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Oroville Spillway. Photo Courtesy of the California Department of Water Resources

OROVILLE SPILLWAY

Personal Reflections on a Global Dam Safety Incident

Michael F. Rogers

This paper presents the Oroville Dam Spillway incident, response, and recovery through the personal reflections of the author, as a member of a large, single-focus team with a goal to recover from a significant event and restore a functional service spillway in less than 8 months to a fully functional project within two years. Driven by the hydrologic cycle of northern California, the Oroville Spillway incident that started on February 7, 2017, needed to have a functional service spillway by November 1, 2017, to allow the project to pass flows, as needed, during the following flood control season. Restoration of complete project spillway capacity, including the Emergency Spillway, was needed within a two-year period. The author presents first-hand experiences from the initial global television emergency broadcast of a developing situation at Oroville Dam to construction in record-breaking heat, to repair two damaged spillways and restore the functioning capacity spillways at the tallest dam in the United States of America. The author worked with hundreds of engineers, scientists, managers and construction professionals on one of the greatest stories of recovery in the history of dam engineering.

My Story

The period from February 7 to November 1, 2017 will remain with me as the most challenging and rewarding eight months of my nearly 40-year professional career in dam engineering. The events surrounding the Oroville Spillway Incident of 2017 have reverberated around the world as the spillways at the tallest dam in the United States suffered significant damage leading to one of the largest dam safety evacuations in American history.

Beginning my career in dam safety in 1979, I've seen hundreds of dams around the world and worked with many dam owners and operators on their dam safety programs. Before February 2017, I was aware of Oroville Dam because of its prominence in the dam industry. The project is owned and operated by one of the most responsible water agencies in the world with a strong dam safety program: the California Department of Water Resources (DWR). The project is under the regulatory jurisdiction of the top national dam safety agency in the world, the Federal Energy Regulatory Commission (FERC), as well as the top state dam safety organization in America, the California Division of Safety of Dams (DSOD).

During a business trip to Australia, I saw a news broadcast that was a developing situation at Oroville Dam, and it was distressing. I felt a strong pain in my heart and in the pit in my stomach to consider that one of the critical pieces of infrastructure for water and power in the United States was in trouble. A few days later I was further shocked to see breaking news that evacuations were underway. I knew that I had to help.

I have worked on dam safety projects in California since moving from my hometown of Chicago in 1995. I joined the Association of State Dam Safety Officials (ASDSO) a year later in 1996 and would later become President of the United States Society on Dams (USSD), as well as actively participating in the International Commission on Large Dams (ICOLD). As a result, I have a full appreciation of the importance of dams and hydropower plants to meet critical infrastructure needs of the world's population for clean water and renewable power. I also understand the risks posed by structures that retain billions of gallons of water.

After watching the initial broadcast in Australia, I made a call to an old friend, David Gutierrez, the former Chief of the California Division of Safety of Dams (DSOD), California's dam safety regulating agency. Unsurprised at being directed to voicemail, due to the nature of the incident, I left a message, offering my help on whatever scale was necessary, including support from USSD and ICOLD during this emergency. My company, Stantec, had already supported DWR in the initial hours of the incident, monitoring the situation around the main spillway. I jumped on a plane back to California, hoping that the worst would not come to pass, and the engineers could stem the threat.

Landing in Los Angeles the next day, I was relieved to find out the emergency had been avoided – at least for the time being, but the situation was still uncertain as releases of 2831 m^3/s (100,000 cubic feet per second, cfs) of water continued to erode the main spillway's foundation. While walking out of the international terminal, my phone rang – it was Dave! He reported that he was helping DWR with the emergency response and that he needed help from me on two things:

1. First, DWR wanted ASDSO and USSD to identify highly experienced and reputable individuals in the dams and hydropower industry to serve on an independent forensics review board.

2. Second, he asked me if I was interested in coming to Sacramento to be part of a growing DWR team that had started to look at the recovery process and rehabilitation design.

Of course, I agreed to both requests, and we talked about roller-compacted concrete (RCC) that Stantec had used to build dams in San Diego. Dave was certain that RCC would be needed somewhere to replace the nearly one million cubic yards of rock and soil lost in the main spillway foundation. I told him that I would contact the then-USSD President, Dean Durkee, and that Dean could begin that process with ASDSO to identify suitable candidates for a forensics review board. I also told Dave that I would travel to Sacramento as soon as DWR needed me.

