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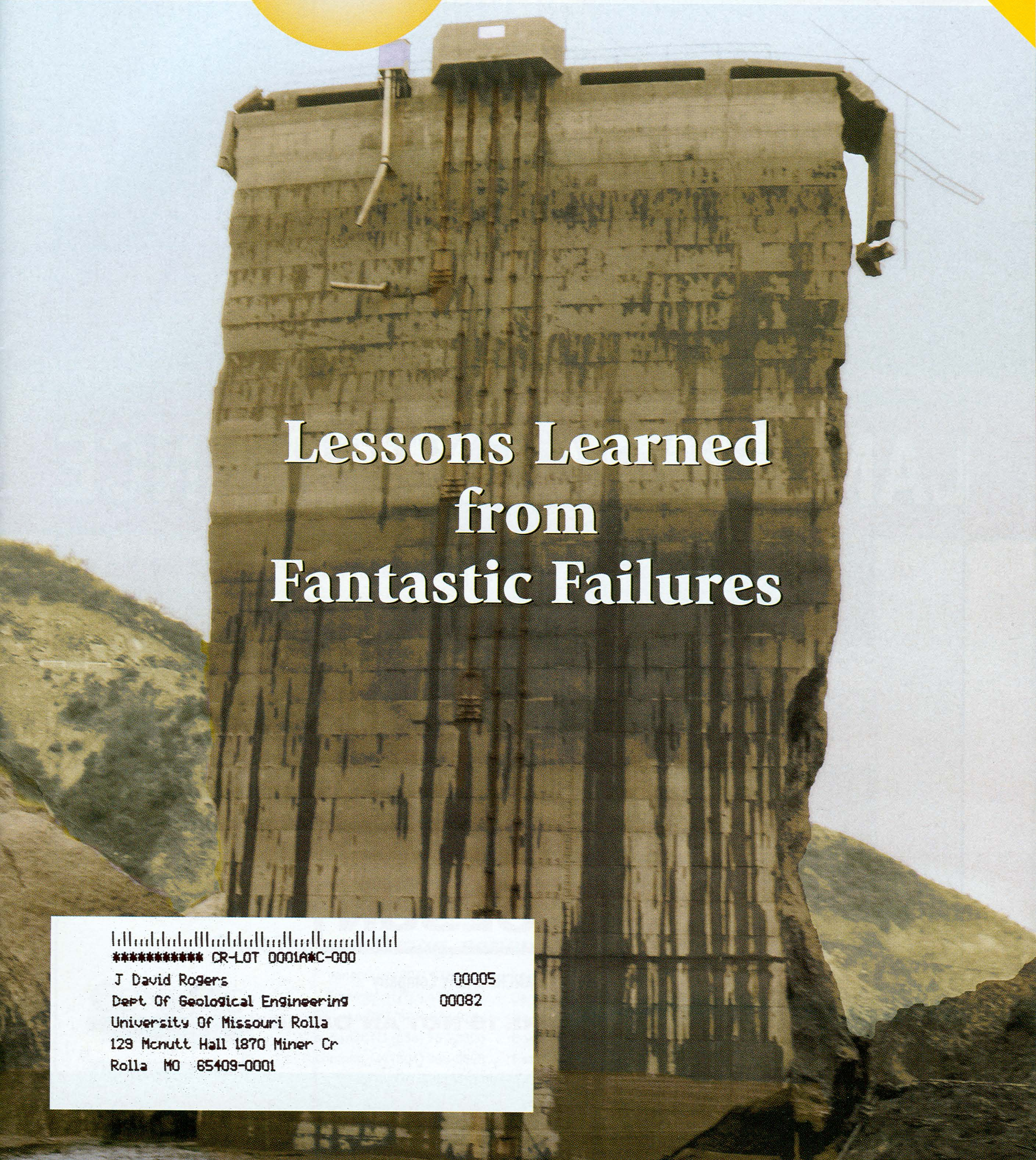

Lessons Learned from Fantastic Failures

Geo-Strata

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Features

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Lessons Learned from the St. Francis Dam Failure

By J. David Rogers, Ph.D., P.E., P.G., M.A.S.C.E.

