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Hazard Classification and Hydraulic Remediation Options for Flat-Topped and Ogee-Crested Low-Head Dams

Riley J. Olsen
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HAZARD CLASSIFICATION AND HYDRAULIC REMEDIATION OPTIONS FOR
FLAT-TOPPED AND OGEE-CRESTED LOW-HEAD DAMS

by

Riley J. Olsen

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

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UTAH STATE UNIVERSITY
Logan, Utah

2013
ABSTRACT

Hazard Classification and Hydraulic Remediation Options for Flat-Topped and Ogee-Crested Low-Head Dams

by

Riley J. Olsen, Master of Science
Utah State University, 2013

Major Professor:  Dr. Michael C. Johnson
Department:  Civil and Environmental Engineering

The dangerous hydraulic conditions that can form downstream of a low-head dam were investigated.  These dangerous hydraulic conditions have been the cause of hundreds of drowning incidents since the construction of the first low-head dams.  Two primary objectives were identified for this study, each of which were primarily performed using the Computational Fluid Dynamics software, Flow-3D®, with physical models used to verify the numerical results.  The first objective was the identification of a risk factor made up of easily measured parameters that could accurately predict when the dangerous hydraulic conditions are present at a low-head dam.  The risk factor that was found to achieve this objective was calculated as \((h_u - h_d)/P\), where \(h_u\) and \(h_d\) are the upstream and downstream water depths, respectively, and \(P\) is the dam height.  For the flat-topped dams tested, the dangerous condition was present within the range of risk factors from 0.343 to 0.708.  For the ogee-crested dams tested, the dangerous conditions were present between risk factors of 0.093 and 0.798.  The second objective was to identify possible remediation options that would be capable of eliminating the dangerous hydraulic
conditions, therefore reducing risk to the public. It was also desired to keep the options easily and inexpensively implemented. Two different remediation options were found to this end, and consisted of either upstream facing ramps spaced along the width of the channel below a low-head dam, or spaced platforms protruding from the downstream face of the dam slightly below its crest. Three different designs of each configuration were tested, with those for the ramp configuration being identified as R1, R2, and R3. The platform designs were identified as P1, P2, and P3. The options were evaluated based on how long it took for human dummies introduced into the flow to pass through the high risk region of the simulations, with the maximum allowed time being 50 seconds. Any test in which a dummy remained in the danger region for longer than 50 seconds was deemed ineffective. The option found to perform the best was the P2 design, which had an overall performance time of about 17.4 seconds.
Public Abstract

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by

Riley J. Olsen, Master of Science

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Riley J. Olsen
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# NOTATIONS

\[ A_x, A_y, A_z = \text{Fraction of flow through the face of a cell in the subscript direction} \]

\[ cc = \text{Cubic centimeter} \]

\[ C_d = \text{Discharge coefficient for a weir} \]

\[ \text{CFD} = \text{Computational Fluid Dynamics} \]

\[ \text{FAVOR} = \text{Fractional Area/Volume Obstacle Representation method} \]

\[ f_i = \text{Reynolds stresses} \]

\[ Fr_d = \text{Downstream Froude number} \]

\[ Fr_u = \text{Upstream Froude number} \]

\[ \text{ft} = \text{Feet} \]

\[ g = \text{Gravitational acceleration due to gravity} \]

\[ g_i = \text{Gravitational acceleration due to gravity in the i direction} \]

\[ \text{gr} = \text{Gram} \]

\[ h_p = \text{Platform height} \]

\[ h_r = \text{Ramp height} \]

\[ H_t = \text{Total head above the crest of a dam} \]

\[ h_d = \text{Downstream water depth} \]

\[ h_u = \text{Upstream water depth} \]

\[ (h_u - h_d)/P = \text{Risk factor} \]

\[ \text{kg} = \text{Kilogram} \]

\[ L = \text{Roller length} \]

\[ L_d = \text{Dam length} \]

