additional physical factors included lack of a spillway for the secondary dam, instability and erodibility of the foundation rock at the secondary dam, and grossly inadequate discharge capacity for the reservoir, which was exacerbated by clogging of spillways and outlets. The human factors contributing to the failure included hasty design and construction of the secondary dam after a late decision to raise the height of the main dam, inadequate geologic investigation and missed warning signs related to the foundation of the secondary dam, and lack of rainfall data to adequately design spillways and outlets. This paper describes these and other factors, viewed in the context of a general framework for assessing human and physical factors contributing to dam failures.

I. INTRODUCTION

Circa 1925, construction of two dams – the Bric Zerbino main dam and Sella Zerbino secondary dam – was completed near the village of Molare in northwest Italy, about 20 miles northwest of Genoa (Figures 1 to 3), primarily for hydropower.

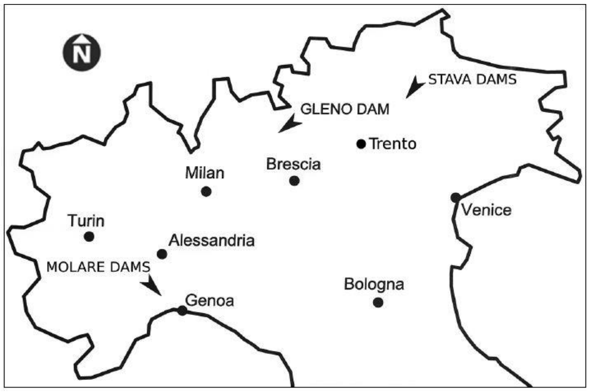

Figure 1. Location of Molare Dams in Northwest Italy [4]

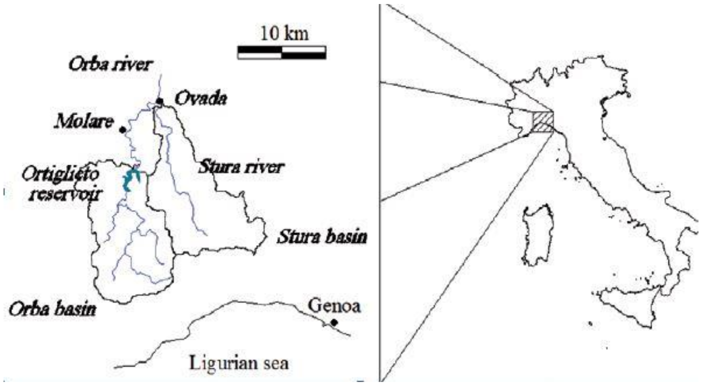

Figure 2. Orteglieto Reservoir Basin [5]

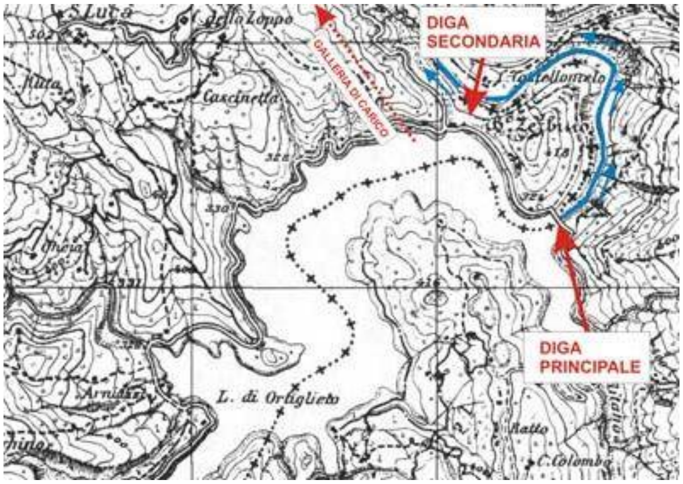

Figure 3. Bric Zerbino Main Dam (“Diga Principale”) and Sella Zerbino Secondary Dam (“Diga Secondaria”) [6]

The Bric Zerbino main dam was a curved concrete gravity dam about 154’ high (Figure 4), located on the Orba River. Discharge from the dam was via a valved bottom outlet (Figure 5), a mid-level pressure outlet with inflow through a shaft with a valved intake (Figure 6), 12 siphon spillways (Figure 4), and a gated chute spillway (Figure 4), providing a total discharge capacity of about 31,000 cfs [6]. This discharge capacity represented an increase from the originally planned capacity, in response to the 1923 failure of Gleno dam in northern Italy after heavy rain [3], which had resulted in at least 356 fatalities.