The St. Francis Dam (Figure 1), a curved concrete gravity structure 209-feet high, located in the mountains about 35 miles north of downtown Los Angeles, failed catastrophically near midnight just before March 12, 1928. The failure released 36,180 acre-feet of water down San Francisquito Canyon on a turbulent 55-mile journey to the Pacifica Ocean near Ventura, killing 450 people. As the deadliest American civil engineering failure of the 20th century, the city of Los Angeles paid more than $7 million in restitution to the victims' families and affected landowners. The sudden failure of a new concrete dam constructed by a reputable public agency had enormous repercussions within the civil engineering profession, especially in California.

The city of Los Angeles and its chief water engineer, William Mulholland, came to national prominence between 1906-13 with the construction of the 237-mile long Los Angeles-Owens River Aqueduct, the longest water conveyance system ever conceived until that time. Designed to provide 258 mgd, the city suffered water shortages in the early 1920s because of a regional drought. Mulholland devised a 5-year plan to increase municipal storage by 67,000 ac-ft in Los Angeles by constructing eight new dams. He had already built 22 hydraulic fill earth dams, but his last two dams were mass concrete because their mountainous sites were devoid of sufficient clay or water to construct hydraulic fills.

The St. Francis site was wonderful from a topographic perspective, lying just below a broad, tree-filled glen in the Sierra Pelona between the San Gabriel and San Andreas faults. The linear canyon was structurally controlled by the ancient San Francisqito Fault, juxtaposing pre-Cambrian Pelona Schist against Oligocene Vasquez formation (then called the Sespe fm), an arkosic sandstone and conglomerate. Mulholland's subordinates designed the two concrete dams using the methods then in use—which ignored formal considerations of hydraulic uplift beneath the dam and assumed the concrete to be impermeable. (These assumptions were proven erroneous in the years following the St. Francis failure.) The city's concrete dam designs were relatively crude, in that they lacked grout curtains, grouted contraction joints, internal drains, or inspection galleries. There also was no engineering geologic input regarding the suitability of the foundations or abutments for such high structures. The shear key excavated along the upstream heel was only 3 x 3 feet deep, and the sloping abutments were not provided with stepped shear keys.

Figure 1. St. Francis Dam was a curved concrete gravity arch structure 209 feet high, constructed between April 1924 and May 1926 (W.L. Huber Collection, U.C. Water Resources Center Archives, Berkeley, colorized by P. Horton).

Potential Problems

The July 1923 plans specified a 500-ft radius of curvature for the main structure, rising 175 feet high above the streambed with a maximum base width of 141 ft, sufficient to store 30,000 ac-ft of water, which equaled the amount consumed by Los Angeles' citizens in 1922-23. Shortly before construction began in April 1924, the reservoir capacity was increased to 32,000 ac-ft, so the dam was raised 10 feet, without increasing the base width. In July 1925, the dam was raised an additional 10 feet because of Los Angeles' meteoric growth—now to a capacity of 38,000 ac-ft, but again without increasing the base width.

The dam was completed in May 1926, using 130,500 yds^3 of concrete with an average compressive strength (fc') between 1760 and 2430 psi. The city began filling the reservoir on March 1, 1926, but it was not filled to capacity until just five days before the failure, in March 1928. On the day of the failure (March 12th), Mulholland personally inspected the dam along with his assistant chief engineer, Harvey Nan Norman. They observed nothing to register alarm, yet twelve hours later the dam failed.

Why the Failure Occurred

The dam failed catastrophically just before midnight on March 12, 1928, killing nearly 450 people. A dozen panels were appointed to investigate the failure by various agencies and interested parties. They pointed to the dam's inadequate foundation as the culprit—specifically, the tendency of the Vaqueros formation to slake profusely upon saturation, and alleged hydraulic piping of this material along the San Francis-

Figure 2. Ground view looking upstream at remains of the St. Francis Dam after its untimely failure in March 1928. Note the dramatic fault contrast between the Vasquez conglomerate at extreme left with the silvery Pelona Schist. The San Francisquito fault pierced the dam's right abutment and was blamed for the dam's collapse (C.H. Lee Collection, U.C. Water Resources Center Archives, Berkeley, colorized by P. Horton).

quito fault, about halfway up the right abutment (Figure 2). The most cited investigation was that of the commission appointed by California Governor C.C. Young, comprised of four engineers and two geologists. The commission convened in Los Angeles on March 19—a week after the failure. They spent one day at the dam site, two days reviewing documents, and two days writing its report, which was released on March 27.