\[ L_p = \text{Platform length} \]
$L_r$ = Ramp length

$m$ = Meter

$P$ = Dam height

$P'$ = Pressure

$P_1, P_2, P_3$ = Platform remediation designs

$Q$ = Flow rate

RANS = Reynolds –Averaged Navier-Stokes equations

RNG = Renormalized Group Theory model

$R_1, R_2, R_3$ = Ramp remediation designs

$S$ = Submergence factor

$S^*$ = Critical degree of submergence

$s$ = Seconds

$s_p$ = Platform spacing

$s_r$ = Ramp spacing

$u$ = Component of velocity in the $x$ direction

$U_i$ = Component of velocity in the $i$ direction

$U_j$ = Component of velocity in the $j$ direction

$v$ = Component of velocity in the $y$ direction

$V_f$ = Fraction of fluid in a cell

$V_s$ = Upstream directed free surface velocity

$V_{x,min}$ = Minimum surface velocity in the $x$ direction

$V_I$ = Supercritical inflow velocity

$V^*$ = Dimensionless velocity factor
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CHAPTER I
INTRODUCTION

A low-head dam is a small hydraulic structure, usually between 5 and 15 feet tall (Tschantz and Wright 2011), that acts similarly to a linear weir in a canal or river. These dams can be found throughout the United States and the World, and can take many shapes, including flat-topped and ogee-crested. They have been built historically to serve a wide variety of purposes. During the 1800s and early 1900s, they were most commonly constructed to raise the water surface just enough so that mills could take advantage of the few feet of extra hydraulic head to turn their water wheels (Robinson and Houghtalen 2007). Today, however, they are primarily built to impound small volumes of water to be diverted for irrigation, industry, municipality use, and to create recreational venues. Some are also built to improve water quality downstream through the entrainment of air, or to act as grade control structures (Robinson and Houghtalen 2007). Others are simply built to house and protect utility lines, such as sewers, at river crossings (Tschantz and Wright 2011).

Under certain flow conditions, a submerged hydraulic jump can be formed downstream of a low-head dam. When this occurs, a strong countercurrent may be present, which contains a velocity component directed upstream. This characteristic countercurrent has come to be known as a “hydraulic” by recreational water users (Leutheusser 1988) or “reverse roller” by the engineering community. Figure 1 shows an ogee-crested low-head dam that features a so-called roller.
On Sunday, August 1st, 2010, Kelly and Joseph Glasser paddled over a low-head dam on the Jordan River in Murray, Utah in individual kayaks. Both individuals were experienced whitewater kayakers, but had never paddled this particular stretch of the river before. It is unknown if the couple ignored warning signs about the dam and associated dangers, or if they simply didn’t see them, but after paddling over the drop, both Joseph and Kelly were trapped in the “hydraulic” below this dam and drowned before they could be rescued or ejected from the roller (Carlisle and Alberty 2010).

Due to a surprisingly large number of incidents in the past at low-head dams similar to that of the Glasser’s, these structures have been appropriately dubbed “drowning machines” by hydraulic engineers and water safety experts alike (Leutheusser 1988). Although the hydraulic conditions present at low-head dams are similar to those at weirs, which have been studied in depth for over a century (Leutheusser 1988), it is amazing that little research has been performed to try to correct the potentially deadly flow conditions often encountered downstream of these structures.

Upon beginning this project, it became apparent that several studies have been performed on submerged hydraulic jumps, the hydraulic phenomenon that gives drowning machines their potentially deadly characteristics. It was also found that studies
on sediment transfer and fish passage at these structures are also very abundant. But when it comes to studies on the currents created downstream of these dams and how to reduce or eliminate the inherent public danger, it seems that very little has been accomplished. This is surprising because, as the First Fundamental Canon of the American Society of Civil Engineers (ASCE) Code of Ethics states: “Engineers shall hold paramount the safety, health and welfare of the public…” (ASCE 2013). It is the responsibility and duty of hydraulic engineers to design structures that are not only structurally safe, but that also do not create public hazards under normal operating conditions. Because of the deaths reported at these structures each year, low-head dams deserve much more attention from hydraulic engineers.

The primary objectives of this thesis were as follows:

1. Identify a relationship between easily measured parameters and roller strength using numerical models, which can be used to classify hazards at these structures.

