REASSESSMENT OF THE ST. FRANCIS DAM FAILURE

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INTRODUCTION

The St. Francis Dam was a curved concrete gravity dam built by the City of Los Angeles Bureau of Water Works and Supply in 1925-26. The dam failed upon its first full filling near midnight on March 12-13, 1928, killing at least 450 people. Investigations of the failure followed, most of which attributed the failure to a fault that lay beneath the right abutment. Others attributed the failure to softening and swelling of argillaceous sandstones and conglomerates of the Sespe formation, which formed the upper two-thirds of the right abutment (adjacent to the fault). The right abutment appears to have been the focus of most of the investigations because blocks from that side of the dam were found furthest downstream following the failure.

A modern review of the evidence suggests that the base of the dam was not as thick as previously assumed, and that portions of the dam were prone to overturning failure. Large arching stresses would have prevented overturning, but may have contributed to block failures along schistosity planes in the east (left) abutment. Piping in the area of the block failures may also have served to undermine the dam's east abutment as the failure sequence initiated. Geomorphic assessments reveal that the entirety of the east abutment was comprised of an ancient megalandslide within the Pelona Schist. Portions of the landslide were buttressed by the dam, however the dam's buttressing effect would have been removed when the structural integrity of the dam became compromised. During the failure sequence, more than 500,000 cubic yards of the left abutment appear to have translated as a large landslide, and this material was then washed away, leaving a sizable void where the left abutment had been. Modern analyses of buoyancy effects (due to the high solids content of the flood wave picking up the 500,000 yards of slide debris) and rapid unsteady channel flow within the canyon can account for blocks from the right abutment ending up furthest downstream.

HISTORICAL PERSPECTIVE

The St. Francis Dam was originally conceived and built under the supervision of one man, William Mulholland, without any independent review. In many ways Mulholland was an exemplary engineer. He immigrated from Ireland and started working for the Los Angeles Bureau of Water Works and Supply (LABWWS, later the Department of Water and Power, LADWP) as a water-supply ditch tender. Through hard work and self-imposed study, he became a skilled professional. He served as Chief Engineer of the LABWWS from 1886 until his retirement in 1928, 6 months after the dam failed. During his career he supervised the design and construction of 19 dams and over 300 miles of canals. He was among the first in America to conceive and construct a long-distance municipal water system, and he was among the first to recognize the potential impact of seismic hazards to his structures. His crowning achievement, the Los Angeles-Owens River Aqueduct, crossed a segment of the San Andreas fault that had ruptured in January 1857. Recognizing the threat that fault rupture posed, Mulholland designed the St. Francis dam to store a one-year emergency supply of water on the Los Angeles side of the San Andreas fault. In this respect Mulholland was a visionary, as it would be another 50 years before the other major municipalities in California appreciated the same seismic risks and incorporated similar contingencies for their water supply infrastructure.

The failure of the St. Francis dam spelled the end of Mulholland's long and distinguished career. The organization which he had so painstakingly built came under enormous criticism at a most inopportune time, for in early 1928 Los Angeles was embroiled in controversy over the colossal Boulder Canyon (Hoover Dam) project on the Colorado River. Public outcry following the St. Francis dam disaster led to the selection of more than a dozen separate boards of investigation and inquiry into the failure. Looking back on the conclusions of these boards, we are reminded that published "experts" or academicians may not be experienced in forensic engineering techniques, many of which simply demand a great deal of exacting and oftentimes laborious work. The most prestigious of the 13 boards of inquiry convened by various agencies was that appointed by Governor C.C. Young of California. This group made one site visit, convened for 5 days, and issued their final report on the 6th day, which was widely published and accepted as the "final word" on the St. Francis disaster. Little, if any, original work was performed by the Governor's Board. When the hearings did convene, Bill Mulholland modestly offered himself up as a scapegoat, and the people of California gladly accepted, placing the blame squarely on the back of one man. The fact that Mulholland oversaw the construction of similarly-designed dams which have not failed seems to have been overlooked by most journalists and historians.

