Saving the Guajataca Dam Spillway: Emergency Actions and Interim Risk Reduction Measures (IRRMs)

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Extended Abstract

Background

Guajataca Dam is located in the northwest quadrant of Puerto Rico and is owned and operated by Puerto Rico Electric Power Authority (PREPA). The dam system consists of an earthen embankment (approximately 1,000 ft long by 120 ft high), with an intake tower and outlet tunnel along the right abutment, and an uncontrolled concrete spillway on the left abutment. The approximately 30,000 cfs capacity spillway has a semicircular concrete weir, with 9 inch concrete slabs in the upper half or so, and 4 to 6 six inch thick lightly reinforced slabs in the lower half (pre-Maria). The original dam was designed and built approximately between 1923 and 1928, with significant modifications performed in the early 1980s. The outlet works discharge water to the west to a water supply canal, as well as to the Guajataca River to the northwest, with an estimated system discharge capacity of about 650 cfs.

The dam was designed and built primarily for irrigation and water supply purposes by the Isabela Irrigation Service (IIS), a state or municipal agency no longer in existence. The meager documentation available, dating back to a 1918 War Department report, indicates that two types of dams were initially considered at the time of inception, a concrete dam with incorporated spillway, and an earthen dam with a spillway on its left abutment. A 1923 US Bureau of Reclamation report indicated that the concrete dam option was dropped over concerns for potential movement and/or foundation conditions, based on limited geological information, and both reports recommended additional geologic studies. The first geologic mapping of Puerto Rico (by USGS) was not published until the 1960s and has been updated only once since. Today we know that the valley in which the dam was founded is landslide territory. From its beginning, there were troubles with movement of the dam as it was being built, as well as issues with cracking of the concrete spillway slabs, leading to design changes and retrofits over its 90+ years of life.

The dam was built using the semi-hydraulic method of construction, an apparent popular practice at the time. While the scant documentation and a few photos indicate that the dam foundation may have been cleaned to some degree, the spillway is founded in what is now understood to be an actively creeping landslide mass. This creeping landslide mass, although observed and recorded since at least the 1950s, may not have been fully studied until a 2002 work by the USBR and, more recently, the Corps of Engineers' (USACE) involvement following Hurricane Maria in September 2017.

The largest of the dam and spillway retrofits occurred in the late 1970s to the early 1980s, not without incident. The initial modification work, which involved construction of a drainage system on the downstream slope, a berm and upgrades to the water distribution system / outlet works quickly resulted in modifications to the berm, backfilling of the river channel downstream of the dam (it runs nearly parallel to it), construction of a buttress and reconstruction of the upper half of the concrete spillway. But, as Galileo may have said, yet the earth moves; instrumentation records (from surface movement points, piezometers and inclinometers) indicate that the left abutment including the spillway and portions of the dam are still experiencing slow creep movements toward the river valley and in a downstream direction. The 1980's modifications done may have slowed down movement, and even shifted its direction based on field recovered samples, resulting in rotational movement (along its

centerline axis). The movement over the years resulted in significant cracks along the spillway, providing a direct path for flows to get under the concrete slabs, potentially jeopardizing their stability.

Incident

On September 20, 2017, Hurricane Maria, one of the strongest tropical cyclones in history in the Caribbean basin, struck the island of Puerto Rico dead on, causing anywhere between $43B and $139B in damage, depending on estimates. Every corner of the island (US Territory) was affected, especially their power grid and water supply systems, both primarily administered by PREPA. The island, approximately the size of Connecticut, has about 40 dams. Guajataca Dam, in the northwest region of the island, was most impacted by this historical hurricane.

On September 22nd, news media reported significant damage to the emergency spillway. Soon thereafter, the Corps of Engineers was called in to support the dam owner, PREPA, to address the emergency. Since droughts just a few years earlier, Guajataca's water supply lake had been maintained within 3 to 6 feet of the spillway weir crest. Hurricane Irma had passed by just a few weeks earlier, raising the lake level to within inches of the weir crest. As Hurricane Maria approached, efforts were made to lower the lake, but the USGS-reported 7 inches of precipitation (in 48 hours) within the basin overwhelmed the system. The upstream and downstream gages were wiped away early during the storm, but post-storm water levels were estimated at about 4 ft depth over the weir crest and may have lasted for over 24 hours based on video and pictorial references (no gages available). At its peak, flows may have reached 10-15,000 cfs, largest on record, and flow velocities of over 30 plus ft per second, displacing large riprap placed years earlier at the toe of the concrete chute. The displacement of the riprap and the presence of minor erosion caused by previous flows over the spillway opened a window for further scour of the foundation materials. As the fill material (clay/sand/gravel mixture) at the end of the spillway eroded, the evidence suggests that the first spillway slab was undercut and plunged. The continued scour at the toe of each remaining slab had a dominoes effect, with sliding and plunging of subsequent concrete slabs; as the slabs shifted or separated from each other, the rushing water most likely overcame their internal drains, possibly creating buoyancy effects, permitting further sliding of the un-anchored thin slabs and further exacerbating the situation. The limited evidence left suggests that by the end of the first 24-48 hours, the erosion had left a scour hole approximately 50 ft deep, over 200 ft wide and over 400 ft in length, with nearly half of the 700 ft concrete spillway lost, in addition to the loss of the water supply line that siphoned under the spillway. Anywhere between 250,000 to 325,000 people in the northwestern part of the island were left without water, for weeks, because of this single event.

