PUBLIC SAFETY AT LOW-HEAD DAMS

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Abstract

Low-head dams across the United States, from New Jersey to Oregon, continue to needlessly take lives as victims are lured into the seemingly placid water below the dams. Yet, the submerged hydraulic jumps and resulting reverse rollers can be readily analyzed, and various types of dam retrofits can provide cures.

Low-head dams are often called "drowning machines." The submerged hydraulic jump is an energy-dissipating underwater jet that can often maintain enough kinetic energy to cause it to travel downstream and then rise to the surface as a "boil," with a portion of the water of the jet flowing back toward the dam. This represents the reverse roller. Hydraulic engineering analyses can define the approximate location of the boil and the likely velocity of the reverse flow. It is this reverse flow that carries a victim back to the base of the dam, where he or she is trapped in a vicious cycle.

Six case studies of drowning are described, the related adverse hydraulics are presented, and suitable dam retrofits are outlined. Included in the case studies are a grade control structure (GCS) on the Salt River in the Phoenix area, a fish ladder in Oregon, a water supply structure on the Raritan River in New Jersey, a low-head dam owned by a water supply agency in West Virginia, a Clear Creek drop structures in Adams County, Colorado, and a U.S. Army Corps of Engineers (USACE) dam in Denver. Tragic loss of life at each of the structures could have been prevented had the design engineer and owner exercised a reasonable standard of care and had been familiar with the related published literature.

Introduction

Hydraulic jumps are well known to most civil engineers, particularly hydraulic engineers, as a method for dissipating excess kinetic energy under controlled conditions at the base of spillways or GCS (Forster 1950). Controlled conditions generally incorporate the use of a stilling basin; however, matching the tailwater and conjugate depth curves over a range of operational discharges is a necessary and important design step that, if inadequately investigated, will cause the jump to be swept out of the basin, backed up against the spillway chute (or GCS face), drowned out, or submerged (Chow 1959). It is the latter condition that is the subject of this paper, because a submerged hydraulic jump is often associated with a reverse roller where there is an upstream current. When the submerged hydraulic jump occurs below a low-head dam or GCS and a reverse flow occurs, the dam may be characterized as a drowning machine and, therefore, a public hazard (Wright 1995).

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Submerged Hydraulic Jump

The reverse roller, often resulting from submerged hydraulic jumps, was analyzed by Rajaatman (1965) in his American Society of Civil Engineers (ASCE) paper entitled *Submerged Hydraulic Jump,* where he described the "backward flow" phenomena and provided the results of laboratory experiments and methods for computing the velocity distribution of the reverse flow. Investigators Cotton (1995) and Leutheuser (1991) have further defined the reverse roller and its hydraulic character in a user-friendly manner for practicing engineers so that GCS and low-head dam designs need not create public hazards. The published literature is rich on hydraulic jumps, submerged hydraulic jumps, and reverse rollers.

For practical purposes, the civil engineer can envision a submerged hydraulic jump as a super-critical-flow jet plunging into quiescent water and maintaining its character as it travels downward, and then horizontally, along the bed surface. The jet gradually expands as the jet loses momentum due to its friction interface with the quiescent water. Equal forces are applied to the surrounding water, causing the surrounding water to tend to flow along with the higher velocity jet. As a result, the conditions are ripe for a backward flow above the jet. As the jet diffuses, it tends to rise upward likely because of entrained air. If the jet has maintained enough kinetic energy by the time it reaches the water surface, the kinetic energy is partially converted to potential energy, as represented by a slightly higher water surface at a location identified as the boil. If the water surface of the boil is higher than the water surface upstream, a reverse slope is formed that can be measured; such a reverse slope will cause a reverse flow, that when coupled with the drag exerted by the submerged jet, will cause a reverse roller to be formed.

Public Hazards

Low-head dams and GCS installations often range from about 5 to 10 feet high (bed to crest), sometimes operating with a moderately high tailwater elevation so that the hydraulic drop over the structure may be only a few feet with a smooth streamline over the crest and relatively placid appearing water below the structures, except for bubbles rising to the surface. A reverse flow velocity in this scenario may be so modest as to go unnoticed by recreational boaters, fisherman, or swimmer. Under these conditions, one might see tree limbs or tires bobbing at the base of the dam. The upstream velocity from the boil area to the face of the dam, even if only a few feet per second (fps), can form a trap that is often fatal to even strong swimmers.

