St. Francis Dam

Henry Petroski

Los Angeles could not have grown into the metropolis that it is today without the expansion of its water supply. In 1900 the city's population was about 100,000 and growing rapidly, to reach 175,000 within five years. Since the Los Angeles River watershed was capable of supporting only about 200,000 people, the city had the choice of limiting growth or finding new sources of water. A drought in 1904 raised the issue to crisis proportions.

Los Angeles's need to import water had been foreseen a decade earlier by Fred Eaton, who as city engineer had identified the Owens Valley, north of the city, as a likely candidate. In the meantime, the U.S. Reclamation Service had begun looking into the feasibility of an irrigation scheme for the farmers of the Owens Valley, and Los Angeles had to act fast if it was to obtain the water rights. Eaton took William Mulholland, manager of the newly formed Los Angeles Bureau of Water Works and Supply, to the valley to investigate the possibility of constructing a gravity-flow aqueduct from there to the city nearly 250 miles south. The distance was unprecedented. The longest Roman aqueducts were less than 60 miles long, and New York's Croton Aqueduct was even shorter. However, Owens Lake was more than 3,000 feet higher than the city, providing a much greater average gradient than existed in the successful Croton Aqueduct. Thus the engineering problems, which would involve inverted siphons and pressure tunnels to get the water over and through the mountains in the way, seemed solvable.

Mulholland Drive

William Mulholland was an engineer of the old school, which essentially means that he had learned by doing. He was born in Ireland in 1855, went to sea at 15, landed in New York City four years later, worked at a variety of jobs in the East and Midwest, and sailed via the Isthmus of Panama to San Francisco. He settled in the Los Angeles area at the age of 22, working as a "water ditch tender" with the Los Angeles City Water Company, a small private provider. According to one account:

> Mulholland later recalled that he became interested in things technical when serving as a helper on a drill rig digging water wells that pierced a buried tree trunk at a depth of 600 feet. He went to the library to investigate the manner by which a tree could become buried at such great depth, and read University of California Professor John LeConte's *Introduction to Physical Geology*. Mulholland liked the subject matter so much that he later recalled, "Right there I decided to become an engineer"....

Mulholland eventually became general manager and chief engineer of the Los Angeles Water Company. He proved himself to be so knowledgeable of the poorly documented infrastructure and workings of the water distribution system that, when the company was acquired by the city in 1902, the self-taught engineer was retained as its manager. It was in this capacity that he accompanied Fred Eaton to the Owens Valley and secured $1.5 million from the Los Angeles Board of Water Commissioners for engineering studies of the situation.

The scale of the project and Mulholland's "lack of substantive experience in constructing such facilities" were used by "other engineers, newspaper editors and electric power interests" to discredit the scheme. In response to the criticism, the City Commissioners appointed an Aqueduct Advisory Board, comprising three distinguished consulting engineers, to "make an independent evaluation of the proposed aqueduct design." One of the consultants was John R. Freeman, who had been among the principal designers of the New Croton Aqueduct and who had served on the advisory board to review the design of the Panama Canal. When the external board found Mulholland's aqueduct design "admirable in conception and outline," criticism was quelled. The $23 million bond issue passed overwhelmingly in 1907.

The construction of the 233-mile aqueduct and its initial filling were not without incident. Upon first carrying water, one of the major siphons in the aqueduct began leaking and was lifted up by the resulting hydraulic forces. The seepage from the riveted steel conduit also triggered a landslide in which the pipe became entangled. Such setbacks were forgotten by most of the 30,000 people who gathered on November 5, 1913, to

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Figure 1. St. Francis dam impounded 38,000 acre-feet of water prior to its failure on March 12, 1928. (Photograph by the Los Angeles Department of Water and Power.)

watch the opening of the world's longest aqueduct, which was capable of transporting 258 million gallons per day to Los Angeles.

While the aqueduct was being planned, speculators bought up large parcels of land in the San Fernando Valley, located north of Los Angeles. Water from the aqueduct would make the semi-arid region arable, they anticipated, but when it became clear that no such water would ever be made available outside of Los Angeles, the San Fernando landowners argued for annexation. By 1924, their successful campaign had quadrupled the area of the city. This growth, combined with a three-year drought, severely taxed the water supply. Under the worst conditions, ranchers in the San Fernando Valley were intercepting virtually all of the aqueduct's base flow. The city of Los Angeles sought to acquire more water rights in the Owens Valley, but angry residents, still bitter from the original conflict over the claims of the rural valley versus a growing city, balked, and some turned to violence reminiscent of the Old West. Among the retaliatory acts was the dynamiting of the aqueduct, which subsequently had to be protected by armed guards.