The St. Francis disaster did result in the formation of a separate State entity to oversee the safety of all but Federally-owned dams and reservoirs in California. This became a model dam safety agency for the rest of the country. Dam safety regulations and responsibilities eventually evolved into the California Division of Safety of Dams (or DSOD) within the State Department of Water Resources.

In the 65 years since the St. Francis dam's demise, many individuals have attempted to re-examine the failure. Some of these efforts were important, but none of them were coordinated within the framework of an independent interdisciplinary board. Several giants of the civil engineering profession offered up minority views of the failure, including C.E. Grunsky, E.C. LaRue and Lars Jorgensen. Their views were largely ignored at the time, but in retrospect possess amazing insights into the likely mechanisms promoting failure. Stanford Professor emeritus Bailey Willis, working with Grunsky on behalf of the injured ranchers of the Santa Clarita Valley, correctly asserted that the dam's left abutment was comprised of a megalandslide complex within the schist. Although this important factor was not considered with regards to the St. Francis design, the State canceled the Forks Dam project a year later (in the midst of construction) for identical reasons (paleomegalandslides on the right abutment). One young man who watched the flood sweep through his hometown in the early hours of March 13, 1928, was Charles Outland. Outland became a prominent historian and journalist in Ventura County, and published the only definitive account ever presented of the disaster, first in 1963, then in a revised edition in 1978. He died in 1985. Outland's research was fastidious, and his interviews with key eye witnesses eventually proved invaluable in unravelling the failure so many years later.

SITE CONDITIONS

The right (west) abutment was underlain by argillaceous sandstones and conglomerates of the Sespe formation. The center of the dam and the left (east) abutment were underlain by foliated schist of the Pelona formation. These two formations were separated by a fault located beneath the right abutment.

Mulholland's attraction to the dam site was linked to what he perceived as favorable topography: a natural narrowing of the canyon downstream of a broad, upstream platform, thereby creating a large water storage area. Mulholland did not realize that the site had already served as a natural reservoir formed by the damming of San Francisquito Creek by ancient megalandslides in the Pelona Schist. The waters of San Francisquito Creek had eventually overtopped the landslide dam and re-excavated a channel at the base of the landslide, which later became the dam site.

EFFECTIVE STRESS

In his testimony before the Ventura County Coroner's Inquest, Mulholland stated that the St. Francis dam was designed with a safety factor (presumably against overturning) of 3 or 4. The dam's maximum cross section was presented as shown in Figure 1a. Eight uplift relief wells were provided beneath the dam's maximum cross section, but not beneath the sloping abutment sections. Re-analysis of overturning assuming full hydrostatic pressures acting at the heel of the dam and atmospheric pressures acting at the toe (a triangular distribution) suggests that the actual safety factors against overturning were just under 1 for much of the dam, as shown in Figure 1b. Comparing these results with Mulholland's testimony, it would appear that considerations of uplift were not accounted for in the original design.

ARCHING STRESSES

Although conceived as a concrete gravity dam, the St. Francis dam was arched upstream on a constant 492-feet radius. Even though portions of the dam appear to have been over-stressed with respect to overturning, the dam may have maintained stability through the shedding of excess overturning loads to the abutments through arching. A crude estimate of the arching stresses at the abutments was made by determining the loads required to stabilize a given section. These loads were distributed vertically within a section based on the area of layers in proportion to the total area of the cross-section. The vertically distributed loads were then summed horizontally to estimate the arching stresses. The resulting distribution of arch thrust on the abutments is shown in Figure 1c.

