Feature

St Francis: the world's worst dam site

Lying just north of Los Angeles, the total collapse of the St Francis Dam in 1928 has been described as America's worst civil engineering disaster of the twentieth century. Although poorly remembered among today's residents of Los Angeles, the event is better known to engineering geologists. The dam's failure was largely due to the geology of its site, which was inappropriate to the point of disastrous, in more ways than one.

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Los Angeles is one of America's great cities, wealthy with oilfields, industries and port facilities, all in a spectacular setting between ocean and mountains. However, it has its drawbacks: a significant earthquake hazard zone, a susceptibility to landslides in many of its districts, and a semi-arid environment that leaves the city short of water. It is a shortage of water that has prompted the creation of a mammoth supply system, but sadly this included the St Francis Dam—at arguably the world's worst dam site.

Los Angeles' water supply

Major expansion of the city in the early 1900s left no alternative to importing water from distant sources. Consequently the Los Angeles Aqueduct was born, with a pipeline 375 km long from the Owens River in eastern California to the Van Norman holding reservoirs in the northern suburbs of the city. This carried 12 m^3/s of water, gathered from the eastern slopes of the Sierra Nevada. Its construction was a massive feat, completed between 1905 and 1913, and largely through the sheer dynamism of its chief engineer, William Mulholland. Subsequent expansions—with the Colorado River Aqueduct from the Parker Dam (downstream of Boulder Dam, later known as Hoover Dam), and the Mono Lake Diversion (which lowered the lake level and exposed the famous tufa towers)—were also initiated by Mulholland, though their construction was after his time.

There are many who regard Mulholland as a great man for his successful leadership of the project. Though there were detractors among the farming communities of the Owens Valley, who saw Owens Lake dry up, and lost access to their natural water supplies through political actions that bordered on the nefarious and underhand. Mulholland had no training as an engineer, but was self-taught, aided by his admirable work ethic, sharp mind, formidable memory and dedicated reading of text books. He started work in 1877, maintaining a water-supply canal, and by 1911 had worked his way through the ranks to become Chief Engineer for the Los Angeles Water Department. His visionary developments gave the city the water supply that it needed to be able to expand. In recognition of his success, a school, two highways and a dam within Los Angeles all bear the Mulholland name.

Building the St Francis dam

There were always new demands for further water infrastructure, including a back-up holding reservoir convenient for the aqueduct crossing the San Gabriel Mountains on the edge of the city. Mulholland recognized this need, but avaricious land-owners drove him away from his first choice of site for a reservoir in Big Tujunga Canyon. He instead turned to a site 60 km further north-west, in the San

Fig. 1. The San Francisquito Canyon as it appeared in 1979. The dam had been built in the V-shaped section to the right of the natural spur of rock extending from the left. On the far right, on what was the eastern abutment, the scar of the main landslide is a slope of grey schist with sparser vegetation than on the slope above.