Storage to Stretch Supply

In the meantime, in recognition of the fact that the aqueduct could not supply enough water for both urban Los Angeles and the rural San Fernando Valley without enormous storage capacity, additional reservoirs had been planned and designed and were under construction. In fact, between 1920 and 1926, a total of eight new reservoirs were built by the Los Angeles Bureau of Waterworks and Supply, during which time Mulholland made it known that it was his goal to have enough reservoir capacity to hold in reserve an entire year's worth of water for the city. Among the additional reservoirs Mulholland planned was one that would account for about half the total water required. This dam, to be located in San Francisquito Canyon, was to be called the St. Francis.

The St. Francis Dam site was chosen after inflated land values made another location too expensive for Mulholland's tastes. In fact, he had imagined a dam in San Francisquito Canyon during the construction of the aqueduct. Mulholland saw then that a relatively small dam built where the canyon narrowed would hold back an enormous amount of water. He also recognized early on that the geology of the location called for special caution, but these conditions did not keep him from designing a dam for the site. He assumed that the buttressing effect of the dam would mitigate any slippage at the canyon walls.

Until 1923, all the dams whose designs Mulholland had overseen were earthworks—large embankments whose fine-grained silt and clay cores were more or less impermeable to water. The first concrete dam built for Los Angeles was the 200-foot-high Weid Canyon Dam, which was designed to impound the Hollywood Reservoir. It has been speculated that Mulholland decided to adopt a concrete-dam design over the clay-core type with which he was so familiar because of the limited supply of clayey materials in the sides of Weid Canyon. A year before the unique concrete dam was completed, in 1925, it was christened Mulholland Dam, a testament to the stature to which the chief engineer had risen in Los Angeles.

St. Francis Dam was similarly designed to be made of concrete, because there was no suitable clay or silt available at the San Francisquito Canyon site. The new dam would also be a stepped concrete gravity arch structure: Its downstream face was constructed like a wide set of steps, its material was mass (unreinforced) concrete, and the structural principle by which it held back the water was through its sheer weight pressing down on the ground, aided by an arched plan that took advantage of the water pressure behind it to compress or wedge the dam between the sides of the canyon, which served as abutments.

The original design of the St. Francis called for a dam reaching 175 feet above the San Francisquito Creek bed, which would have given it a capacity of 30,000 acre feet of water—that is, enough water to flood 30,000 acres to a depth of one foot, enough to supply Los Angeles for a year. But because of increased water use by Los Angeles, before the first concrete was poured, the dam's capacity was increased to 32,000 acre feet by raising its height and adding a wing dike that extended from the west abutment. Almost a year after the beginning of the placement of concrete, apparently in response to further growth in water usage, the reservoir capacity was once again increased by raising and extending the wing dike and by adding another 10 feet to the dam's height, to increase its capacity to more than 38,000 acre feet—more than 25 percent greater than the original design. The changes in its height had been made without a proportionate widening of the dam's base, but Mulholland believed that the design still had a "factor of safety of three or four." A gravity dam derives its ability to hold back water without tipping over from the width of its base, however, so the factor of safety of the dam was definitely reduced by the design changes.

Less Than Conservative Design

Construction of St. Francis Dam lagged that of Mulholland Dam by about a year, and the successful advance of that structure must have provided plenty of confidence in the safety and robustness of the basic design, in spite of some less than conservative design features. St. Francis Dam contained 130,000 cubic yards of concrete but no reinforcing steel. The main structure also lacked contraction joints, which allow concrete to crack in a controlled manner as it cools. (The grooves in a concrete sidewalk cause it to crack at the base of these reduced sections, thus keeping the predictable cracks more or less straight and hidden.) No doubt the arched nature of the dam was expected to close as much as possible any cracks that did develop. St. Francis Dam was also constructed without drainage galleries, tunnels that run through a structure to allow inspection for cracks and sources of leakage, and to provide a means for monitoring the amount of water flowing through the dam. Finally, the structure was built without cut-off walls (concrete-filled trenches designed to reduce water seepage under the dam) or a grout curtain (a further seepage-prevention measure taken by forcing grout under pressure into holes drilled in the rock under a cut-off wall). These measures reduce the possibility of water infiltrating under a dam and exerting upward hydrostatic pressure, thus making the structure somewhat buoyant. Such buoyancy provides an uplift force that reduces the effect of the weight of the dam in keeping it in place. In extreme cases, uplift forces can cause a dam to tend to tilt forward or slide downstream. In short, many of the design features of St. Francis Dam, which were in accordance with standard engineering practice of the time, in retrospect contributed to making it less watertight, less inspectable and less stable than should have been considered wise.