The following week, I got a call from Ted Craddock, DWR Project Manager for the Oroville Spillways Recovery, asking me to come to Sacramento. I arrived in Sacramento on February 28, 2017 not knowing what my role or responsibilities would be. I don't think anyone knew what lay ahead of us or the challenges that we would face. When I arrived at the Oroville main recovery design center, located on the 16th Floor of the DWR office in downtown Sacramento, everyone knew that we were working the problem with a common mission.

"Restore the spillway capacity to ensure public safety in advance of the 2017-2018 flood season."

The Dam

Oroville Dam is located on the Feather River in northern California. At 234.7 m (770-ft) tall, it is the tallest dam in the United States. With its 4.3 billion m^3 (3.5 million acre-feet) of storage, Lake Oroville is also the second largest reservoir in California, supplying water to cities and farmland as far south as San Diego.

The Oroville project is the flagship of the State Water Project (SWP), which is owned and operated by the State of California, Department of Water Resources (DWR). The original mission of the project was originally conceived as follows;

"Oroville Dam and its appurtenances comprise a multipurpose project encompassing water conservation, power generation, flood control, recreation, and fish and wildlife enhancement. The Lake stores winter and spring run-off, which is released into the Feather River as necessary, to supply project needs. The (United States) Federal Government shared in the cost of the Dam, which provides 750,000 acre-feet of flood control storage. The 15,805-acre surface of the Lake with a 167-mile shoreline provides water-oriented recreational opportunities." (State of California Department of Water Resources, 1974).

The Oroville facility design was started in 1953 with construction completed in 1968. The major structures consist of a main earthfill dam that is 235 m (770 ft) high and a crest length of 2110 m (6920 ft); two saddle dams; two spillways; and the hydropower generating station (Hyatt Powerplant) with a low-level River Valve Outlet.

Figure 1. Flood Control Outlet Structure and Emergency Spillway

The project's two spillways include the Flood Control Outlet (FCO) structure and an Emergency Spillway as shown in Figure 1. The function of the FCO structure is to provide regular releases to support the flood protection mission of the project that protects the downstream communities. The FCO structure is designed to release 8283 m^3/s (296,000 ft^3/s) during the probable maximum flood (PMF), although actual owner operational plans limit the FCO discharges to about 4247 m^3/s (150,000 cfs) due to the downstream levee capacity. The FCO spillway has three main structural components as shown in Figure 1: a gated Flood Control Outlet, a 1310 m (4300 ft) long spillway chute, and an energy dissipater ("dentates"). The chute is a rectangular, reinforced-concrete open-channel chute that closely follows the original natural terrain. FCO discharges enter the Feather River.

The uncontrolled Emergency Spillway was designed to discharge extreme floods to prevent overtopping of the main embankment dam. The Emergency Spillway consists of two sections; an ogee section and a low-height sill weir adjacent to the public-access parking lot. The ogee section consists of multiple concrete monoliths founded on bedrock with varying heights. The tallest monolith has a height of about 16 m (50 ft) from the original ground, and excavated into a shear zone down to rock for a total structural height of 90 ft. The Emergency Spillway was sized to release a maximum flow of 10,506 m^3/s (371,016 cfs) when the reservoir elevation is at 297.5 m (917 ft) enabling the combined project to pass the PMF.

The Incident

The 2016-2017 winter storms brought record breaking precipitation to the Northern California, including the Feather River watershed that feeds Lake Oroville. Following several years of record drought, the snow and rain precipitation was welcomed to a parched California experiencing record-low levels of storage in its lakes. California water agencies watched with great anticipation as bountiful precipitation fell across northern California and, in a single season, began filling the thirsty reservoirs that had taken more than a decade to nearly drain.

For Lake Oroville, it was almost "too much of a good thing" as the lake level rose high enough that flow releases through the FCO became necessary to control the rapid rise in lake level. The FCO spillway has operated in about 50% of the yearly flood seasons since the project came into service in 1968. In early February 2017, DWR followed the flood control plan and started releasing from the FCO. During this routine spillway operation on Tuesday, February 7th, DWR staff observed a disturbance in the flow regime down the spillway chute, including the appearance of dark, murky water in the lower left side of the 914-meter (3000-ft) long spillway. The FCO spillway was damaged, which would eventually result in the loss of approximately 427 m (1400 ft) of the lower concrete chute, including the scour of more than 1.2 million m^3 (1.6 million yd^3) of soil and rock materials.

DWR managers and engineers would struggle with additional damage to the FCO spillway for days attempting to balance the release of flows necessary to control the lake level while at the same time trying not to damage the spillway any more than necessary. Under steady runoff from melting snowpack and multiple storm inflows, the lake rose in a controlled manner, with outflow through the power plant and FCO.