With a lower tailwater level, the plunging jet will not be operating in a deep enough water environment to be able to commence the rotational flow conditions. If the tailwater is low enough, of course, the jet will transform into a normal hydraulic jump with a standing wave that is not hazardous in the same manner as a reverse roller.

Case Studies

Six case studies are described below. Each study represents a condition where the in-river structure was a drowning machine, as defined by Leutheuser (1991), while at the same time, in appearance, representing a rather placid and reasonable looking water feature compatible with water-based recreational activities.

Salt River at Tempe, Arizona

As a result of a highway project and improvements to the channel of the Salt River through Tempe, Arizona, GCSs in a series were under construction in the 1991–1993 period to control bed erosion. One GCS, No. 5, immediately downstream of the McClintock Bridge, was built of compacted soil cement 378 feet with a height of 5 feet, with a stilling pool 64 feet long and 4 feet deep, as illustrated in Figure 1.

On a pleasant Sunday afternoon on March 25, 1993, four local men took a canoe ride: two men in each canoe. The Salt River had been flowing for several months. On this date, the flow was 4,090 cubic feet per second (cfs) with 3,500 cfs going over the partially completed GCS section, resulting in a unit discharge ranging from 9 to 17 cfs per foot of GCS length, the range being due to the crest sloping toward the river center.

From upstream, canoeists' view of the GCS water would have appeared rather tranquil, and the four canoeists proceeded over the crest. Although the first canoe passed over the structure successfully, the second canoe capsized, and its two occupants were drowned.

At the likely location where the two canoes passed over the GCS, the vertical hydraulic drop on March 25, 1993 was only 4 feet. The velocity of flow at the crest was about 9 fps, with a depth of 1.4 feet. Where the overflow jet met the downstream water surface, it had an estimated velocity of 17 fps, plunging into the stilling basin to create a submerged hydraulic jump. Kinetic energy in the submerged jet was maintained until the jet rose to the surface downstream of the crest where a boil was formed. Some of the jet flowed downstream and some flowed upstream, back towards the GCS face and the plunging jet. Based on photographs and video records, the water flow character downstream of the GCS appeared somewhat smooth and tranquil, but bubbles rising to the surface and some debris bobbing in the water at the downstream face of the GCS told another story; this was a drowning machine.

On March 14 of the previous year, a young man was drowned at the same location while attempting to retrieve his dog that had become trapped in the reverse roller. Later, after the 1993 incident, the Tempe Fire Rescue Squad practiced recovery techniques at the subject GCS. Official video of the practice exercise demonstrated the danger and drowning hazards posed to rescue personnel, even with ropes and full water safety equipment.

Swackhammer Dam Fish Ladder at Union, Oregon

The tragic drowning of a mother and daughter near Union, Oregon on June 30, 1996 was caused by one or more reverse rollers, where the hydraulic drop from one set of weirs to another was only 1.3 feet. It was here on Catherine Creek that the old Swackhammer Dam was replaced with a modern drop structure to facilitate fish passage, as shown in Figure 2. The U.S. Bureau of Fisheries and the State of Oregon designed the structure; both neglected to consider hazards created by submerged hydraulic jump reverse rollers to the general public.

The total hydraulic drop across the new structure was only 2.9 feet at 160 cfs, the vertical drop being distributed over three concrete weirs in series. The flow velocity at each weir crest was 4.3 fps, while the jet velocity impinging on the lower water surface was 9 fps. Water depth in the pools was 5.6 feet, and the reverse roller was about 10 feet long. A relatively slow reverse current of 2.0 fps provided the hydraulic trap for the two victims.

While the Oregon stream classification for Catherine Creek included fishing, recreation, and water contact recreation, the new Swackhammer Dam was designed to provide for adequate fish passage and water diversion purposes, but without consideration for public safety.