2. Simulate possible remediation options and determine which ones are most effective at eliminating the reverse roller.

This thesis will begin with a presentation of the general hydraulic background and description of flow at a low-head dam, followed by a discussion of statistics regarding the numbers of low-head dams and related fatalities. Next, a detailed literature review on the past studies related to low-head dams will be presented, followed by an explanation of the theoretical background of the Computational Fluid Dynamics (CFD) software Flow-3D®, which was used for the numerical models in this study. The process used to identify a relationship between roller strength and easily measured parameters will then be
presented, along with results and discussion. Similarly, following this, the process of simulating remediation options and choosing the most appropriate solutions will be described. Finally, the results from the two major portions of this research will be summarized and briefly discussed, after which suggestions for future research will be given.

Certain chapters of this thesis, those regarding hazard classification and remediation options in particular, were prepared for submission to a peer-reviewed journal. The thesis itself contains more detailed information, whereas the chapters associated with the journal articles were trimmed and formatted in a way consistent with the journal requirements. For this reason, some of the information in the earlier sections of the thesis is repeated briefly in the subsequent chapters.
CHAPTER II
BACKGROUND AND LITERATURE REVIEW

Hydraulic Background

As water flows over the crest of a low-head dam or a drop structure in a mildly sloped channel, the flow regime smoothly transitions from subcritical to supercritical (assuming that tailwater conditions are not so excessive that the structure is completely drowned out). As it continues past the dam, the flow must eventually return to subcritical flow at a distance downstream depending on the slope of the channel and the tailwater conditions present. This transition from supercritical to subcritical flow is not smooth, and a hydraulic jump is usually formed where the transition takes place to dissipate the excess kinetic energy possessed by the high velocity supercritical stream. This transition can be very turbulent, and can therefore entrain air into the water (Leutheusser 1988).

Leutheusser (1988) presented the four possible states of weir flow that can be found downstream of a low-head dam. These four different cases are shown in Figure 2, and include: the swept-out (or repelled) hydraulic jump (a), the optimum (or free) hydraulic jump (b), the submerged hydraulic jump (c), and the surface nappe (flipped-nappe) case (d). Of the four states of weir flow, the most dangerous one is that of case c, the submerged hydraulic jump.

When the tailwater conditions at a low-head dam are such that a submerged hydraulic jump is formed, a strong countercurrent is created at the downstream face of the dam, which features a characteristic upstream directed surface velocity. This reverse roller, and the associated upstream-directed surface velocity, is formed as a result of two primary actions.
Fig. 2. Possible states of flow at a low-head dam
The first contribution to the roller is the strong force of the overflowing nappe as it impinges on the downstream subcritical pool. As the nappe impacts the water and plunges below the surface, it entrains nearby surface water and carries it towards the bottom of the channel as it becomes a submerged jet (Hirt 1994). Also, because of the severe turbulence and splashing caused by the impacting nappe, air is entrained into the water thus slightly decreasing its density (Leutheusser 1988). Upon reaching the bottom of the channel, the jet is deflected downstream and begins to rise towards the surface as a result of the decreased density, as well as friction interactions with the slower moving water above it (Govinda Rao and Rajaratnam 1963).

The point where the water reaches the surface can be slightly elevated above the surrounding water surface as the kinetic energy of the jet is converted into potential energy (Tschantz and Wright 2011). This point of higher water level is known as the boil line due to the bubbling and boiling appearance present at this location. Upstream of this high point on the water surface, the water flows upstream towards the dam as a result of the difference in surface elevation, or hydraulic gradient, created by the depression at the point of nappe impact and the rise at the boil (Robinson and Houghtalen 2007). This is the second contributing factor to the countercurrent located at many low-head dams. The water on the downstream side of the boil line continues to flow downstream.

There are several dangers associated with the hydraulic conditions at low-head dams. The first, and most obvious, is the potential for getting trapped by the reverse roller below the dam. If one were to go over the crest, whether by choice or involuntarily, the person would experience a dunking action as the falling water forces them to the bottom of the channel (Leutheusser 1988). The submerged jet would then
carry them downstream to the point of the boil line, where they could be carried back to
the point of nappe impact (assuming a sufficient upstream directed surface velocity), at
which point the victim would likely begin the cycle again. The victim could be re-
circulated through this cycle countless times, as they constantly struggle to stay afloat and
escape the hydraulic. Far too often, the victim will become exhausted and drown before
being ejected or pulled clear by rescue personnel.