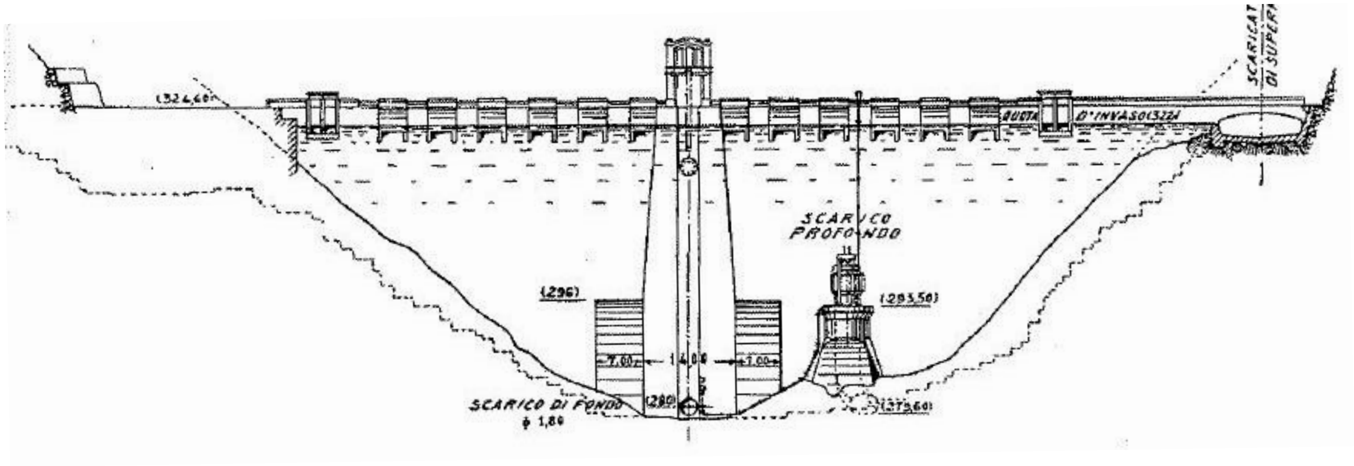

Figure 4. Upstream Face of Main Dam

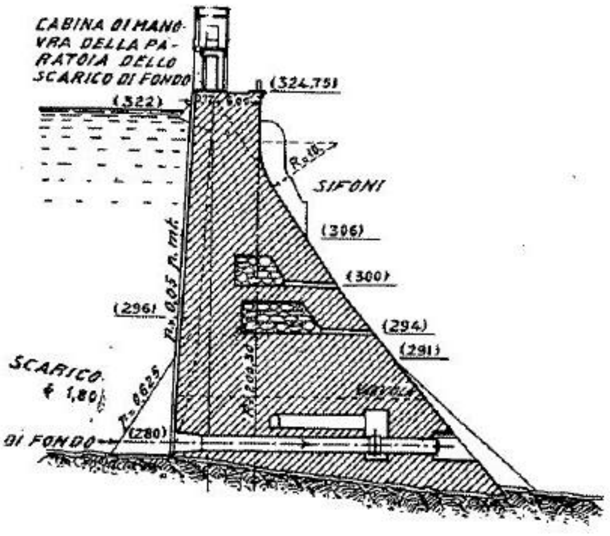

Figure 5. Bottom Outlet of Main Dam

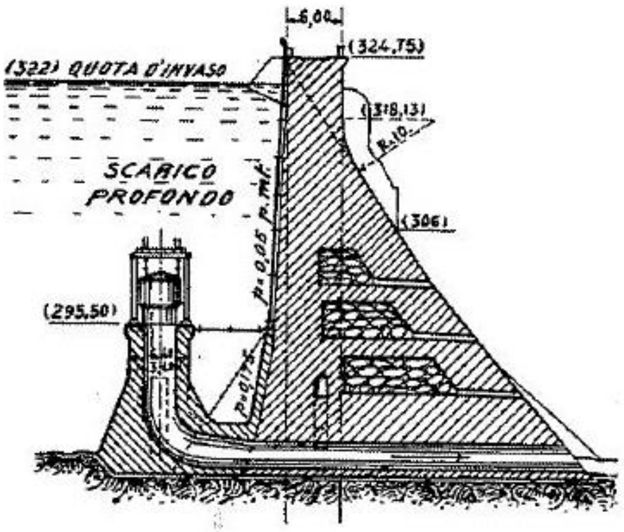

Figure 6. Mid-Level Outlet of Main Dam

The Sella Zerbino secondary dam augmented the main dam by closing a saddle-shaped gap in the rim of the reservoir, about 1000’ northwest of the main dam (Figure 3) [4]. The secondary dam was a straight concrete gravity dam with a height of 46’, a crest length of about 360’, and no spillway or outlet (Figure 7).

Together, the two dams created the Orteglieto Reservoir (Figure 2), with a basin area of 54 square miles, reservoir surface area of 5 square miles, storage of 14,600 acre-ft, and time of concentration of 5.5 hours [5].

Figure 7. Downstream Face of Secondary Dam

About a decade after construction, on August 13, 1935, the secondary dam suddenly failed after several hours of very heavy rain, resulting in rapid release of nearly 80% of the reservoir storage, flooding extending about 30 miles downstream, at least 111 fatalities, destruction of a hydroelectric plant about 2 miles downstream, destruction of about 90 houses and 4 bridges, and large impacts to farming in the area. The main dam remains in place today, with the flow of the Orba River continuing to be diverted through the breach of the secondary dam [4].