Subsequent studies I have made suggest that the dam's untimely demise was more complex than originally thought, involving the partial reactivation of an ancient bedrock landslide which comprised the dam's entire left abutment. A Steven's Water Stage Recorder on the dam's surviving central block (Figure 3) recorded a slight drawdown of the reservoir pool from 8:00 pm onward, which dropped with increasing severity during the last 40 minutes of the record. The 1928 investigations assumed the gage recorded simple outflow, but post-failure images show a massive tension crack at the dam's upstream heel, containing the gage attendant's wooden access ladder (Figure 3). This suggests that the dam's heel was in tension and tilting downstream when the dam failed. After the failure, Mulholland testified that the factor of safety against overturning "was in excess of 4," but the repeated heightening of the dam without commensurate increases in the base width created a dangerous situation. A simple check of full reservoir pressure inside the heel crack shows that the overturning factor of safety would have been reduced to 0.77! The Stevens Gage actually recorded a half degree of cantilever tilt, which I confirmed using a 2D finite element model.

Southern California Edison County's 70 KV Lancaster power line ran along San Francisquito Canyon, past the dam. It was destroyed at 11:57-1/2 pm where it crossed the dam's left abutment 40 ft above the dam crest. Physical evidence suggests that the entire left abutment detached itself as a massive landslide carrying a portion of the dam on 700,000 yd^3 of schist (Figure 4). This formed a temporary landslide dam which the outpouring reservoir quickly enlarged, reaching a peak outflow of about 1.7 million cfs.

Lessons Learned

Mulholland subsequently faced criminal prosecution by the Los Angeles County District Attorney, and willingly accepted responsibility for the disaster, stating: "Don't blame anyone else. Whatever fault there was on the job, put it on me. If there were any errors in judgment—and it's human to make mistakes—the error was mine." When all of the forensic investigations were completed, the most often-cited conclusion about St. Francis came from the Los Angeles County Coroner's Inquest, which addressed the need for peer review of any criti-