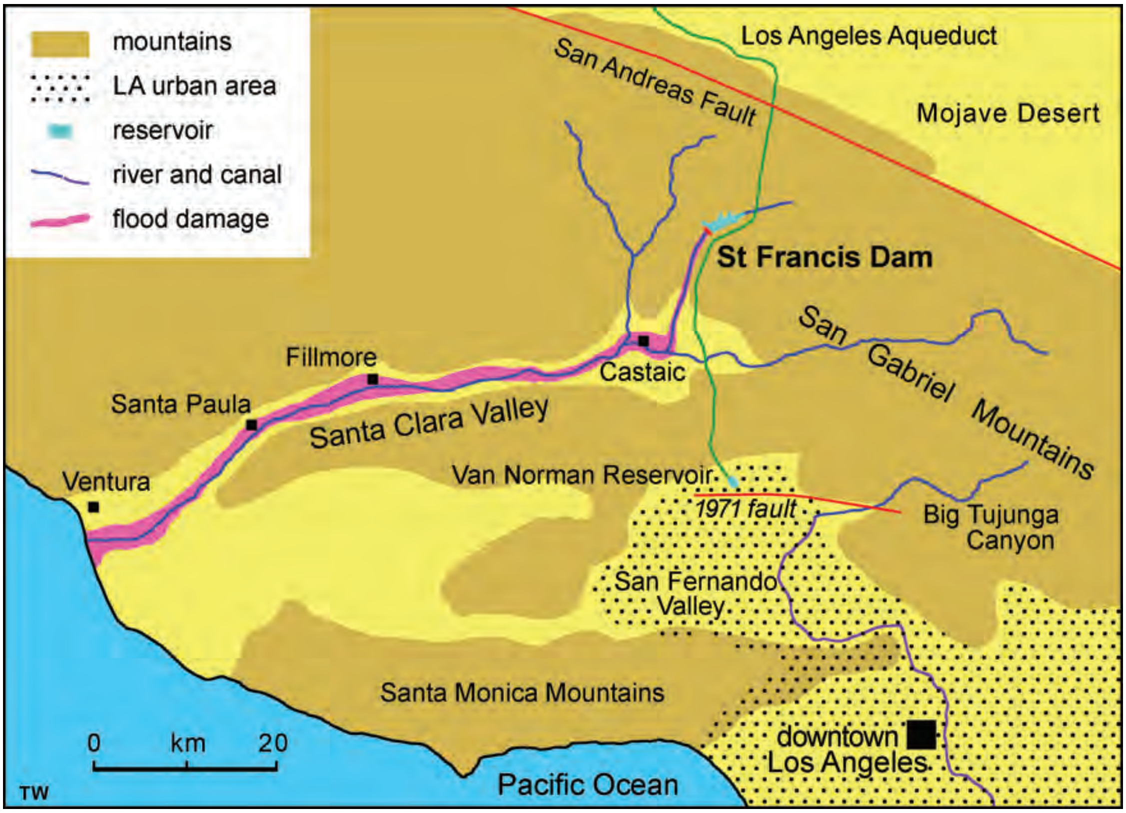

Fig. 2. The location of the St Francis Dam and related features north of Los Angeles.

Francisquito Canyon, a tributary valley to the Santa Clara River. This had an ideal topography, with a spur of the western hillside creating a narrowing of the valley (it could barely be described as a canyon) downstream of a wider section that could hold a large reservoir, and there was no farming or housing in the valley (Fig. 1). It was still only 80 km north of downtown Los Angeles, and it had the aqueduct buried in tunnels high in its eastern slopes (Fig. 2).

Construction of the dam started in August 1924, but carried with it a catalogue of engineering mistakes, mostly minor, though that would be debated by some. The dam was a very simple, conventional, gravity-arch design, built with nearly 90 000 cubic metres of mass concrete. It was 213 metres long, on a gentle curve, with a wing wall 180 metres long extending its crest along the natural spur that formed the western abutment. The original design was for a dam 56 metres high, with a nearly vertical water face and a stepped downstream face that reached to a basal width of 53 metres. However, there was no specific design for the dam, as it was simply a copy of the Hollywood (or Mulholland) Dam that had been completed in 1924 just 60 km to the south, and even that had been only crudely designed with no formal calculations.

During construction, the height of the St Francis Dam was raised 6 metres by adding a vertical upper wall, without any increase in the basal width. At 62 metres high, the dam's overall stability declined with respect to both rotation and sliding when exposed to the horizontal stress of the filled reservoir. Furthermore, photographs taken during construction appear to indicate that the toe of the dam reached only to about 46 metres, short of its design extent and thereby reducing its stability even further.

There were other contentious issues with respect to the dam's design. The dam was built on bedrock that had been cleared only to depths varying between one and four metres beneath the original, weathered,

Fig. 3. One of the few photographs of the reservoir after filling and of the dam before failing.

ground surface. The cut-off trench, filled with concrete to provide a shear key beneath the upstream wall of the dam, was only a metre wide and deep. There was no grout curtain beneath the dam. Relief wells and drains were only installed beneath the central section of the dam, and they did not extend under either flank; it was not appreciated at the time how the shortage of relief wells would allow hydrostatic uplift forces to increase when the reservoir was filled. There was no drainage tunnel and inspection gallery within the dam. All these features contributed to the potential instability of the dam, and then in addition, the geology of the dam site had barely been considered.

In the semi-arid San Francisquito Canyon, unconsolidated soils were only thin, and were simply removed during site clearance. But the bedrock geology was unbelievably inappropriate for a major dam. The western side of the valley is floored by Palaeogene Vasquez Conglomerate (formerly known as the Sepse Formation), the eastern side is cut in Cretaceous Pelona Schist of greenschist facies, and the two rock units are separated by the San Francisquito Fault, which extends directly beneath the site of the dam. William Mulholland may have been an inspirational engineer, but he made the two-fold mistake of not knowing enough geology, and not consulting a competent geologist.