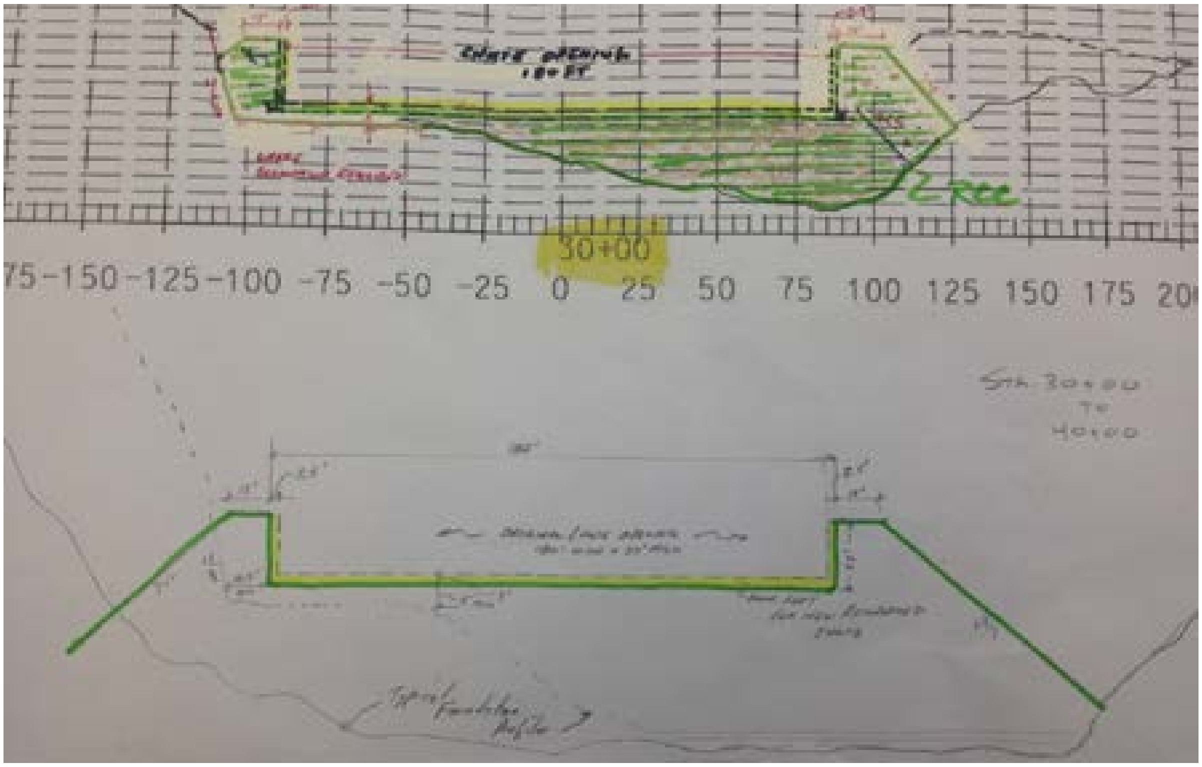

Figure 2. Initial Sketch of RCC for "Fill the Hole" Solution

On the morning of February 11th, inflow filled the reservoir to capacity and water flowed over the Emergency Spillway for the first time since the project was completed in 1968. A simple concrete ogee weir varying in height from 1- to 16-m (3- to 50-ft), the Emergency Spillway discharged onto the hillside towards the Feather River below. Erosion and scour caused by the overflow began washing down the hill creating deep crevices in the hillside and moving debris into the Feather River below.

After about 24 hours of overflow at the Emergency Spillway, concern was raised to an area near the middle of the overflow weir where headcutting was moving back towards the ogee structure. No one could know when or if this erosion would stop. In a worst-case scenario, the headcutting could lead to undermining the ogee.

On February 12, out of an abundance of caution, local authorities decided to order the evacuation of about 188,000 persons from the immediate downstream communities. A few days later, after the lake had receded several feet and water no longer flowed over the Emergency Spillway, authorities would cancel the evacuation and residents would return home. Soon after the incident happened, DWR managers started critical planning to restore the project. The recovery was just beginning.

Recovery and RCC

Immediately following the incident, DWR assembled the Oroville Emergency Recovery (OER) Spillway Task Force headquartered out of their downtown Sacramento office. The OER Spillway Task Force was composed of experienced engineers from DWR's Division of Engineering, Project Operations Office, and other units from within DWR. DWR also contracted with knowledgeable and experienced engineering professionals from a variety of sources, including an independent Board of Consultants who oversaw the reconstruction of the spillways from start to finish.