Island Farm Weir, Bridgewater, New Jersey

Completion of the Island Farm Weir on the Raritan River occurred in October 1995. The Raritan River was classified by New Jersey as being suitable for recreational uses, including boating. Nevertheless, neither the owner, engineer, or the local government was inclined to install warning signs on the landings for boaters. Six months later, on April 12, 1996, a recreational canoeist paddled over the dam crest and was drowned in the recirculation flow of the reverse roller, while attempting to rescue his comrade, who had capsized. The river discharge on this date was 2,000 cfs over the 200-foot-long dam that was 8 feet high. The unit discharge was 10 cfs per foot. Following a total of four drownings, the dam was retrofitted to satisfactorily eliminate the reverse roller characteristic.

Even though the dam was 8 feet high, the hydraulic drop across the dam, from upstream to downstream, was only 2.8 feet, due to the stilling basin depth and the high tailwater conditions. At the crest of the dam, the velocity was 7 fps, with a depth of 1.55 feet. Meanwhile, where the overflow jet met the downstream pool, the velocity had increased to over 13 fps, with a Froude number of 2.8.

Figure 3 illustrates the dam and hydraulic characteristics at the time of the drowning and shows the length of the reverse roller at 30 feet, with an upstream velocity toward the dam of only a modest 2.0 fps; yet the current was able to trap the victim causing his expiration and the injury of two companions.

Prior to the subject drowning incident, a jet skier went up to the base of the dam where he was trapped and drowned. Then, following the subject event, a local television station was at the Island Farm Weir to do a piece on water hazards. During the filming, a canoeist unexpectedly appeared upstream and paddled over the dam crest. He capsized, his canoe bobbed (sometimes being vertical), and the victim drowned on the evening TV broadcast, his drowning being spectacularly recorded.

The Island Farm Weir was finally retrofitted in 1998 after four drownings in only three years following its construction. The successful retrofit consisted of merely flattening the downstream face of the dam by providing a series of steps to dissipate energy and to eliminate the opportunity for a reverse roller to form below the dam structure.

Highland Dam Near Clarksburg, West Virginia

The 13.5-feet-high and 165-feet-long Highland Dam, which is owned by the Clarksburg Water Board, had a flow over its crest of 900 cfs on February 27, 2000, when three recreational boaters in a 15-foot-long Old Town fiberglass canoe approached the base of the dam on a pleasant Sunday afternoon outing. The victims put the canoe into the water downstream of the dam to enjoy the relatively wide and pleasant appearing pool.

At the time of the incident, the depth of the flow over the crest was 0.97 feet at a velocity of 4.0 fps. The tailwater elevation was 7.9 feet below the dam crest with a vertical upstream-downstream water surface drop of 8.9 feet and a jet velocity of 24.2 fps where the jet plunged into the downstream pool (Froude number of 9.0). The jet surfaced approximately 40 feet downstream of the dam at a boil, where the remaining kinetic energy in the jet caused a small water surface rise with bubbles, with a portion of the jet flowing upstream at a relatively high velocity of 6.5 fps. The tailwater rating curve and the submerged hydraulic jump characteristics are presented in Figures 4 and 5.

When the 15-foot canoe overturned upstream of the boil, the three occupants were carried to the base of the dam by the reverse current, where they encountered the force of the spillway jet, causing them to be submerged along with the plunging jet, only to be carried downstream, rising to the surface near the boil and then being carried back to the face of the dam in a continuing cycle. All three of the canoeists drowned at the base of the Highland Dam on the West Fork River that was classified by the State of West Virginia for recreation, including boating. There were not warning signs above or below the dam to warn recreationists.

Clear Creek Drop Structures, Adams County, Colorado

The Colorado Department of Transportation (CDOT) constructed three low-head GCS structures in series in Clear Creek under Interstate 25 during 1991 and 1992. On June 30, 1996, a man and wife floated down Clear Creek in Adams County, along with another couple; upon encountering the first GCS, their raft capsized, and the first couple was tragically drowned. The second couple survived. The stream flow was about 700 cfs at the time of the incident. The GCS structure is shown in Figure 6.

In May 1992 prior to the accident, the director of the local county Parks and Recreation Department wrote to CDOT informing them of the hazardous nature of the GCS design and construction. By June 1998, the three GCS structures were retrofitted by creating a 1:10 sloping, grouted, riprap surface downstream of each crest. This created enough of a horizontal flow vector, hydraulic roughness, and shallow enough flow depth immediately below each structure so that reverse rollers no longer form.