Aftermath

Dam safety Corps of Engineers personnel were soon on site and with support from PREPA (dam owner) and its onsite contractor, Del Valle Group, S.P., started emergency response efforts to stabilize the site and prevent further back-cutting erosion of the remaining spillway. The Corps team included geotechnical, structural, and hydraulic engineers from Jacksonville District and the Risk Management Center in Denver, who guided the stabilization efforts with air support from US Navy, Marines, and Army helicopters. Once the immediate emergency was contained, Interim Risk Reduction Measures (IRRMs) were planned, designed and constructed in about 1.5 years to bring the spillway to a serviceable condition. The following section of this extended abstract discusses and presents the IRRMs that were successfully executed during very challenging circumstances.

The emergency stabilization plan can be summarized in four primary tasks: 1) protect the remaining slabs, and primarily, the foundation of the downstream-most slab from erosion, 2) create a plunge pool to reduce flow velocities in the scoured channel area (emergency response), 3) stabilize the channel side slopes with and 4) re-establish water supply. The IRRMs basically consisted of the temporary reconstruction of the spillway to bring it back in service, including its water supply siphon line (under the spillway). In general terms, this work involved: 1) backfilling the scour hole, 2) constructing a plunge pool at the toe of the spillway, 3) anchoring of the remaining spillway slabs, and 4) construction of 18" thick concrete slabs overlying the remaining anchored slabs.

Task one of the emergency actions led to the placement of riprap and concrete debris at the toe of the remaining spillway, and the airborne operations, which consisted of the placement of just over 500 jersey barriers at the toe of the downstream-most remaining slab. This work and task 2, which included placement of approximately 1330 super sacks (filled with sandy gravel (quarry spoils)) just beyond the barriers to create a plunge pool, were carried out over three weeks or so with helicopters from the military services aiding this civil works emergency mission. Following this, slopes and small landslides were cut back to safer angles as part of Task 3. Simultaneously, ten 18-inch diameter pumps were procured and which after repairs to the distribution canal beyond the dam site, provided up to 95 cfs of flow to the distribution canal for supply water to the western side of the island, and around 20-25 cfs to the river, both actions aiding in lowering the lake level.

While fill placement was ongoing, IRRM work commenced. The design and construction included the reconstruction of the municipal water supply line passing under the spillway, which was in the critical path, receiving zealous attention, while fill placement elsewhere occurred. To protect this 42 inch siphon, its foundation materials were excavated to the top of the basal hard clay and replaced with grouted granitic riprap, with construction of a 6.5 feet (2m) deep key-in into the hard clay layer. In addition, an internal drain system immediately upstream and underneath the siphon was engineered to collect and transport any seepage or springs that may otherwise have put pressure on the reinforced concrete-encased siphon. Upon its completion, backfilling with grouted riprap continued until the target spillway floor elevation was reached.

Meanwhile, the scour hole area was expeditiously backfilled with well-graded rock fill ranging in size from rock dust to 18 inches maximum size particles and topped off with at least 6.5 ft (2m) of grouted riprap, typically 18-24 inches in size, which reformed the surface of the temporary spillway channel. The IRRMs also included construction of a plunge pool or stilling basin to provide energy dissipation during most flows. The remaining upper portion of the concrete spillway, which was only slightly damaged during Hurricane Maria, also received some attention; the cracks were backfilled with flowable fill, and nearly 600 grouted anchors were installed, consisting of single No. 7 & 9 bar, 4 inch diameter grouted anchors approximately 5-6 meters long. These were installed along the base slabs and portion of the side slabs composing the trapezoidal shaped spillway. After anchoring, the slabs were overlaid by a new 18 inch concrete chute.

Local residents benefited from the hard work of numerous entities who collaborated closely. From beginning to end, the design and construction period for the IRRMs was an expedited 1.5 years. Over 50 individuals from the Corps within its engineering, project management, construction, and contracting divisions accomplished the mission in spite of immense challenges. Excellent support was provided by PREPA's dam safety office, the dam's engineers and operations management, and its field personnel, along with FEMA and other individuals, and the Contractor, whose staff worked diligently.