KEY BLOCK ANALYSES

Rock mechanics analyses of "key blocks" located just downstream of the east abutment suggest that effective vertical and arching stresses imposed on the abutments were insufficient to resist sliding along foliation planes within the schist (which are markedly visible on the abutment today). This susceptibility to sliding on the left abutment is ascribable to the low frictional resistance of planes in the mica schist combined with the line of thrust with respect to the foliation. Any hydraulic pressures acting along the same planes would reduce the effective stress and magnify the potential block failure problem.

HYDRAULIC ANALYSES

Over 500,000 cubic yards of landslide debris from the left (east) abutment were washed away by the flood wave. Survivors of the flood wave 7,000 feet downstream of the collapse described the flood wave as a wall of mud, rock and trees. Clearly the outpouring incorporated a large percentage of entrained solids. By comparing the volume of solids washed away with the total reservoir volume, a preliminary assessment of buoyancy effects on the downstream transport of the dam's many blocks can be approached quantitatively. Such evaluations suggest that the dam's displaced blocks could have weighed as little as one-third their dry weight while submerged in the muddy deluge, as shown in Figure 2. Post-failure assessment of scour lines on San Francisquito Canyon and eyewitness reports of water elevations in the flood wave were combined with flow calculations using the HEC II program to demonstrate that the peak flood wave was as great as 1.7 million cfs at the dam and up to 1.3 million cfs at Powerhouse 2 (7000 feet downstream). The high flood flows combined with the low effective weights of the concrete blocks help to explain how large blocks of the dam were washed so far downstream.

Blocks of concrete as large as 10,000 tons were found from 1750 to 3500 feet downstream of their original positions, some 40 feet above the channel bed. Of all the blocks whose original positions within the dam were established, block 16 (from the right abutment) was found about 2,500 feet downstream. However, four other large blocks whose original positions could not be identified were found further downstream, and blocks 11 (right abutment), 12 and 14 (left abutment) were all found within 500 feet of each other. Based on the similar locations of blocks from each abutment and the number of blocks whose original positions were not determined, no conclusions can be made about which side of the dam failed first. However, based on the low elevation of scour on the right abutment and the deep scour channel under the left abutment (despite the landslide debris and blocks 2, 3 and 4 falling backward, into this void), it appears as if the largest flows occurred beneath the left (east) abutment.

CONCLUSIONS

Although the St. Francis dam was originally intended to be a gravity dam, the designers did not consider uplift pressures acting along the base of the dam. The uplift pressures would have caused overturning failure immediately upon filling had it not been for arching. The failure of the St. Francis Dam may have been initiated by excess arching stresses which resulted in block failures downstream of the left (east) abutment, within the schist. Subsequent cracking and seepage may have removed portions of the base of the dam and eroded a deep trough at the base of a paleomegalandslide. The concentration of arching stresses into the remaining intact portions of the dam possibly combined with reactivation of portions of the paleomegalandslide could have overstressed the remaining upper portions of the concrete dam and may have resulted in an explosive compressive failure of the remaining dam mass. The explosive failure appears to have created shock waves comparable to a small earthquake, and landsliding appears to have carried the left flank of the dam across the main section and created a small seiche wave. Any loss of dam/abutment integrity would have removed the arching stresses that had acted to stabilize the dam mass, so the right abutment would have failed soon after the left abutment failed.

As evidenced by a gauge ladder that was found wedged in a crack after the failure, the overturning and/or arching stresses appear to have caused the heel of the dam's center section to crack and lift at least 18 inches, and then tilt back enough to return the crest of the dam to within 0.6 feet of its original position. The opening and closing of the dam's upstream heel testifies to the enormous overturning and/or arching forces that were experienced during the failure sequence, and to the sensitivity of the net overturning forces to changes in water elevation due to drawdown. A reservoir stage recorder preserved on the back side of the tilted main section recorded an apparent gradual drop in reservoir pool level for the 40 minutes prior to the dam's collapse. The subject of much controversy at the time, the stage record appears to have been a measurement of the dam's structural tilt at the beginning of the failure sequence.