The fault was marked on existing geological maps, which were not consulted. Back in 1911, the Pelona Schist was described as an unstable fractured material that should be avoided, along the east wall of the canyon; this had been documented by Mulholland's own department when preparing a route for the aqueduct, but had apparently been forgotten by 1924. A propensity for the Vasquez Conglomerate to dissolve in water was noted by an engineer, Frederick Finkle, when he visited the site in 1924, but this was ignored by Mulholland, perhaps because there was some previous bad blood between the two engineers. There was no adequate desk study that should have revealed these problems with the dam site; and there appears to have been no site inspection when the ground had been cleared prior to pouring any concrete. Complete exposure of the bedrock in the essential site clearance should be a gift to a project engineer, allowing re-assessment of the ground conditions and any appropriate design changes. But it appears that Mulholland just ignored the geology of his chosen site; and that was the tragedy of the St Francis Dam.

Catastrophic failure of the dam

Aqueduct water was first re-directed to start filling the reservoir in March 1926 (Fig. 3). During filling, the first of many vertical cracks were seen to develop in the dam's downstream face. Such cracks are not uncommon in the unreinforced mass concrete of a gravity dam, and were not regarded as hazardous. In April 1926, the water reached the level of the fault outcrop beneath the dam, and some leakage was observed, but this too caused no concern.

Fig. 4. The remains of the St Francis Dam after its catastrophic failure, with only the narrow middle section, subsequently known as the tombstone, still standing. The landslide scars in the eastern abutment are devoid of any plant cover on the right. On the western abutment, on the left, the reddish ground of scoured conglomerate is separated by the fault outcrop from the lower grey slopes of scoured schist. The boundary with grass-covered slopes above marks the lower level of floodwater erosion due to the delayed failure of the western part of the dam.

By 7 March 1928, the reservoir was full to spillway level for the first time. Within the previous week, various new leaks had been observed increasing their flows of water from the conglomerate in the dam's west abutment. Then on the morning of 12 March, the dam keeper found a new and larger leak that was discharging muddy water, so called in Mulholland (who soon arrived with his assistant, Harvey Van Norman) to assess the situation. They estimated the flow as about 75 litres per second, but considered that its muddy nature was due to surface erosion. Of greater concern was periodic surging of the flow from the new leak. This had to be a sign of underground erosion, and Mulholland deemed that corrective measures were required, but could wait until a convenient later date.

At about 8.30 that same evening, Ray Silvey and his family were driving up the canyon road that passed just above the dam on its eastern side. Some 30 metres upstream of the dam's crest, they were stopped where the road was broken by a step clean across it. The road beyond had dropped about 30 cm, where a slice of the hillside of Pelona Schist had slipped down towards the new reservoir. News of the Silveys' encounter did not emerge until later, but it was a significant precursor to events that followed during the hours of darkness.

Two minutes before midnight on 12 March, the St Francis Dam collapsed. The timing is known from the recorded break of a power line on the eastern abutment, and also because Ace Hopwell, passing by on his way home, then heard a rumbling noise over the sound of his own motorcycle. The rumbling was from blocks of concrete tumbling away from the dam within the floodwater; one block weighing nearly