This paper presents a history of the reservoir and dams, a chronology of events on the day of failure, and an assessment of the physical and human factors which contributed to the failure.

II. RESERVOIR & DAM HISTORY

Planning of the Orteglieto Reservoir began circa 1895. This included a short geologic report prepared in 1898, which was not based on detailed geologic surveys, borings, or analysis of rock masses [2]. The report noted that the rock in the valley, belonging to the Voltri Group, was highly variable (Figure 8), yet the report seemingly ignored this variability by concluding that "… in any part of this area it is possible to build a dam in full safety conditions." Moreover, there is evidence that fluvial erosion had exposed joints and shear zones in the rock, but this was not reflected in the report [2]. There was essentially no further geologic investigation after this initial report until the secondary dam failed four decades later.

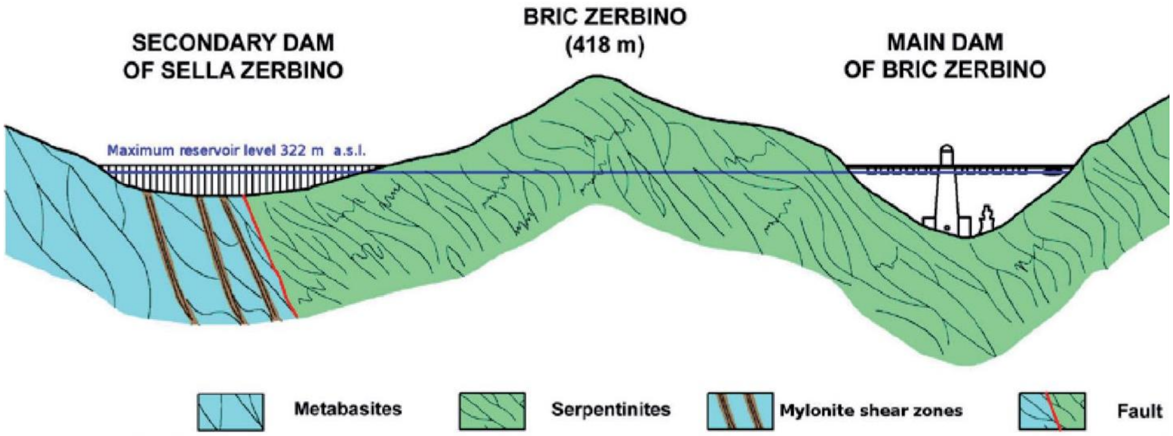

Figure 8. Geologic Section Developed After the Dam Failure [2]