Careful scrutiny of the dam and its foundations reveal many shortcomings in light of today's understanding of dam engineering. The failure of Malpasset arch dam in France in 1959 appears to have been fostered by similar mechanisms, which took many years of study to unravel. While the failure sequence presented in this paper appears to match the physical evidence, the interrelationships between the overturning and arch stresses and the behavior of the sloping abutments need to be explored in greater detail utilizing modern engineering methodologies. This and many other aspects of the St. Francis dam failure remain to be evaluated more thoroughly.

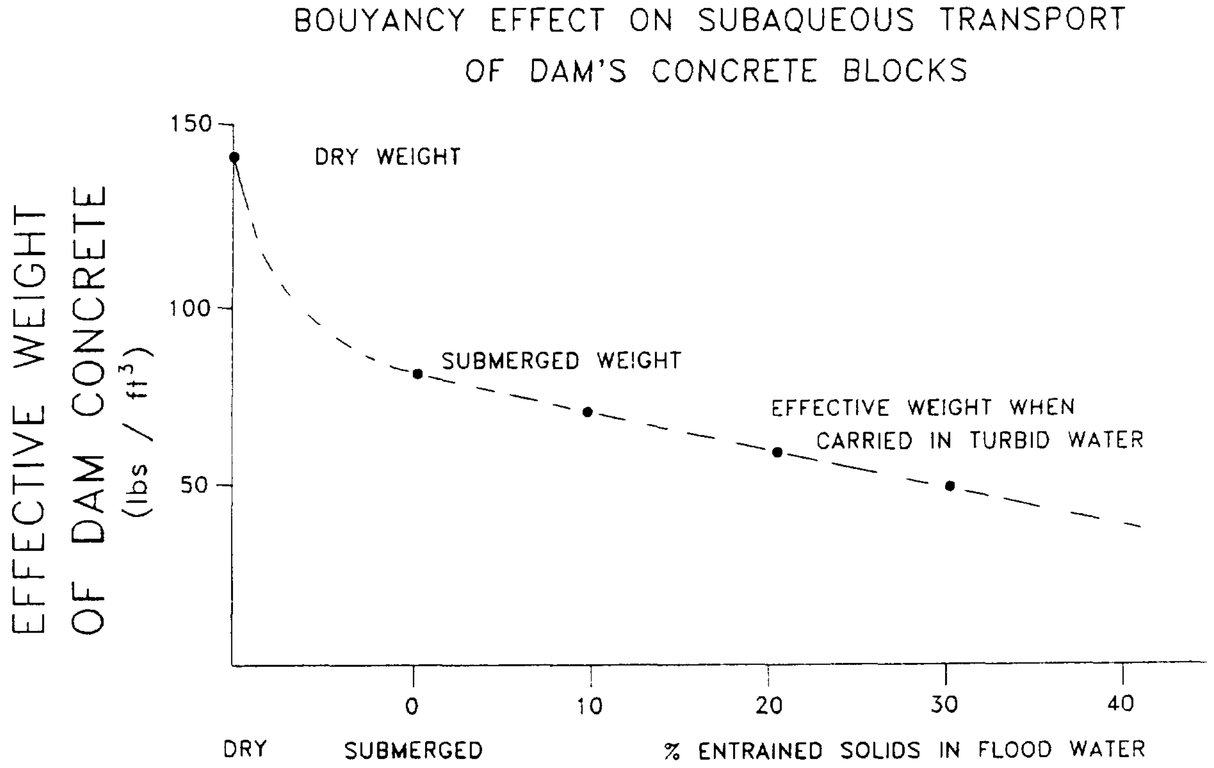

Figure 2: The effective weight of concrete blocks was descreased up to two-thirds by rock and other debris that was incorporated into the turbid flood waters.