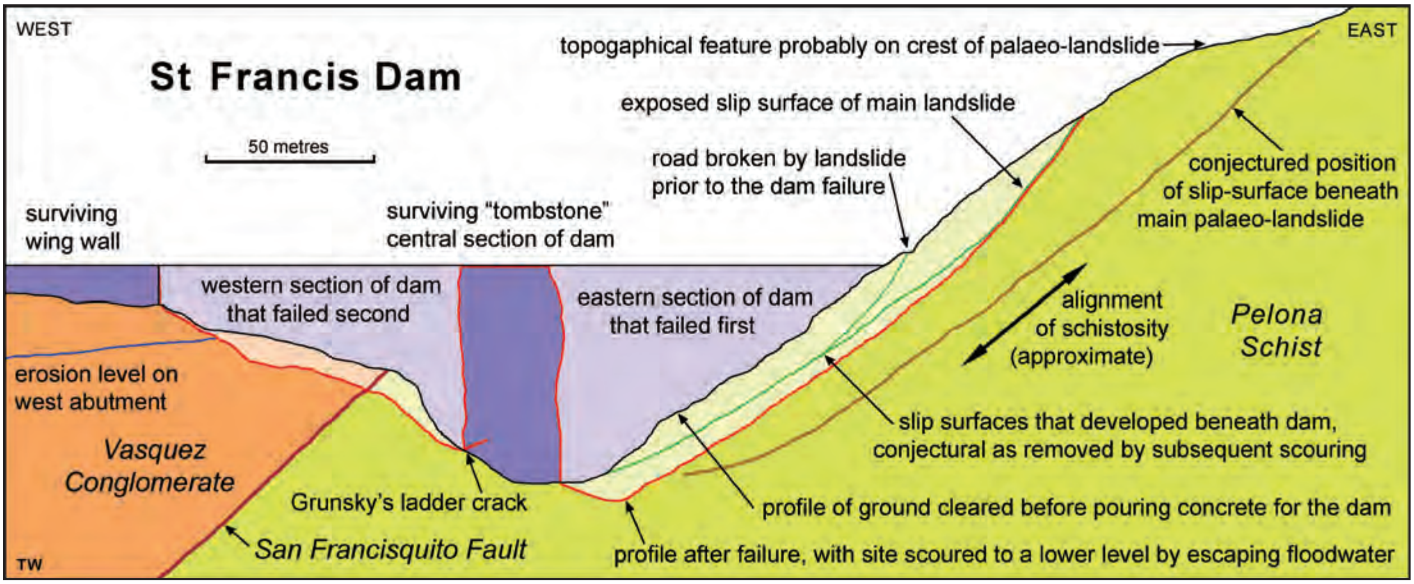

Fig. 5. Profile along the length of the St Francis Dam, looking upstream, with features of the ground before and after its collapse.

10 000 tonnes was carried more than a kilometre down the canyon in a dense slurry of reservoir water with an entrained load of schist fragments scoured from the eastern abutment.

The dam's collapse was almost complete and almost instantaneous, although not quite in both respects; a central segment of the dam (later known as the tombstone) was left standing (Fig. 4), and subsequent studies revealed a complex sequence within a staged failure. The entire western and eastern sectors of the dam were swept away from each side of the surviving central tombstone. Within about an hour, all 47 million cubic metres of water in the reservoir poured out through the massive double breach. A flood wave 40 metres high tore down the canyon at nearly 30 km/h, and peak flow was close to 50 000 m^3/s (about three times the mean flow of the Mississippi).

Nearly an hour later, the floodwaters hit the main valley where the small town of Castaic was almost totally destroyed. At about the same time, telephone messages were sent to towns further down the Santa Clara Valley. In both Fillmore and Santa Paula, switchboard operators phoned everyone they could, and highway patrol officers cruised the streets with sirens wailing, so that most residents woke up and rushed to high ground. The flood wave, by then slower, lower and wider, struck around 3 AM, causing massive damage, but taking few lives in the almost empty towns, although residents of isolated farms fared worse as they received no warning. At about 5.30 AM, the flood wave entered the Pacific Ocean just south of Ventura, some 87 km from the ruined remains of the dam. By then, at least 432 people had died in the floodwaters.

Aftermath investigations

Very soon after the dam failure, a whole series of commissions and inquiries were set up at city, state and national levels. The California Governor's Commission was the first to report back, after just eleven days. The Commission blamed the failure on the conglomerate beneath the dam's western abutment, as this was clearly a weak rock and was the site of conspicuous precursor leakages. They were the first to record that that there had been an error in engineering judgement in developing the dam design, and responsibility for that lay with the water bureau's chief engineer (Mulholland), but they cleared him of any criminal culpability on the grounds that he could not have known of the instability of the rock beneath the dam. That reasoning was developed by the lawyers, bureaucrats and politicians who formed the official commissions, and it really has to be regarded as highly dubious. No competent geologist could have agreed that elements of ground instability were not recognizable in even the most cursory of inspections of the dam site. However, Mulholland was an honourable man; he resigned from his post and accepted full responsibility for the disaster, saying repeatedly that no blame should fall on any other person.