Upon arriving in Sacramento that first week in March 2017, I was struck by the number and quality of professional dam engineers, mostly from California that were coming together. Although I had never worked for DWR, I immediately recognized their strong leaders, especially Ted Craddock, Project Manager and Dale Brown, Project Engineer. I also immediately recognized key regulators from the State of California, Division of Safety of Dams (DSOD) and the Federal Energy Regulatory Authority (FERC), mostly from my previous work in California as well as the professional dam societies.

On one of the first days, I recall sitting in a conference room, watching spectacular drone video of the service spillway continuing to pass 2832 m^3/s (100,000 cfs). I watched the 50-year-old spillway tearing itself apart at the foundation, wondering how we could ever fix it by November. While the room was overcrowded and a bit stifling, there was no lack of enthusiasm from the team to get started. While a portion of the team started to investigate the original design to identify possible causes of the damage to be sure that the new design addressed any issues associated with the cause of the incident, the group I was in started to consider options for repair and recovery.

The Task Force developed a wide-ranging list of potential recovery approaches for both the FCO Spillway chute and

Emergency Spillway. For the FCO Spillway chute, we were faced with a spillway chute that was abruptly terminated by the foundation erosion and chute loss at about the mid-point of its length, leaving an approximate 30.5 m (100-ft) deep hole across the full width of the chute and extending beyond with extensive and irregular areas of exposed rock. Some portions of the lower spillway remained, though they were torn and cracked. Large automobile-sized chunks of concrete were strewn about leaving twisted rebar and missing pieces of what was once one of the largest spillways in America.

My group focused on what to do with the large holes carved into the foundation by more than a million horsepower of pure water energy. Though a cadre of concepts came out of our brainstorming sessions, including unlikely options such as building a water bridge across the divide, or using the hole as a new plunge pool, the team quickly coalesced around an option to use roller-compacted concrete (RCC) — placed in 30-mm (1-ft) layers, one on top of each other. RCC could be placed fast and it could be developed using on-site materials, including the very rock eroded out of the foundation and deposited into the Feather River. It was also flexible enough to infill the jagged and rough exposed rock foundation. The RCC "Fill-the-Hole" solution as shown in Figure 2 was born.

Figure 3. RCC Side Slopes formed at 1:1

Left: Figure 4. Rough RCC Chute Forming

Right: Figure 5. General construction of the RCC chute (Courtesy of DWR)

The design was elegant, yet simple in its approach to fill only the area necessary to support a new spillway. The decision was made to build the FCO back to its original dimensions since this concept offered the least unknown risks as the geometry had already been confirmed by the original designers for hydraulic performance.

The RCC design offered two key challenges. First, we didn't have enough time to form the outside slopes, which would typically be done for an RCC dam. At the Olivenhain RCC Dam in San Diego completed in 2004, the downstream side of a portion of the dam was left unformed at a 1:1 slope. I took that experience, knowing that the RCC could stand on the natural angle of repose, and used it for the design of the left and right sides of what would come to be a new RCC chute. The actual construction of this 1:1 side slope is shown in Figure 3, which the Contractor (Kiewit Infrastructure) constructed using a custom fabricated steel plate on a vibrating head that compacted and sealed the 1:1 slope.

The biggest challenge, however, was creating a rectangular chute with vertical side walls on a 4H:1V chute slope. RCC is typically placed in 30 mm (1-ft) thick lifts and had never been used for such an application as steep, smooth sloping spillway chute. We came up with an approach to form a rough chute surface using horizontal placements with a flat plate vibrator to seal the 4:1 slope as shown in Figure 4. The general construction of the RCC chute is shown in Figure 5.

The inside vertical side walls posed a significant design challenge as forming such large vertical walls on a 4:1 chute slope had never been done before using RCC. The performance specification left it open to the contractor to develop an innovative and cost-effective solution. In the end, the contractor used a methodology typically used for stabilized earth walls developed by Hilfiker ("a Hilfiker basket"), which worked very well once the inside wall was covered with shotcrete as shown in Figures 6 and 7.