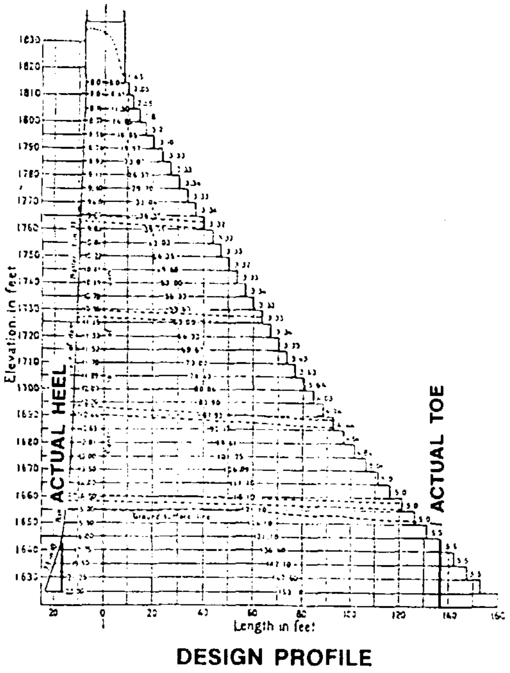

Figure 1a: The actual toe and heel of the dam were slightly less than shown in the design profile (design profile was used in the analyses).

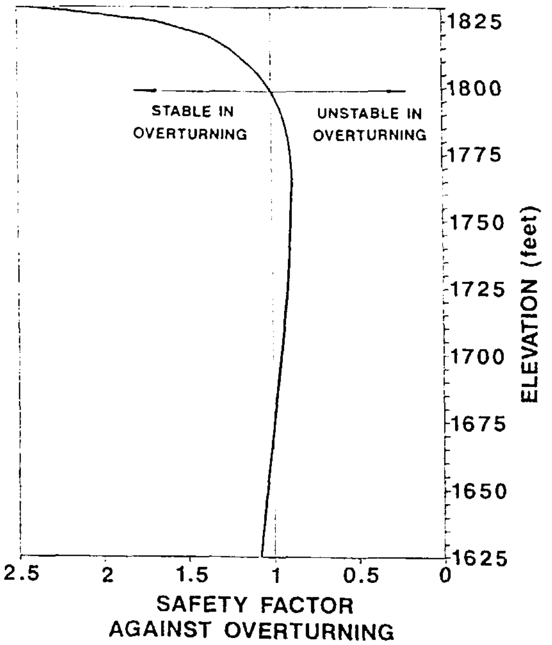

Figure 1b: The safety factor against overturning was less than one for most of the the middle portion of the dam, resulting in arching.

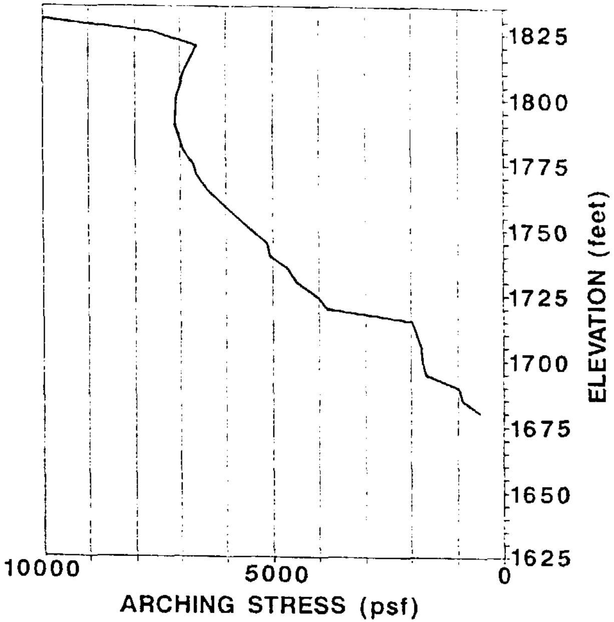

Figure 1c: The arching stresses were largest near the top of the dam. Stress concentrations are due to dam and abutment geometry.