The air entrained into the water at the point of nappe impact and the resulting
decreased water density is responsible for additional hazards faced by victims of the
hydraulic. The decreased density, which can be reduced by as much as 30%, causes a
similar decrease in buoyant force exerted on submerged objects (Robinson and
Houghtalen 2007). This decreased buoyant force causes life vests and other floatation
devices to lose their effectiveness in keeping the victim above the surface (Tschantz and
Wright 2011). Also, swimming thrust loses its effectiveness (Robinson and Houghtalen
2007). Because of these two effects, the victim is forced to struggle harder than if they
were caught in a current of normal density water, thus causing the victim to become
exhausted more rapidly.

Another danger faced by victims already caught in the reverse roller is the
possibility of being struck by other debris caught in the re-circulating cycle, or passing
over the dam (Robinson and Houghtalen 2007). Debris could include anything from logs
to tires and other trash that has become trapped by the roller. If the victim were to be
struck by such an object, it could knock them unconscious, cause blunt force trauma, or
other forms of bodily injury (Robinson and Houghtalen 2007).
On top of all other hazards discussed thus far, exists the hazard of cold water (Robinson and Houghtalen 2007). If the water the victim is exposed to is sufficiently cold, as is often the case in rivers during winter or spring, the body will lose heat faster than it can replace it (MAYO 2011). This condition, known as hypothermia, can cause several symptoms that are extremely detrimental to the victim’s already dire struggle for life. These symptoms include a lack of coordination, confusion or difficulty thinking, poor decision making, drowsiness, lack of concern about one’s condition, and progressive loss of consciousness (MAYO 2011).

These structures can be dangerous to people participating in many forms of recreational activities in the vicinity of a low-head dam; from kayakers and canoers to fishermen, waders, and swimmers. The small sight angle of paddlers from kayaks and canoes, combined with a small overall drop height and deceivingly calm water at these structures, can make them hard to see and often conceals the associated dangers (ACA 2003). Often by the time the danger of the dam is detected, the strong current is already working to suck the victim into the hydraulic below the dam. From below the structure, the apparently quiescent pool of water can lure recreationalists closer and closer to the falling cascade of water, until they find that they are already under the influence of the strong countercurrent upstream of the boil, and cannot escape.

Although it would be reasonable to assume that most, if not all people that go over a low-head dam do so involuntarily, many do go over these structures intentionally. During the review of literature, several anecdotal accounts of people going over low-head dams intentionally were found. Usually these people were adrenaline seeking whitewater
enthusiasts, to whom the thrilling sight of the falling cascade of water at a low-head dam was just too tempting to resist.

Statistics

The United States Army Corps of Engineers (USACE) keeps an inventory of dams in the United States known as the National Inventory of Dams (NID). In order for a dam to be included in the NID it must meet at least one of the four criteria listed below (USACE 2010):

1) High hazard classification – loss of one human life is likely if the dam fails

2) Significant hazard classification – possible loss of human life and likely significant property or environmental destruction

3) Equal or exceed 25 feet in height and exceed 15 acre-feet in storage

4) Equal or exceed 50 acre-feet storage and exceed 6 feet in height

As of 2011, the NID contained information on over 84,000 dams across the country and 818 dams in Utah (USACE 2010). Because of the small height and the small volume of water normally impounded by them, however, most low-head dams do not meet any of the criteria listed above, and therefore are not included in the NID. Aside from the USACE database, no other significant inventory of dams, large or small, was found to exist at a national level.

Because low-head dams are so small and pose little danger to public safety and property if they were to fail, these dams rarely fall under federal or state regulations (Tschantz and Wright 2011). In fact, it was learned through email communication with engineering personnel at the Utah Division of Water Rights that until recently, Utah did not require application or permitting for the construction or use of low-head dams in the
state. For this reason, it is very difficult for state dam agencies, which are often understaffed and underfunded to begin with, to keep track of just how many low-head dams fall within its borders (Robinson and Houghtalen 2007). The Utah Division of Water Rights does maintain its own dam inventory, but like the NID, it mostly consists of larger dams that pose significant risk to the public.

Tschantz and Wright (2011) state that, for the reasons addressed above, the number of low-head dams in most states is largely unknown. Through a 2004 national survey however, they found that 17 states estimate to have close to 1,700 of these structures. Other states throughout the mid-west and eastern U.S. are estimated to have between 100 and 400 low-head dams (Tschantz and Wright 2011).