By the time he was building St. Francis, Mulholland's record of successful dams appears to have given him a confident attitude toward the ability of the gigantic structures to hold back the force of water, but at the same time, he had resigned himself to the fact that some water leaked through. Although his experience was with earthen dams, he evidently felt comfortable transferring his confidence to concrete dams, which, after all, were made of a stronger and less permeable material.

St. Francis Dam was completed in May 1926, but months before that date water from the Owens aqueduct was diverted into the reservoir. At first, enough water was allowed to pass through outlets in the dam to maintain the flow in San Francisquito Creek. Shortly after St. Francis Dam was completed, however, Los Angeles requested the appropriation also of "flood and surplus waters," and blocked the flow into San Francisquito Creek. Mulholland is said to have believed that the Santa Clarita Valley ranchers downstream could continue to draw water from their wells, not appreciating that the replenishment of the groundwater depended on the creek flow. An agreed-upon test release of water from the dam caused the resulting stream to dry up within a few miles, indicating that the water indeed was going into the ground. This incident was one of Mulholland's few public embarrassments over water issues, but it also demonstrated that his assertions about water flow through the ground were not always fully informed.

A year after St. Francis Dam was completed, the level of its reservoir reached within three feet of the crest of the spillway, which was designed to keep water from overflowing the top of the dam. The water did not reach the spillway, however, for the spring runoff ceased and the level of the reservoir began to drop. The cracks that had developed in the dam during its filling were described by Mulholland as "transverse contraction cracks" and did not appear to alarm him. The downstream crevices were "infilled with hemp and sealed with wedges of oakum" and "backfilled with cement grout to seal off active seepage."

The next year's spring runoff caused the reservoir to fill again, this time to maximum capacity. In the meantime, new leaks developed in the dam, some manifesting themselves in springs in the foundation and others in the old cracks—through which the discharge was increased over the previous year. Still other leaks developed on either abutment of the dam and in the wing dike. Mulholland ordered a concrete pipe installed to drain water from this last leak toward the abutment of the dam.

Disaster

March 12, 1928—75 years ago—was a windy day, and water from the reservoir was blown in waves against the dam and over its spillways. This water naturally washed over the stepped downstream face of the dam, making it difficult to tell if new leaks were developing or old ones were growing. Full reservoirs throughout the system and winter runoff combined to present an abundance of water, which was allowed to flow into San Francisquito Canyon for the first time in almost two years. Earlier that day, the St. Francis damkeeper had called Mulholland to bring to his attention a new leak, of "dirty" water, at the west abutment. Such water could indicate that foundation material was being washed out from under the dam, which could lead to it being undermined—certainly a dangerous condition. Mulholland, who claimed to have made it a practice to visit all 19 dams under his supervision at least once every two weeks, immediately drove with his assistant to the St. Francis, where they spent two hours inspecting the dam. The "dirty" water seemed clear to them, and the dam was declared safe.

A little before midnight that same day, the dam gave way and the contents of the reservoir inundated San Francisquito Canyon. The water rushed down the canyon, destroying everything in its path. Some large sections of the concrete dam, weighing thousands of tons, were washed as much as a mile downstream, leaving only the tall center section of the structure remaining in place, with some other large blocks scattered nearby, mostly between the center section and what was the east abutment. A powerhouse located about a mile and a half downstream was washed away, as were a construction camp and houses in little towns and villages in the path of the water. Hundreds of people were killed, most no doubt unsuspecting as they slept. The official death toll was in excess of 430, but the actual total is debated to this day.

According to *Engineering News-Record*, the magazine of the construction industry that had long ago established its reputation for accurate and incisive reporting on the failure of structures, it was "the first time in history a high dam of massive masonry" had failed. The disaster was compared to the Johnstown Flood of 1889, which had claimed more than 2,000 lives, a disaster that was once considered "the worst in history resulting from failure of manmade structures." However, the trade magazine declared, "the washing out of an old neglected earth dam was not an engineering tragedy" so much as a case of carefree modifications and poor maintenance by the hunting and fishing club that had patched an abandoned Pennsylvania state canal system reservoir to make a recreational lake. The failure of the St. Francis Dam was indeed different, for here the latest engineering materials, design philosophies, construction techniques and operational procedures were overseen by an engineer with an impeccable record of success. That is not to say that Mulholland's work was without critics, but in the business of holding back vast quantities of water, he had been able to answer their fears. At least in the minds of those who were in the position to give the go-ahead for such great projects, a concrete dam built by Mulholland would certainly be stronger than the water that pushed against it. But, as an editorial in *Engineering News-Record* put it, "Men have always been in awe of these vast forces, and often has bitter protest been made against the erection of a dam above populous communities. In every instance engineering science answered the protest and gave assurance that the waters would be safely controlled. The destruction of the St. Francis Dam challenges that assurance."