These Clear Creek drownings occurred on a water body that was classified for recreation by the Colorado Water Quality Control Commission, and the structures were built by a sister state agency. The warning about the hazard was made to CDOT in a timely manner by the local government in whose jurisdiction the three GCS structures were built.

Union Avenue Dam, Englewood, Colorado

When the USACE replaced the historic St. Petersburg Ditch diversion dam in 1985 on the South Platte River with a new structure, they did not give adequate consideration to the pre-design period recommendations of local recreational boaters. The new structure was called the Union Avenue Dam. Its profile is shown in Figure 7.

The new dam was an 18.5 feet high, concrete gravity dam with an over-the-dam spillway that sloped at 33 percent into a stilling basin, the hydraulic drop being 15 feet. Typical spring river flows over the dam of 700 cfs, and even up to higher flows such as 1,300 cfs, gave the sound and appearance of a good whitewater rafting experience, and the stilling basin provided an attractive urban setting for recreationists to practice hazard maneuvers. The South Platte River classification by the State of Colorado included recreational uses.

During the three years (1985-1988) following the new dam completion, three boaters drowned. At this point, it was obvious that a public water hazard had been created. The USACE and the state wanted to cure this hazardous public works problem.

The solution was to build a boat chute near the right abutment and to flood the downstream face of the dam with a series of four downstream stair-stepped embankments so that each hydraulic drop would be only 3 to 4 feet high, and each embankment would include a designed boat chute that would safely convey recreational boaters without a reverse roller being formed.

Fortunately, the state agency was willing to have the design tested using a 1:18 hydraulic model built by the U.S. Bureau of Reclamation's hydraulic laboratory at the Denver Federal Center. The extensive model testing effort also included the placement of rock fill on the downstream face of the dam to eliminate dangerous currents, even during higher flow periods when discharges exceeded the boat chute flow. Their thorough and comprehensive model study and report by Klumpp, Pugh, and Fitzwater (1989) was highly successful; the resulting retrofit of the Union Avenue Dam converted a serious public hazard into a popular water recreational park.

Remedies

Dangerous downstream currents are unnecessary for a successful low-head dam or GCS. Hydraulic engineering techniques such as downstream ledges, filling of slopes with rock fill, horizontal deflectors, and other methods to keep the reverse roller from forming are well known and effective. Model studies can test them in the laboratory. Providing take-out landings and take-out facilities, coupled with simple boat chutes and warning signs are reasonable steps for the design engineer to include in his work product.

Conclusions

Hydraulic jumps are well understood by the hydraulic engineering profession, and a wealth of technical literature exists for them. The submerged hydraulic jump is sometimes not treated with adequate respect by design engineers because it occurs below the water surface, and its special characteristics are often neglected. Nevertheless, the practical evaluation of a plunging super-critical jet can readily be understood, even by non open channel flow specialists, by observing currents downstream of low-head dams and by the reading of non-technical whitewater boating safety literature. In essence, with high tailwater conditions below a low-head structure, the conditions are ripe for a reverse roller to form that is hazardous.

Six case studies of low-head dam or GCS across the United States provide a tragic, yet remarkable picture of the lack of concern for public safety in the design and operation of low-head hydraulic structures. Most states have engineering licensing laws that hold paramount the duty of professional engineers to serve the public health, safety, and welfare, the duty being superior to that due the owner or client. This duty requires the engineer to design works that do not create reasonably avoidable hazards to the public. Avoidance of dangerous reverse rollers below low-head hydraulic structures can be reasonably achieved using a variety of design techniques to control downstream currents. The techniques such as those used for the Island Farm Weir, the Clear Creek Drop Structures, and the Union Avenue Dam are effective. When incorporated into the original design and construction, the costs are reasonable and a part of the basic cost-benefit ratio analysis.

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Figure 1 – GCS at Salt River Tempe, Arizona

GRADE CONTROL STRUCTURE (GCS) @ McCLINTOCK DR.
MARCH 25, 1993

(1) Overflow jet produces large submerging force on victim.

(2) Air bubbles reduce bouyancy of victim.

(3) Reverse flow in upstream direction carries debris and victims back into overflow jet.

(4) Water too deep for standing.