Similar to statistics concerning the number of low-head dams throughout the U.S. and Utah, the search for a compiled list of documented deaths attributed to low-head dams yielded little success. One source that was found regarding general recreational boating statistics was an annual United States Coast Guard (USCG) publication (2010). This publication contains statistics of all kinds regarding recreational boating accidents that occurred throughout 2010, from the skill level of those involved, to the size and manner of watercraft, to the documented causes of the incident. Although this publication does not focus specifically on low-head dams, it does paint the picture of just how many boating accidents occur around the country each year.

Some of the relevant statistics from the USCG’s (2010) report were presented as follows. Canoes and kayaks, as a combined category of vessel, ranked fourth highest in number of casualties of all boat types with 128 drownings, 13 other deaths, and 96 injuries. The number of drownings categorized by non-motorized small vessel type were
as follows: canoes with 86, kayaks with 42, rowboats with 33, and inflatables with 22
drownings. 157 deaths and 548 injuries were attributed to environmental causes, of
which, 6 deaths and 6 injuries were attributed to dams/locks, the category under which
low-head dams would fall. Even though the number of incidents that occurred at dams
may seem small, any contributing factor that continues to take any number of human
lives regularly each year should be considered a significant problem and should be
addressed. In 2010, 10 boating fatalities occurred in the state of Utah, two of which were
Kelly and Joseph Glasser as mentioned earlier.

According to the American Canoe Association (ACA) (2003), during the five-
year period from 1996 to 2000, about 27 canoeing and kayaking deaths throughout the
United States involved low-head dams or weirs. The ACA (2003) also reports that
kayaking is currently growing faster than any other outdoor activity, on land or water.
With this increased popularity in paddle sports, the ACA states that of the canoeing and
kayaking fatalities reported to the USCG, a significant proportion involved paddlers with
“little or no experience with canoes or kayaks, who lack fundamental paddling skills, and
who have not been effectively reached with safety messages” (ACA 2003). Many of the
paddlers who die every year probably do not consider themselves true “canoeists” or
“kayakers” according to the ACA, and for that reason probably do not seek safety and
educational information concerning their particular paddle sport. In fact, of all of the
incidents included in the USCG 2010 report, only about 14% occurred on boats where the
operator had received boating safety instruction of some sort (ACA 2003).

Although there is no centralized inventory of documented drowning incidents
occurring specifically at low-head dams, there are countless news articles and anecdotal
stories about recreational boaters, swimmers, waders, fishermen, and thrill seekers being caught by the reverse roller at the downstream side of a dam and drowning. Some incidents were also reported by local fire authorities who had worked on swift water rescue teams. So many stories of such incidents were found, in fact, that there is no doubt that low-head dams truly pose to be a large public hazard and have earned their nickname of “drowning machines.”

**Studies**

Leutheusser (1988), in an attempt to generate engineering interest in public safety at low-head dams, presented some hydraulic and physiological considerations encountered at these structures. As presented in Figure 2, the four different states of flow below a low-head dam are explained, and case (c) (the submerged hydraulic jump) is emphasized as being the most dangerous scenario. Upon performing an analysis of a dam where a drowning had recently occurred, it was predicted that the maximum upstream directed surface velocity present at this dam under the reported conditions was about 1.3 m/s (4.27 ft/s). He notes that the maximum human swimming velocity, attained only by highly trained athletes, is about 1.8 m/s (5.9 ft/s). But, due to the entrained air and associated loss of swimming thrust in the water below a low-head dam, this velocity is likely significantly less. This analysis explains how so many people, including exceptional swimmers, can succumb to the forces of the reverse roller and drown as a result. In conclusion, Leutheusser (1988) recommended making entry into the pools below low-head dams difficult through the construction of fences and placement of warning signs. He also suggests the use of continuous energy dissipation devices, such as baffled chute spillways, to eliminate the submerged hydraulic jump.
Govinda Rao and Rajaratnam (1963) performed a study on submerged hydraulic jumps in open channels from an energy dissipation standpoint. The objective was to determine whether the submerged hydraulic jump should be preferred over an optimum, or free, hydraulic jump for the purpose of energy dissipation. In order for a free hydraulic jump to occur, the tailwater depth \( Y_4 \) must be equal to the subcritical sequent depth of the jump \( Y_2 \) as calculated from the momentum equation. If the tailwater depth is less than this sequent depth, the jump will be in the swept-out state. On the other hand, when the tailwater depth is greater than that of the sequent subcritical depth of the jump, the hydraulic jump is submerged. They make use of a submergence factor \( S \), as presented in Equation 1, to predict the form of hydraulic jump at varying flow conditions. A swept-out jump is created when values of \( S \) are less than zero. When \( S \) is greater than zero, the jump is in the submerged state. When \( S \) is equal to zero, the jump is in the free form. It was seen that when the jump took the submerged state, the length of the roller increased with increasing submergence.