The general opinion in those early days after the disaster was that the weak conglomerate had caused the collapse of the dam, and that the many other factors related to both the dam design and the ground conditions were merely contributory. Too many people jumped to conclusions with undue haste, before all further investigations were prematurely curtailed. This was because plans for the Boulder Dam on the River Colorado were up for congressional approval in Washington. That dam was also a gravity structure, although much larger than the St Francis Dam, and it was founded on strong granite that provided an excellent site. Nevertheless, any doubts or complications raised by further inquiries into the St Francis failure would have been very unwelcome at the time.

A common criticism from the commissions and inquiries was that Mulholland had been able, in his senior position, to advance his great projects virtually unchecked. The only people with authority over him were politicians, lawyers and committee folk who had no engineering knowledge and were unable to challenge his decisions. At that time, there were no rules demanding that engineering plans were checked through by another engineer, a situation that was subsequently changed by law. Analogy can be drawn with Ferdinand de Lesseps, who achieved massive success with the Suez Canal, and followed with massive failure at the Panama Canal because by then he thought he knew it all, ignored any outsiders' advice, and saw that his autocratic position in the French engineering community was challenged by no-one.

William Mulholland retired into semi-reclusion, and died seven years later, amid memories of his hugely successful Los Angeles Aqueduct mixed with those of the St Francis Dam disaster. Only after his death did re-assessments of the disaster lead some, but not all, to place much of the blame on his shoulders. There is still debate over what Mulholland should have known or done, against what he could not be expected to have appreciated at that time about dam design. But whichever way opinions lean, it appears that he made fundamental errors in not taking account of the geology of his dam site.

The geology of failure

The location chosen for the St Francis Dam was remarkable in that its geology rendered it highly unsuitable through, not just one, but four factors (Fig. 5). The ground was so bad that it was difficult to determine which aspect of the geology was eventually responsible for the almost inevitable failure of a dam that also had inherent failings within its design. Indeed, the first commissions of enquiry came to the wrong conclusions over the geology, and it was only later that the full story of the dam failure emerged. The four factors were a fault, two rocks that each had their own weaknesses, and an ancient landslide.

The fault

Perhaps the most obvious potential hazard at the dam site was the San Francisquito Fault, which is aligned along the canyon with its outcrop beneath the dam within its western abutment. The fault was known, and mapped, but was recorded as inactive. However, all faults in the Los Angeles region demand respect due to the continuing activity of the nearby San Andreas Fault, with all its ramifications in adjacent ground. Just 30 km south of St Francis, one fault had been described as inactive prior to 1971 when it ruptured the ground surface by up to 1.5 metres and caused the magnitude 6.5 San Fernando earthquake. However, the San Francisquito Fault did not move beneath the dam in 1928, and seismic activity in the area was recorded as nil at the time of the dam's collapse.

Though the fault was inactive, it is distinguished by a band of gouge more than a metre wide, along with adjacent zones of sheared, brecciated and veined material. There is no record of any remedial treatment of this where exposed at outcrop across the dam site. When the reservoir was being filled, leakage was noted where the face of the dam crossed the fault, but this never increased to any significant flow. Though a weakness within the ground, it appears that the fault played little or no role in the failure of the dam.

Fig. 6. A pair of fist-sized specimens of the Vasquez Conglomerate were collected in 1979 from the hillside where the St Francis Dam had once stood. One specimen was then placed in a beaker of water for 15 minutes, before being drained and dried, by which time it had completely fallen apart.

The conglomerate

Forming most of the dam's western abutment, west of the fault, the red Oligocene Vasquez (or Sepse) Conglomerate is a seriously weak rock. With a dry unconfined compressive strength of about 1.5 MPa, it barely warrants description as a rock, and in a wet state was described as being so soft that it lost almost all rock characteristics. Much of its groundmass cement is clay that absorbs large amounts of water and thereby exhibits conspicuous swelling. Repeat surveys of the surviving wing wall on the western abutment indicated uplift of 5–15 cm, all or part of which may be ascribed to swelling of the conglomerate beneath it. This clay cement also accounted for the slaking of the material, whereby it virtually disintegrated when saturated in water (Fig. 6). Furthermore, the conglomerate was laced with micro-veins of gypsum,

Fig. 7. Post-collapse, road-side exposure of the Pelona Schist remaining beneath the scoured channel at almost exactly the position of the dam.

which dissolved rapidly in flowing water.