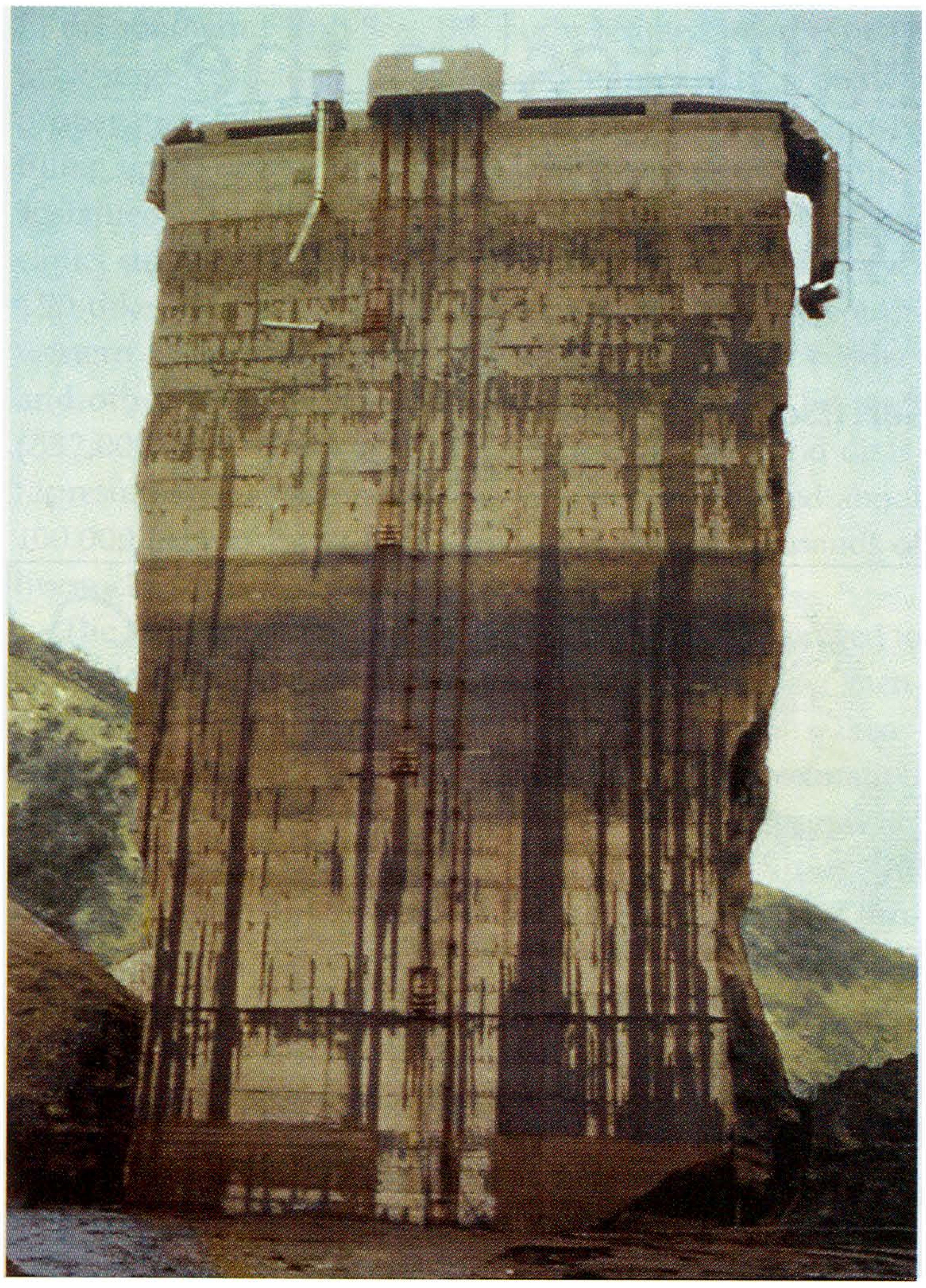

Figure 3. Upstream face of the remaining portion of St. Francis Dam, after the failure. The broken Stevens Gage can be seen near the crest, bent towards the left abutment, indicating out-rushing water flow in that direction. A prominent crack up the upstream heel is seen at lower right hand side (C.H. Lee Collection, U.C. Water Resources Center Archives, Berkeley, colorized by P. Horton).

cal structure. It stated: "A sound policy of public safety and business and engineering judgment demands that the construction and operation of a great dam should never be left to the sole judgment of one man, no matter how eminent, without ... checking by independent experts." Heeding this admonition, California's state engineer (which later became the Division of Safety of Dams—the nation's preeminent dam safety agency) was given review powers over all non-federal dams.

The St. Francis Dam failure also affected the Boulder Canyon Project which was then on the verge of being approved by Congress in 1928. The Boulder Dam project called for a massive curved concrete gravity arch dam 700 feet high which was being promoted by southern California water interests, including Mulholland. Two months after St. Francis failed, Congress named an independent panel, headed by retired Corps of Engineers General William Siebert, to review the Bureau of Reclamation's design of Boulder Dam. The panel ended up selecting the Black Canyon site, ordered the flood storage increased to 9.5 million ac-ft by increasing the dam height another 25 ft (to 730 ft), increased the foundation bearing pressure to 40 tsf, and ordered channel diversion and spillway capacities increased by another 35 percent. Shortly after their findings were released, the $165 million Boulder Canyon Project—the largest federally-funded project in history at that time (December 1928)—was approved by Congress,

The following year in 1929, California enacted professional registration for civil engineers. The St. Francis tragedy also drew attention to the importance of engineering geologic input in site selection, which became standard practice, as did engineering geology in the civil engineering curriculum. A vigorous debate erupted about the development of hydraulic uplift beneath dams, which continued into the early 1950s. The destabilizing impacts of hydraulic uplift on steep-sided abutments was not fully appreciated until after the Malpasset Dam failure in December 1959. The failure took years to unravel.

The three-dimensional complexity of blocky dam foundations under seepage forces continues to evolve. The siting of dams against landslides was not specific to St. Francis. In fact, since Rogers' first article appeared in 1992, Schuster (in press) has compiled a list of 254 American dams greater than 35-ft high, most of which were unknowingly constructed against old landslides. Many of these are being re-evaluated in light of these recent revelations. ❍

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Figure 4. Aerial oblique view of the St. Francis Dam failure taken the following morning, looking upstream. the left abutment landslide is clearly visible, extending almost 200 feet above the reservoir pool elevation (Spense Aerial Photo Collection, UCLA Geography Department).