\[
S = \frac{Y_4 - Y_2}{Y_2}
\]  

(1)

From Govinda Rao and Rajaratnam’s (1963) study, it was discovered that the capacity for energy dissipation by submerged hydraulic jump can be greater than or less than that of the free jump, depending on the Froude number of the supercritical stream and \( S \). It is emphasized that, although the energy dissipation can be greater than that of the free jump in some cases, the actual energy loss occurs over a much greater distance than the corresponding free jump. It was concluded therefore, that the submerged jump should not be preferred over a free jump for the purpose of energy dissipation.
In a study performed by Leutheusser and Fan (2001), the upstream directed free surface velocities of submerged hydraulic jumps at low-head dams were investigated. In this study, the authors found that when the hydraulic jump is in its optimum form, small changes in tailwater depth had surprisingly large effects on longitudinal jump stability. They also expounded on Govinda Rao and Rajaratnam’s (1963) use of the submergence factor. Their results show that the upstream directed free surface velocity ($V_s$) varies significantly depending on the degree of submergence. The maximum value of $V_s$ was found to be approximately one-third of the supercritical inflow velocity ($V_l$) of the corresponding unsubmerged jump. This maximum velocity value occurred at a submergence of $S \approx 0.3$. With increased submergence, $V_s$ drops off until, at some critical degree of submergence ($S^*$), the nappe “flips” from the bottom of the channel to the top, and the roller instantaneously disappears, resulting in flow that is directed entirely downstream. This transformation occurs at a ratio of $h_u/h_d = 1.1$, where $h_u$ is the water depth upstream and $h_d$ is the tailwater depth. When the tailwater depth is decreased from the “flipped” state, the nappe will “flop” back to plunging flow and the roller, along with the associated upstream directed velocities, will reappear. Nappe flop occurs at a ratio of $h_u/h_d = 1.19$.

Several possible remediation options have been proposed by various researchers in an attempt to break up or eliminate the roller and therefore the associated public danger. One such study was performed by Leutheusser and Birk (1991). They state that it is because of the low height of many of these structures that an optimum jump is not allowed to properly form at the point of nappe impact, therefore resulting in a submerged jump instead. Although they acknowledge that it is very difficult for hydraulic engineers
to design structures that function properly over a large range of flow rates, they suggest increasing the height of low-head dams to ensure the formation of a proper jump. After further analysis and calculation however, they realized that in many cases, the height required to form an optimum jump could be unreasonably large (49 ft for their particular flume experiment).

Leutheusser and Birk’s (1991) final recommendation for the drown-proofing of low-head dams was to do away with the hydraulic jump for energy dissipation altogether. Instead, they suggested using the method of continuous energy dissipation by cascading effects, specifically the baffled chute spillway, to dissipate energy. These structures are said to operate well under a large range of flow rates and tailwater depths.

In response to Leutheusser and Birk’s article, Hotchkiss and Comstock (1992) performed a study in order to validate the claims that baffled chute spillways are a safer form of energy dissipation than that of a submerged hydraulic jump encountered at many low-head dams. They used a scaled model of the U.S. Bureau of Reclamation’s Basin IX chute to perform their investigation. They tested the baffled chute spillway at two different discharges and two different tailwater conditions for each of the discharges. They found that the specific baffled spillway tested does indeed eliminate the dangerous submerged hydraulic jump and reverse roller. But, along with the elimination of the hydraulic, they found that when floats were introduced at the top of the spillway, they got caught by the baffles and held there by the force of the flowing water the majority of the times introduced. Only when the flow rate was above 157% of the design flow rate, were the floats able to safely flow over the spillway without incident. They concluded that, because of the potential for injury to a victim while attempting to navigate the baffles, the
use of baffled chute spillways should not be used as a blanket replacement of low-head dams.