In the semi-arid environment of the San Francisquito Canyon, the conglomerate is and was an unremarkable feature where exposed in natural outcrops. But its response to inundation and saturation beneath and beside the reservoir was catastrophic. It is likely that the initial survival of the dam's western abutment was at least in part due to the support offered by the dam, though that only lasted while the dam was intact and in place. With no grout curtain in place, seepage was significant, and must have led to considerable piping failure within the conglomerate; this was confirmed by the observed surging in some leakage flows prior to the dam's collapse. Then, around 6 metres of conglomerate that had been beneath the dam was eroded away by the escaping floodwaters, and this was only during the small proportion of the hour-long outflow when the conglomerate was exposed.

It is easy to see why the early investigators of the disaster were quick to pin blame on the inadequacy of the conglomerate as a foundation material beneath its western abutment. But this weak rock was actually no more than a secondary factor, which was active only in a late stage of the dam's total collapse.

The schist

Two thirds of the dam stood on the Pelona Schist, east of the fault, across the valley floor and up the eastern abutment. This is another weak rock, but with weaknesses totally different from those of the conglomerate. Metamorphosed in California's late Cretaceous orogeny, it is a mica schist containing traces of talc. It has a conspicuous schistosity and is generally broken by numerous cross fractures. It was described by Stanley Dunham, the construction supervisor at the dam, as a hard rock, but this referred to the intact rock; his assessment was not of the rock mass strength, as it took no account of its major planar weaknesses; these are clearly visible in outcrops remaining at the dam site (Fig. 7). At one of the post-disaster inquiries, the Pelona Schist was described as having the shear strength of a pack of cards.

Furthermore, the orientation of this rock's schistosity, at the dam site, is almost exactly parallel to the valley side that formed the dam's east abutment. It was therefore parallel to the stresses imposed on the dam by the head of water confined within the reservoir. Its schistosity made the dam prone to wholesale sliding down the valley when the reservoir was filled. It was the geologist Bailey Willis and the engineer Carl Grunsky, working together, who were the first to recognize this inherent weakness of the dam, where the real cause of the dam's failure lay beneath its eastern abutment.

The old landslides

There was, however, more to the weakness of the eastern abutment than its pervasive schistosity. It appears to have been the geologist Willis who was the first to identify an old landslide within the hillside of schist, but there were probably multiple slip surfaces that had developed on the rock's schistosity, and the dam had been founded on these slices of slipped ground. It has been suggested that no geologist of the 1920s could have been expected to identify such ancient, inconspicuous, and apparently stable, landslides. But Willis did, perhaps just due to creditable lateral thinking. Subsequently, old landslides have been recognized almost all the way along the eastern slopes of the San Francisquito Canyon; those at the dam site were not exceptional. Analogy can be drawn with Mount St Helens, where lateral collapse was barely considered until it happened in 1980, but subsequent studies revealed laterally collapsed volcanoes all over the world.

Siting a dam on an old landslide is not necessarily hazardous. Hundreds of dams stand today on stable old landslides, where the slipped masses create convenient constrictions within a valley. Their stability is due in part to the inherent redundancy in dam design, whereby dams are built with factors of safety that far exceed what may be required at a site with perfect ground conditions. It is significant that the St Francis Dam had lost these margins of safety when its height had been raised during the construction stage and in all probability the toe of the dam had not even reached its design dimensions. At St Francis, multiple factors, some related to dam design, some to the site

Fig. 8. The remains of the St Francis Dam very soon after its almost total collapse. The largest blocks of concrete were not moved far by the floodwaters and lie beside the central, tombstone remnant that survived. The landslide scars are conspicuous on the eastern abutment, on the right. The western wing wall still stands along the crest of the natural rock spur left of the breached dam.

geology, were coming together and were heading only towards disaster.

Placing a dam on the lower part of a landslide should improve the stability of the slide, by providing load and support that opposes the ground movement. That would be the case in dry rock. But impounding a reservoir raises nearby groundwater levels, hence increasing uplift pressures. By effectively allowing the bedrock to partially float, these uplift forces greatly weaken the ground unless adequate drainage measures have been incorporated within the dam's design and construction. There were no drainage measures within the eastern abutment of the St Francis Dam.

Uplift forces beneath the dam

At the St Francis site, both the gravity dam and its underlying landslide improved their own stability by their own deadweights simply holding them in place. But that was before account was taken of the uplift pressure provided by the groundwater. This concept is well known to geotechnical engineers, who define effective stress as the structural load minus the pore-water pressure. The fine-grained, almost impermeable, nature of the Pelona Schist rendered pore water pressure insignificant, but its many fractures and planes of schistosity meant that the joint water pressure was of immense importance.