Figure 2. William Mulholland *(left)* views the remains of St. Francis dam. (Photograph courtesy of the Wilkman Productions Collection.)

Devilish Details

A great failure is the perfect counterexample to a hubristic hypothesis. William Mulholland and his staff had evidently so gained confidence in their mastery of the great hydraulic forces pent up behind the successful dams they had built that they began to build them with less and less attention to detail, especially the all-important local detail of the geology underlying the site. Or, if they did pay close attention to it, they missed some key elements of its character.

More than a dozen official boards and commissions were appointed by various California offices and interested parties, ranging from the state governor to the Los Angeles County district attorney, to investigate the St. Francis Dam disaster. Within a month or so of the incident, studies were made, witnesses were interviewed, hearings were held, and a half dozen reports were filed. All six of these identified the foundations of the dam to have been inadequate, but there was no unanimity over the exact triggering mechanism for the catastrophe.

The reports dismissed early speculations about an earthquake or explosion causing any initial breach. They also confirmed that the concrete was of sufficient strength, and that the design of the superstructure was in accordance with commonly accepted engineering practice. (The failure appears not to have had any significant effect on the structural design of concrete dams at the Bureau of

Reclamation, which had succeeded the Service in 1923.) However, the reports condemned the foundations underlying the St. Francis Dam, a subject that in general was incompletely understood at the time. Among the things that were pointed out in the various reports were that the conglomerate material under the upper right abutment structure was held together with clay that softened when wet and furthermore contained numerous fissures filled with gypsum, which dissolves in water. Any water flowing through this material would in time carry out gypsum, which would not be easily seen, for the water would appear to be clear. When enough gypsum had dissolved and the foundations were sufficiently softened, the dam would settle unevenly, eventually crack and finally have no ability to hold back the water behind it, which would rush freely downstream.

The reports were in general agreement that it was the west side of the dam, where the underlying rock was as described, that gave way first. The east side of the dam had abutted the steep slope of the canyon that consisted of parallel layers of schist. A landslide that was evident at the site of the failed dam was generally assumed to have occurred after the dam was breached. Geological engineer J. David Rogers, however, maintains that it was a landslide of the east canyon wall that triggered the failure, with the rush of water scouring the dam's foundation and causing the dam to lean. This in turn opened up preexisting cracks all along the arched structure. According to Rogers' recent studies, the landslide dumped as much as a million cubic yards of weathered mica schist, which "created an outpouring flood wave supercharged with sediment." If the density of such sediment was about five times that of water, Rogers believes that it could have effectively made large sections of the dam sufficiently buoyant to be pushed and tumbled down the canyon, where they were found in the wake of the ensuing flood. This hypothesis, like others, remains unprovable in any rigorous sense, of course, but it highlights the complexity of anticipating the forces on a concrete dam structure.

Regardless of the exact mechanism by which the St. Francis dam cracked and gave way, William Mulholland took full responsibility for the disaster. On the witness stand, he admitted that he could not explain the failure. According to *Engineering News-Record*, "He had based his opinion as to its safety on previous experience in building nineteen dams. His only suggestions as to the possible cause was that 'we must have overlooked something.'" Overlooking something is, of course, always a danger in the design of large engineering systems, and it is precisely why the opinion of independent experts is sought during the design stage. In addition to the technical error of siting the St. Francis Dam on poor foundations, its collapse was blamed on the "human factor," which manifested itself in the fact that "engineering work in the Bureau of Water Works and Supply always had been dominated by one man, the chief engineer, who took upon himself, in this case at least, entire responsibility, sought no independent opinions and adopted technical policies based on his unconfirmed judgment alone." Since "higher officials had absolute confidence in Mr. Mulholland," outside opinion was not sought and "there was no intervention from above." The plans for the dam were not challenged because "Mr. Mulholland was personally overseeing the work."

No engineer should have such hubris as to think that past successes are sufficient to guarantee the success of the next project. Each new project rests on a new foundation, whose hidden faults may or may not be within prior experience. When all dams and the foundations upon which they rest begin to look alike to an engineer like William Mulholland, he himself should question his own expertise. As *Engineering News-Record* put it just two months after the disaster, "Had the plan of construction used for the St. Francis Dam been brought forward by some comparatively inexperienced engineer, or had the work been done by contract or under any other condition that would naturally have brought independent engineering opinion into the case, it is highly probable that some modified plan would have been substituted and the disaster avoided." Experience is not always the best teacher.

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