After two decades of political wrangling during the planning phase, the project was approved circa 1914 to 1916, with the Officine Elettriche Genovesi (OEG) as owner, and with a reservoir volume more than double what was originally proposed. World War I impeded design and construction, but construction proceeded in earnest starting circa 1919 and accelerated from 1922 until completed circa 1925, after a decision was made circa 1922 to further increase the reservoir storage and raise the height of the main dam from 111’ to 154’. It was this decision which necessitated construction of the secondary dam, which was designed and built quickly, apparently with no significant geologic investigation specific to the site, since “sound rock” was assumed. And in 1925, a technical review by OEG affirmed that “the most important feature of the rocks belonging to the Voltri Group is the absence of deep joints. The layers’ surfaces are soundly cemented to the bedrock; therefore there seem to be no cavities at depth” [2].

While construction of the project was underway, the Gleno Dam (Figure 1) in northern Italy failed in 1923, resulting in at least 356 fatalities. Multiple factors contributed to the Gleno failure and the managing director of the design firm served two years in prison [4]. In response to this failure, the discharge capacity of the main dam (Bric Zerbino) was increased to about 31,000 cfs from the originally planned capacity, and the dam designers apparently designed for a reservoir inflow of 28,200 cfs, which was based on very limited rainfall data [3].

The failure of Glen Dam also resulted in formation of a Gleno Commission to “check” all large dams in Italy. The Gleno Commission visited the Orteglieto Reservoir project in 1924, observed seepage up to 500 gallons/minute through the foundation rock of the secondary dam, and recommended grouting to make the rock impervious, though no geologic study was done. The OEG performed grouting multiple times, which resulted in little reduction of the seepage, possibly due to gouge material in the joints. However, significant seepage was not observed during a final inspection of the dam in 1927 [2].

In 1928, a few years after construction of the dams was complete, a tunnel near the secondary dam experienced a discharge almost twice its design discharge, which resulted in erosion up to 13’ deep into the rock surrounding the tunnel. This evidence of erodibility and low quality of the rock resulted in installation of a reinforced concrete lining for the tunnel. However, there is no evidence that the quality of the nearby foundation rock at the secondary dam was reevaluated [3].

Finally, the secondary dam failed on August 13, 1935. The apparent mode of failure was overtopping of the dam, resulting in erosion of the rock at the toe of the dam, in turn causing sliding and overturning failure. As further evidence of the low quality of the geologic formation, little remained of the secondary dam and its foundation after the failure, and geologic investigations after the failure indicated that while the main dam was founded on compact serpentinites, the secondary dam was founded on highly-jointed schistose rock with intense foliation and slaty cleavage (Figure 8), which many experts concluded was inadequate for a dam foundation [2].

In 1938, in the wake of the failure, a criminal trial resulted in acquittal of 12 people affiliated with OEG, including owners, management, and designers, attributing the failure to “exceptional and unforeseeable rainfall” [6]. Ironically, the same engineer who argued on behalf of OEG that the failure was unavoidable, had assured 15 years prior, in 1923, in the wake of the Gleno Dam failure, that to supply hydroelectric power in Italy, “dams can be built and managed nowadays with a mathematical level of safety” [2].

Despite the tragic consequences of the failure of Sella Zerbino secondary dam, as an indication that sufficient lessons were not learned from the failure, other subsequent dam failures in Europe which had similar contributing factors included Malpasset in France in 1959 (at least 423 fatalities), Vaiont in Italy in 1963 (about 2,000 fatalities), and the Stava tailings dams in Northern Italy in 1985 (at least 268 fatalities).