Figure 1
GCS at Salt River,
Tempe, Arizona

Figure 2 – Swackhammer Dam on Catherine Creek Near Union, Oregon

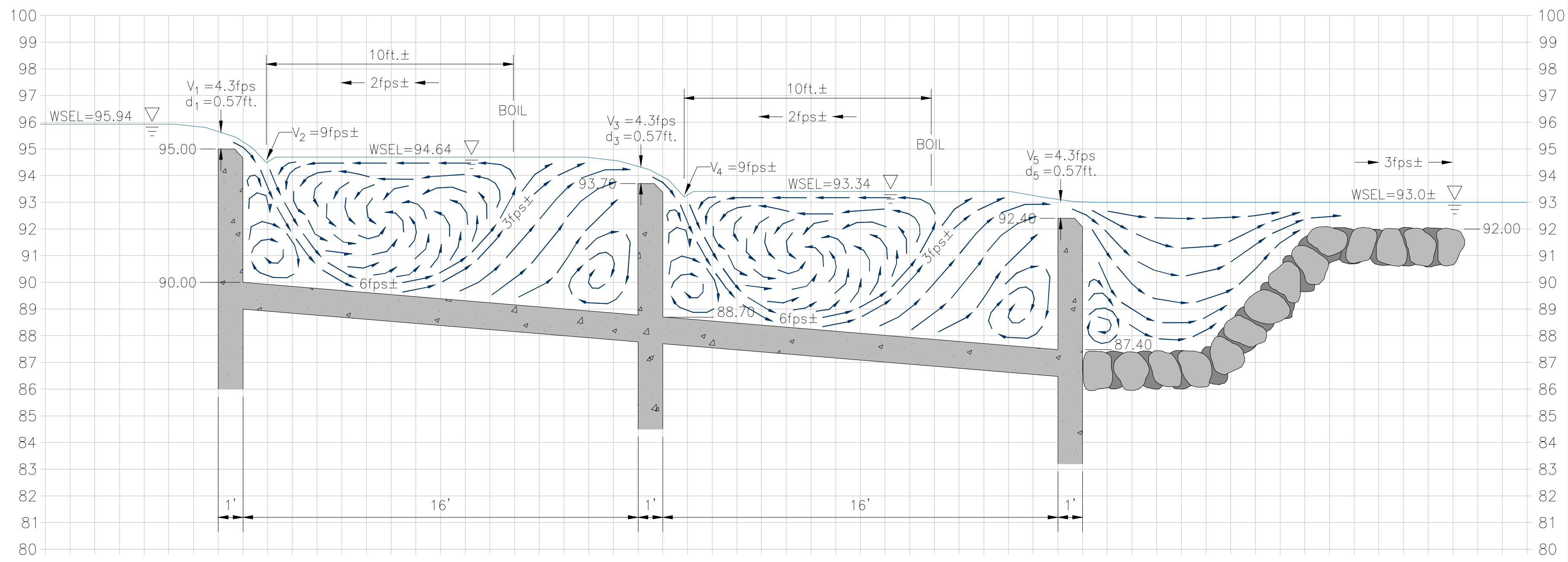