A deep cut-off trench with impermeable fill or an effective grout curtain should hinder reservoir water from reaching beneath a dam, and then drainage adits and relief wells should prevent accumulation of pressure from the reduced seepage of water that will inevitably reach into the ground. But the St Francis Dam had only a small number of relief drains beneath its central part.

Mulholland admitted that he had only been concerned to install drains where the bedrock was conspicuously fractured and fissured. He considered that the rock in both abutments was adequately homogeneous and required no drainage. This was his major mistake. His only excuse was that the understanding of uplift pressures was at that time in its infancy, and the real dangers where not fully appreciated. However other engineers were more aware, drains had been installed beneath dams from the late 1800s, the Austin Dam in Pennsylvania was known to have failed due to uplift pressures in 1911, and the following year saw a major publication gathering data on the subject. Grunsky and Willis were quick to recognize the role of uplift pressures very soon after the St Francis disaster, but Mulholland appears to have been well behind his peers in even a rudimentary understanding of uplift pressures in the 1920s.

Simply expressed, the water pressure within the St Francis Reservoir was transmitted, almost unhindered, to create hydrostatic uplift within the ground beneath its impounding dam. Shear strength within the schist was reduced, slip surfaces beneath the ancient landslides lost almost all resistance to renewed movement, and the groundwater provided partial flotation that almost enabled the massive concrete dam to float away. The St Francis Dam was doomed to failure.

The failure sequence

It took some years for the complex sequence of failure and collapse to be interpreted from the evidence that remained in and around the ruins of the St Francis Dam, and there is still debate over the details.

Failure started well before midnight on 12 March 1928, before the Silvey family found their road broken by a landslide in the schist slope of the eastern abutment, immediately upstream of the dam. Either this or a subsequent slide created a miniature tsunami in the reservoir, as debris was later found washed up on what had been the western shore. Much of this landslide was underwater.

Then just a few minutes before midnight, the critical event was a much larger landslide in the eastern abutment (Fig. 8). Details of this will never be known as the entire slide mass, along with some of the bedrock beneath it and a large part of the dam, were carried away by the ensuing flood through the massive breach in the dam. Although the sheer weight of the dam, braced against the opposite side of the valley, had effectively been holding any potential slide mass in place, the entire hillside had been destabilized from the joint water pressures generated by the adjacent reservoir. With three directions available for displacement to occur, it is difficult to determine the scale and sequence of different movements.

Support had been removed from the upstream side by the initial landslide whereby a slice of hillside slipped down into the reservoir leaving something of a void into which the dam and the ground immediately beneath it could therefore relax northwards.

Hydrostatic pressure in the reservoir continued to exert a force driving the dam and the hillside downstream and southwards. Resistance to this had been provided by the integrity of the intact rock within the hillside and the dam on top of it. But this integrity had been greatly diminished by the groundwater pressure that was forcing open all rock fractures, effectively changing the hillside into a loose pile of disaggregated blocks of rock.

The third available direction of movement was upwards, wherever the uplift forces of the joint water pressure could overcome the immediate loads imposed by the rock and dam. It has been suggested that the rock's fracture geometry allowed wedges of the bedrock to have been forced upwards by a combination of uplift pressures in the groundwater and lateral pressures generated by the hillside sliding downwards beneath the dam. These forces would have been resisted by the presence of an intact concrete dam, but the dam had already developed substantial shrinkage fractures, which left it able to deform as individual blocks were displaced by localized uplift stresses.

All or some of these initial movements rapidly evolved into a much larger landslide that saw displacement of the entire eastern abutment of the dam. Around half a million cubic metres of the hillside moved downwards and downstream, failing along pre-existing slip surfaces and along the pervasive schistosity. It carried the eastern half of the dam with it. Slide debris and scoured bedrock were washed far down the canyon by the escaping floodwaters. So was much of the dam, though the largest intact blocks were just undermined and strewn around the canyon floor closer to the dam site. This landslide was the key factor in the destruction of the St Francis Dam. Its scale could be appreciated after the event by its head scar extending up the hillside to a level 40 metres above that of the dam's crest (Fig. 8). However, part of that new head scar could have been secondary development after the toe of the slide had been removed by the floodwaters; the exact size of this destructive landslide cannot be determined, but it was clearly a major feature.