III. DAY OF THE DAM FAILURE

The following is a chronology of key events which occurred on the day of failure of the secondary dam:

- Around 6:15 am on August 13, 1935, after a long drought which had caused the reservoir level to be very low for several weeks despite closing the outlet valves, a very heavy storm began in the upper Orba valley, producing 15” of rain in less than 8 hours, and more than 30% of the average annual rainfall within 24 hours. The most intense rain was from 7:00 am to 8:00 am and from 2:00 pm to 3:00 pm, but there was also heavy rain between 8:00 am and 2:00 pm (Figure 9). The peak inflow to the reservoir immediately prior to the failure is estimated at 80,000 cfs (Figure 10), and the storm is estimated to have been a 1000-year event [5].

- By 10:00 am, the reservoir level had risen about 25’ and the dam caretaker started an emergency procedure, apparently opening the valves for the bottom outlet and mid-level outlet of the main dam, but the valves became clogged with a large amount of mud and debris within a few minutes [4]. The siphon spillways had a discharge capacity of about 23,000 cfs (less than one third of the peak inflow), and they may also have become partially clogged [3]. There is also indication that a gate for the chute spillway was at least partly inoperable due to rust [3].

- Overtopping began around 12:30 pm (Figure 10). Around 1:20 pm, less than an hour after overtopping began, the maximum depth of overtopping reached an estimated at 6’ to 16’ [2]-[6], and the secondary dam failed, leading to rapid release of the reservoir (Figure 10). The failure mode was overturning and sliding, after the overtopping eroded the rock at the toe of the dam. Inflow to the reservoir was still increasing at the time of the failure, and peaked at more than 100,000 cfs less than two hours after the failure (Figure 10) [5]. It may be noted that the duration of the storm and the time until failure are relatively similar to the 5.5-hour time of concentration of the reservoir, which indicates that the storm duration was close to a worst-case scenario for the reservoir.

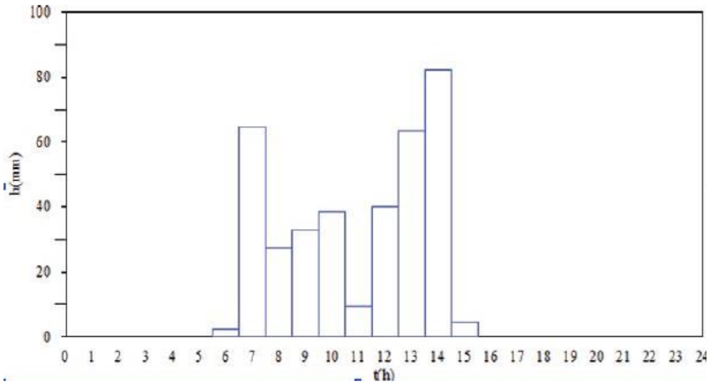

Figure 9. Rainfall Hyetograph on Day of Failure [5]

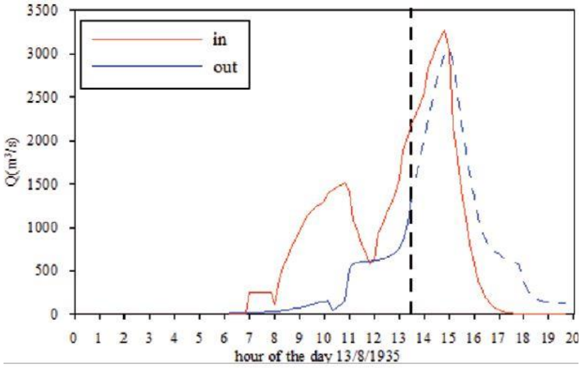

Figure 10. Reservoir Inflow and Outflow on Day of Failure [5]

IV. PHYSICAL FACTORS CONTRIBUTING TO THE FAILURE

The key physical factors contributing to the failure can be summarized as follows:

- The design discharge capacity of about 31,000 cfs was far too low, even with the reservoir level being favorably low due to drought preceding the storm. This discharge capacity was based on very limited rainfall data, and may have corresponded to only a 20-year event. By contrast, the reservoir and dams were subjected to what was estimated to be a 1000-year storm which produced a peak inflow discharge of more than 100,000 cfs.