Figure 3 – Island Farm Weir Hydraulic Conditions on April 12, 1996

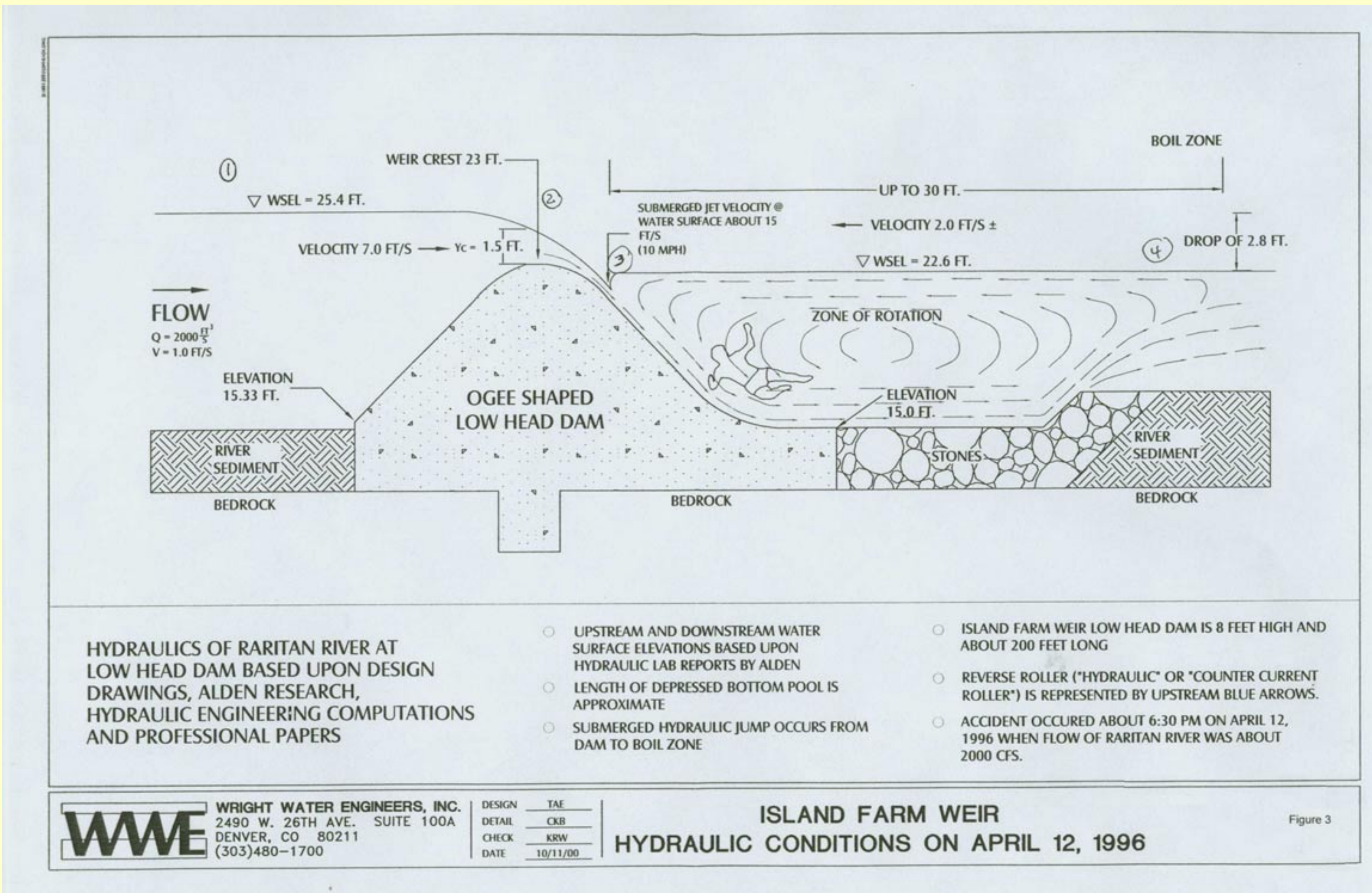


Figure 4 – Tailwater Elevation Rating Curve for Highland Dam