Fig. 9. Remains of the failed Banqiao Dam in eastern China.

Meanwhile, the central section of the dam was still standing, and subsequently became the tombstone remnant. Significantly, it was the only part of the dam with relief wells draining the ground beneath it. This central tombstone block was already isolated from the western part of the dam by the large contraction fractures within the concrete. With loss of support on its eastern side, it actually moved about 15 cm in that direction, as was revealed by a re-survey after the disaster. In addition, Carl Grunsky found a wooden ladder crushed inside a fracture at the base of the western upstream corner of the surviving tombstone block (Fig. 4); this indicated that the tombstone block had rotated a small amount towards the east, before settling back.

The western part of the dam stood on the inherently weak Vasquez Conglomerate, which had been further weakened as reservoir water seeped into it. That part of the dam had already been partially undermined by piping failures that must have been enlarging as the leakage flows increased. The dam was also weakened by shrinkage cracks within its concrete. Then the effect of the dam's central section moving or rotating towards the east was to relax the confining stress on the western part and further reduce its integrity. The net effect of these factors was the complete collapse of the western part of the dam. This occurred around 20 minutes after the failure of the dam's eastern sector. Surviving soil cover on the western abutment indicated that floodwater erosion only reached up to a level about 22 metres below the crest of the dam, as it was by then from a partially emptied reservoir.

Though the conglomerate was not the prime cause of the St Francis Dam failure, it did eventually prove to be an awful foundation material when it crumbled beneath the western sector of the dam.

The San Francisquito Canyon today

There is now little to see at the site of the failed dam, though its position is still recognizable by the spur of bedrock that formed the western abutment. The surviving tombstone fragment of the dam was destroyed with explosives in 1929, and the western wing wall was also demolished. The head scar of the eastern abutment landslide can be identified (Fig. 1), as can various scars eroded by the floodwaters, and blocks of concrete can be found in the downstream alluvium. A canyon road that went right through the dam site was re-routed after it was damaged by a flood in 2005, so few people now reach the site, even when they know about it.

The dam failure was however a national disaster, and legislation is now in the planning stage for the dam site to be designated as a National Memorial, and provided with appropriate visitor facilities.

Disaster among disasters

There are many parameters by which to assess dam disasters and thereby determine the worst in the world. The leader has to be the Banqiao Dam, in the Henan Province of eastern China. This earth dam was overtopped, scoured and destroyed after a major rainstorm event in 1975 (Fig. 9). Around 26 000 lives were lost in seven towns inundated by the escaping floodwaters, and another 145 000 died during the subsequent famine created by the lost farmland. Little information was released by the secretive government of that time, but the failure was clearly due to the dam having only a cost-saving five sluice gates and spillways, instead of the twelve that were needed.

America's worst dam failure, at Johnstown, Pennsylvania in 1889, was also due to rainstorm waters exceeding the capacity of inadequate spillways, though these were also partially choked with vegetation following poor maintenance. The dam was a rock-fill structure easily eroded when over-topped, and 2209 lives were lost when the flood hit Johnstown.

Of dams that failed largely because of their geologically unsuitable sites, the Malpasset Dam is notable. Its 1959 failure caused immense destruction and took more than 400 lives in southern France. It was a thin-walled, concrete, double-arched, cupola dam, and failure was due to hydrostatic uplift and distortion within ground that had an unusual and unforeseen structural configuration. A list of dams that failed due to their site geology could include the Las Cheurfas Dam built partially on poorly consolidated travertine in Algeria before collapsing in 1885, the Eigiau Dam in northern Wales that was built on permeable glacial till and failed in 1925, and the Teton Dam that collapsed over deeply fissured bedrock in Idaho, USA, in 1976; these were disasters, but were on a smaller scale.

The Vaiont disaster in northern Italy in 1963 was the worst to involve a dam and reservoir in the modern Western world. However, this was due to a massive landslide, which was destabilized by the reservoir's groundwater pressures and then landed in the reservoir, creating a huge wave that overtopped the dam and killed 2117 people in the valley below. The thin concrete cupola dam survived within its limestone gorge. Vaiont had a very good dam site, but was perhaps the world's worst reservoir site.

With so many facets to its appalling bedrock geology, it does seem justifiable to label the St Francis Dam as having the world's worst ground conditions.

Suggestions for further reading

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