- At the main dam, the outlets became clogged, the siphon spillways may have been partially clogged, and the gate for the chute spillway appears to have been at least partially inoperable due to rust. This reduced the discharge capacity to below the already-low design capacity.

- The secondary dam had no spillway or erosion protection, and was therefore subjected to undirected and uncontrolled overtopping.

- The foundation rock at the secondary dam was inadequate due to extensive joints, faults, shear zones, and slaty cleavage, which resulted in high erodibility and instability. Before the failure, evidence of these features was provided by exposures from fluvial erosion, seepage through the foundation, and erosion of the rock in a nearby tunnel. After the failure, a large volume of the foundation rock was found to have been washed out.

V. HUMAN FACTORS CONTRIBUTING TO THE FAILURE

Dam failures typically involve an interaction of physical and human factors which begins years or decades prior to the failure. With regard to human factors, the propensity towards failure can be viewed as being determined by the balance of human factors which contribute to failure (‘demand’) versus those which contribute to safety (‘capacity’). Thus, applying a standard engineering metaphor, failure results when demand on the system exceeds capacity, and safety results when capacity exceeds demand. While not done in this paper, it may be possible to subjectivity rate the human factors which contribute to failure versus safety in order to develop a quantitative index of the propensity towards failure (e.g, a demand/capacity ratio).

The human factors contributing to the demand (failure) side can generally be modeled as follows:

1. The system faces three primary drivers of failure:

    A. Pressure from *non-safety goals*, such as reducing cost, increasing profit, meeting schedules, competition, building and maintaining relationships, political goals, and personal goals.

    B. *Human fallibility and limitations* due to misperception, faulty memory, incompleteness of information, lack of knowledge, inaccuracy of models, cognitive biases operating at a subconscious level, use of heuristic shortcuts, adverse effects of emotions, unreliability of intuition, and fatigue.

    C. *Complexity* resulting from multiple interactions of multiple components, which exacerbates the effects of human fallibility and limitations, and can result in nonlinearly large effects from small causes and difficulties in modeling, predicting, and controlling system behavior.

2. These primary drivers of failure lead to various types of *human errors*.

3. Human errors lead to *inadequate risk management*, which may be classified into three types:

    A. *Ignorance* involves being insufficiently aware of risks.

    B. *Complacency* involves being sufficiently aware of risks, but being overly risk tolerant.

    C. *Overconfidence* involves being sufficiently aware of risks, but overestimating ability to deal with them.

The human factors contributing to the capacity (safety) side can generally be modeled as follows:

- *Safety culture* involves individuals at all levels in organizations placing value on safety, which leads to a humble and vigilant attitude of being preoccupied with avoiding failure.
- Safety culture, humility, and vigilance lead to *best practices*, such as described in Table 1.

General Design Features	Organizational & Professional Practices	Warning Signs
• Conservative safety margins • Redundancy, robustness, and resilience • Following generally-accepted best practices for design and construction • Customization to project sites, including scenario planning during design and testing/adaptation during construction • Progressive and controllable failure which generates warning signs • Emergency action planning based on accurate hazard classification	• Safety-oriented personnel selection • Sufficient resources and reasonable schedules • Peer-review and cross-checking • Information sharing (allowing dissent) to 'connect the dots', including thorough documentation • Diverse teams, but with leadership, continuity, and avoiding 'diffusion of responsibility' • Recognizing knowledge limitations, deferring to expertise, and engaging in training • Use of checklists • Appropriate system models (possibly including human factors directly in the models) and failure modes, and careful software use • Professional, ethical, and legal/regulatory standards • Learning from failures and incidents • Autonomy of safety managers	• Look for them actively and monitor, including after unusual events • Investigate to understand their significance • Address promptly and properly, with verification of follow-up • Be suspicious during 'quiet periods'