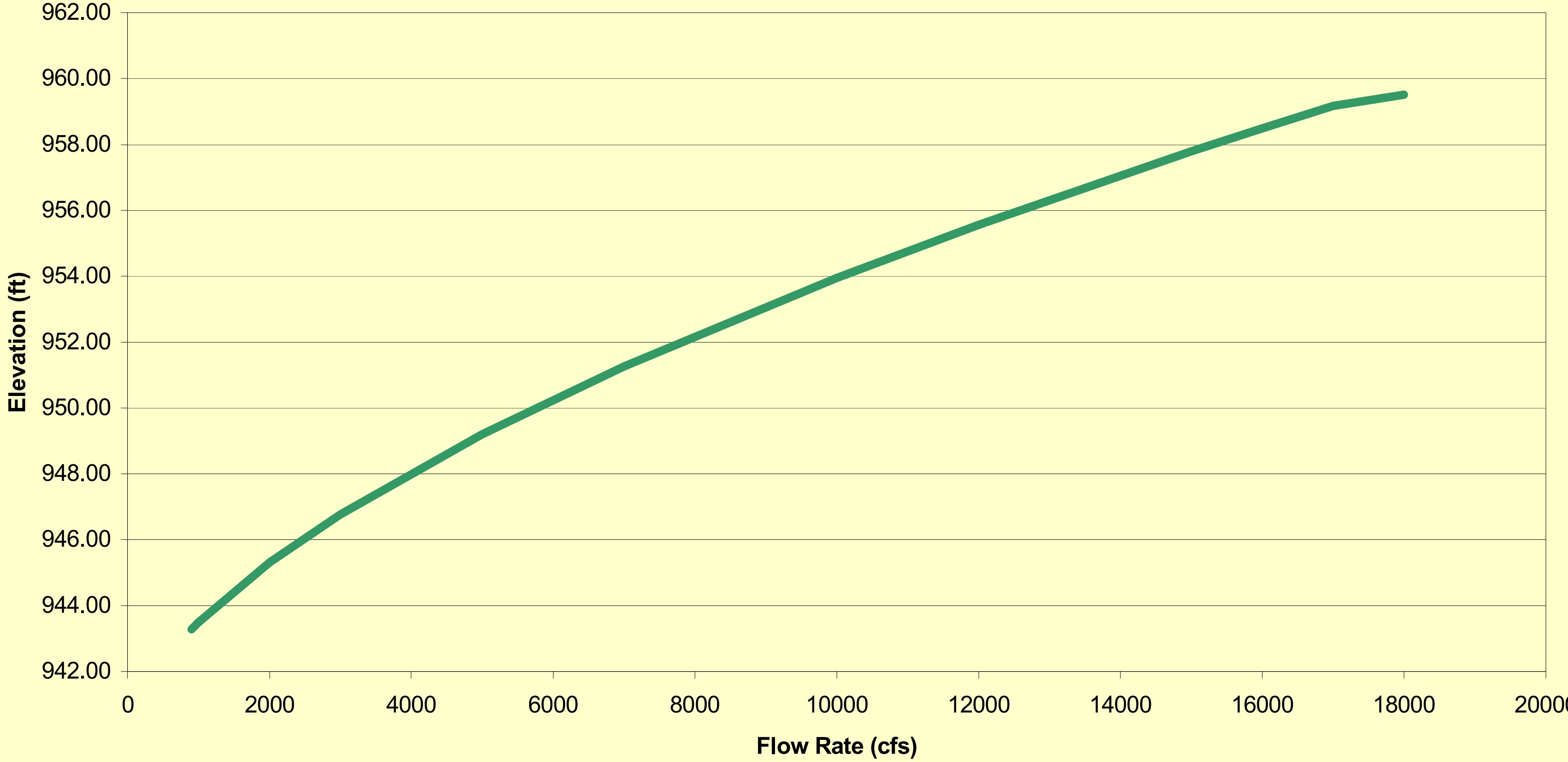


Figure 5 –Highland Dam, West Fork River Submerged Hydraulic Jump Characteristics

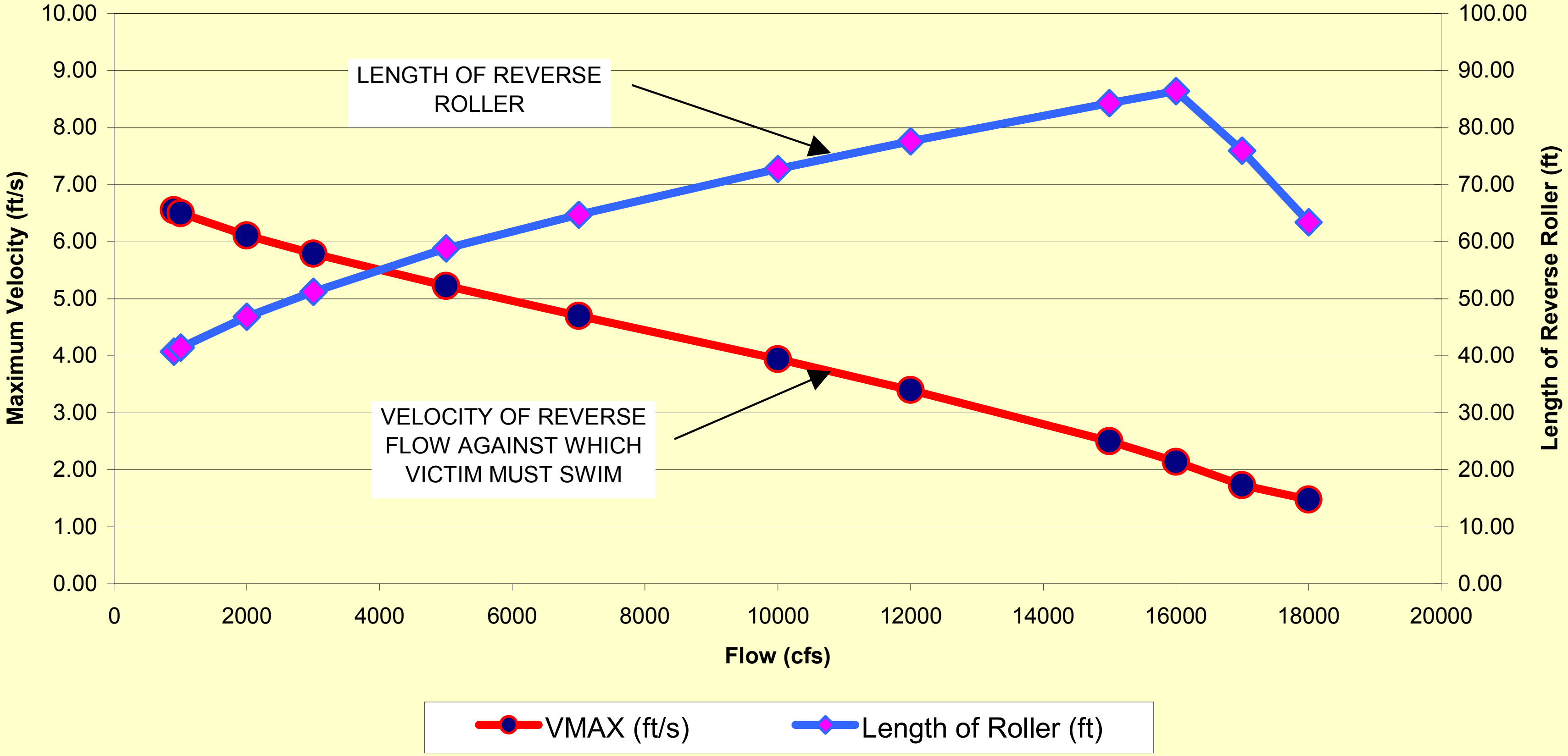
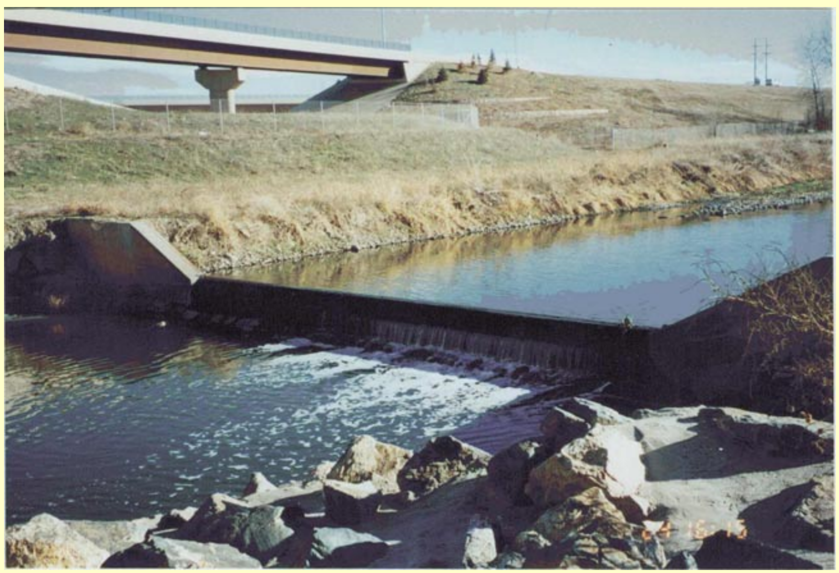


Figure 6 - Photos of GCS Structure in Adams County, Colorado



Wall A

Wall B

Figure 7 – Boating Improvements to Union Avenue Dam (Section Thru Existing Dam)