Once the inside walls were complete, all that remained was a final chute surface. Since the temporary chute would be available for the 2017-2018 winter flood season, we wanted to have a strong surface to resist the erosive forces of high flows down the chute. The basic foundation replacement RCC material was designed for 3500 psi at one year, but the top surface needed to have a strength of 3500 psi at 28 days of age to be available on December 1. A 30-mm (1-ft) thick "enriched" RCC layer was designed with a higher cement content to meet the early strength requirement. The enriched RCC was installed as an overlay to the basic RCC material as shown in Figure 8. This approach of placing RCC on a steep 4:1 slope had never been attempted. The contractor worked with DWR and the engineer to come up with an innovative approach using standard RCC placement equipment along with specialized Marooka trucks with tracks and a rotating cab that perfectly suited work on the steep chute slope.

It should be noted that the design of this RCC chute was considered a temporary solution. DWR wanted to have a new reinforced concrete chute for the entire FCO, but there was only enough time available in the 2017 season to build the RCC foundation replacement. The new reinforced overlying chute would be completed in the 2018 construction season with removal of the outside RCC gravity walls and installation of the final reinforced concrete chute and walls.

The completed FCO Spillway chute portion composed of RCC is shown in Figure 9.

A Global Dam Safety Incident

The 2017 Oroville Dam Spillway Incident was one of the most significant dam safety occurrences in the United States in many years. As the tallest dam in the United States and the keystone of California's State Water Project, Oroville Dam and Lake Oroville stand as a steadfast monument to water resource development in the 20th Century. The Oroville Dam Spillway Incident has provided a testimony to the dedication

Above: Figure 6. Hilfiker Basket Forming of Vertical RCC Chute Walls

Right: Figure 7. Shotcrete at Inside of Hilfiker Walls

Figure 8. Final Placement of Enriched RCC on Steep 4:1 Chute Slope

Figure 9. Completed RCC Portion of the FCO Chute (Photo from DWR, November 2017)

of emergency response and dam safety professionals who came together to meet the challenges of a rapidly changing situation and to assure the safety of the Oroville Dam and the public living downstream. Starting in Oroville, California, this incident has impacted the dam safety profession around the world as the details of the incident, response, and recovery are articulated and understood.

The aging of dams in the United States and around the world is a growing risk facing owners, engineers and regulators. Modern dam safety methods utilizing risk informed decision making and potential failure modes analyses are increasingly identifying our aging structures and mechanical operational systems (i.e. gates, spillways, outlets, etc.) as necessary critical components of dam safety.

Constant vigilance and strong commitment to structured dam safety programs are required in order to be responsible for the public safety. Any dam incident should be a matter of the gravest concern to dam professionals. Although not the situation at the Oroville Dam, uncontrolled breaching of a dam can have catastrophic consequences, resulting in loss of life and injuries, as well as widespread damage to property, infrastructure and the environment.

Dams are unique in personality, character, purpose and risk. Each dam in the world has a name – Aswan, Three Gorges, Hoover, and so forth. Each is recognizable and each uniquely serves our world, but they also each pose unique risks. As a profession, we remain ever vigilant to our responsibilities for our aging infrastructure to sustain these important and unique structures. Dam Safety has been and must always remain a core value of our profession.

As Engineers, we understand that there will always be risk when we undertake endeavors to create important infrastructure that serves our fellow citizens. Those citizens look to us as Engineers to help improve their lives through the application of technology, so we must always address the risk associated with that technology in a responsible manner. One of the best ways to address that risk is to educate and train ourselves as to the current state of the practice – the art of dams and hydropower – and the lessons learned from our colleagues around the world.

Thanks to DWR, the OER Spillway Task Force and the professional dam societies of ASDSO, USSD and ICOLD, the safety of existing and future dams will be better thanks to the lessons learned in the response, recovery and forensic investigations that have been shared around the world.

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Rogers is a vice president and global practice leader for dams for Stantec – an international consulting engineering firm. He has 38 years of broad professional experience, specializing in the design and construction of dams and hydroelectric projects. He has specialized his career in dam safety, including the design and construction of roller-compacted concrete dams.

Rogers serves as President of the International Commission on Large Dams (ICOLD, 2018-2021). Previously, he served as ICOLD Vice President (2015-2018) and Chairman of the Technical Committee on Concrete Dams. He also served as President of the United States Society on Dams (USSD, 2010-2013) and Chairman of the USSD Technical Committee on Concrete Dams.

Rogers has a Bachelor of Science degree in civil engineering from the Illinois Institute of Technology and a Master of Science degree in civil engineering from the University of Minnesota. He is a registered professional civil engineer in the United States (IL, CA, AK, TX, CO) and the Province of British Columbia, Canada.

Association of State
Dam Safety Officials

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Who is ASDSO?

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