Table 1. Best Practices for Dam Safety

Further information regarding the role of human factors in dam failures can be found in [1]. Applying this human factors framework to the failure of the Sella Zerbino secondary dam, based on the information reviewed by the author, the following human factors can be identified:

- The political wrangling for two decades to approve the project may have resulted in political momentum which influenced decisions during design and construction, and may have contributed to denial of warning signs.
- Presumably for economic reasons, a late decision was made to increase the reservoir storage and add the secondary dam, which was then designed and built hastily.
- The secondary dam was not customized to the site, particularly with regard to its foundation conditions. This was especially problematic because geologic conditions were complex, yet this complexity was evidently not appreciated, since the foundation rock for the secondary dam was assumed to be sound, despite evidence to the contrary, and the implications of the inability to effectively grout the rock to control seepage were not understood.

- Information regarding rainfall and geologic conditions was grossly inadequate, and this could have been cost-effectively remedied by gathering more information. As a result, the hydrologic and geologic models were highly inaccurate and the hydrologic and geotechnical safety margins proved to be grossly inadequate.

- Not having a spillway or outlet for the secondary dam resulted in a lack of redundancy for the reservoir system, and a lack of resilience at the secondary dam due to inadequate measures to deal with overtopping. Also, at the main dam, the clogging of both outlets, and possibly also partial clogging of the siphon spillways, showed a false sense of redundancy, since all displayed a shared failure mode.

- The Gleno Commission performed a peer review, but it was evidently insufficient, which suggests a lack of diligence and/or expertise. And given the large loss of life from the Gleno failure, which was proximal in both time and space to the design and construction of the secondary dam, it may be argued that the general lesson of needing vigilance in order to prevent dam failure was not sufficiently learned.

- The design team lacked diversity, since there was little input from geologists (geotechnical engineering was still in its infancy at the time), and the engineers leading the design were focused on engineering works. Yet these engineers made decisions related to geologic matters, rather than recognizing the limitations of their knowledge and deferring to the expertise of geologists.

- There were also numerous missed warning signs related to the foundation of the secondary dam:

    - The rock of the Voltri Group was known to be highly variable, yet there was no detailed investigation of the geology specific to the secondary dam.

    - Fluvial erosion had exposed joints and shear zones in the rock, indicating that at least some of the rock was unsuitable for a dam foundation, but this was missed or ignored.

    - Inability to control extensive seepage through the foundation of the secondary dam by grouting indicated potential presence of numerous joints filled with gouge material, but this was missed or ignored.

    - The severe erosion of rock in a nearby tunnel was another warning sign regarding the unsuitability of the rock for a dam foundation, but this was also missed or ignored.

In summary, the human factors which contributed to failure (‘demand’) included cost cutting, schedule pressure, possible political pressure, lack of geologic and hydrologic information, inaccuracy of geologic and hydrologic models, and cognitive effects of geologic complexity. In addition, with regard to human factors which generally contribute to safety (‘capacity’), there were few positives and many deficiencies, including unconservative safety margins, lack of sufficiently redundant measures for discharge capacity, lack of resilience with respect to overtopping, lack of customization of the design of the secondary dam to the site, inadequate peer review, lack of diversity in the design team (particularly lack of expertise in engineering geology), and lack of detection or inadequate response to numerous warning signs.

Collectively, these human factors resulted in human errors, ignorance and complacency with regard to risks, and possibly also overconfidence with regard to risks, to an extent which ultimately led to failure of the secondary dam.

VI. CONCLUSIONS

The Sella Zerbino secondary dam failed due to a combination of physical and human factors which interacted over a period of four decades prior to the failure. The human factors were numerous, and included several missed or ignored physical warning signs which, if acted upon appropriately, would likely have prevented the failure and the loss of at least 111 lives.

Moreover, lessons were apparently not sufficiently learned from this failure, given that, during the subsequent 50 years, there were three major dam failures in Europe (two of them in Italy) which involved a large loss of life and similar contributing factors.

VII. ACKNOWLEDGMENTS

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IX. AUTHOR BIOGRAPHY

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