In closure to the discussion on his original article, Leutheusser reminds the reader that there is no such thing as a “safe” hydraulic structure. He states however, that although the baffled chute spillway may still be dangerous to anyone who goes over the dam, the sight of heavy agitation and turbulence created by the baffles will make anyone think twice before attempting to run it (Hotchkiss and Comstock 1992). This does not, however, provide any comfort to the fact that many recreationalists are swept over low-head dams involuntarily.

In a study aimed at presenting the capabilities to track multiple free surfaces and represent turbulent flow characteristics, Hirt (1994) used the CFD program Flow-3D® to model a sharp-crested weir operating in an open channel, a structure that can fairly accurately be used to represent flow over a low-head dam. Using dimensions and parameters taken from an actual structure, the weir was modeled two-dimensionally for several different cases. A base simulation of the model was first run in order to verify the ability of Flow-3D® to accurately represent the actual flow conditions at the structure. The discharge rate of the entire structure obtained through Flow-3D® was a mere 2% larger than that of the theoretical value. This close agreement properly verified the ability of the CFD program to accurately model this situation. This base simulation shows a region of upstream-directed surface flow at the downstream face of the weir, similar to the countercurrent found at many low-head dams.

Hirt ran subsequent simulations with various modifications applied to the original simulation in an attempt to eliminate, or at least reduce, both the size and magnitude of
the roller downstream of the weir (Hirt 1994). The first modification included a ramp at the bottom of the pool with the intention of redirecting the bottom jet toward the surface. It was found that this option simply raised the jet off of the channel bottom slightly and did not correct the problem. The best alternative discovered by the author to limit the size of the roller was a deep depression at the base of the weir. Although this solution did manage to contain the jet, a surface countercurrent still existed, but only in the region directly above the depression, thus significantly reducing the original extent of the roller.

Garcia et al. (2005) took part in an eight week National Science Foundation Research Experience for Undergraduates program at Rose-Hulman Institute of Technology. The purpose of their research project was to explore and investigate several affordable remediation options that could be used to eliminate the dangerous hydraulic conditions present at low-head dams. This was done by modeling flat-topped and ogee-crested dams, both of which are common low-head dam configurations, using Flow-3D® as well as physical laboratory models. They first went about validating the ability of the program to accurately reproduce the hydraulic conditions present at low-head dams by comparing data from laboratory experiments of the flat-topped weir and ogee spillway to data obtained from computer simulations. Strong correlation between the physical and numerical data assured the authors that their numerical setup was sufficient to produce accurate results.

Due to time constraints, Garcia et al. (2005) were only able to numerically simulate two remediation designs: the addition of baffled blocks to the downstream face of the dam, and the addition of a four-step spillway on the downstream face. Their results showed that their configuration of blocks added to the dam was an unsuccessful
retrofit alternative because it failed to eliminate the countercurrent. The results of the four-step spillway simulation showed that this retrofit was a successful remediation option that did in fact break up the reverse roller. Although this method of low-head dam remediation was deemed effective, it was also decided by the authors, that because of the high cost involved with construction and implementation, it would be deemed impractical in many cases. They concluded the same for the case of the labyrinth weir, an alternative that was not actually tested in the study.

The last remediation option tested by Garcia et al. (2005) was the rock arch dam conversion. This retrofit option was only tested in the laboratory due to time constraints involved and the complexity of setting up a numerical model. Their results showed that this remediation technique performed best at high flow rates and low tailwater depths. At low flow rates, however, little effect on the hydraulic was observed.

With the advancement of computer power and computational fluid dynamics programs, it has become worthwhile to model some complex hydraulic phenomena numerically rather than physically in the lab, as shown by Hirt (1994) and Garcia et al. (2005). This can save money as well as time normally required to build and test physical models.

**Flow-3D® Theoretical Background**

Flow-3D® is a commercially available computational fluid dynamics software package which uses finite-volume methods to solve the Reynolds-Averaged Navier-Stokes (RANS) equations, the governing equations of fluid flow. The computational domain within Flow-3D® is made up of a Cartesian grid of hexahedral cells. The Fractional Area/Volume Obstacle Representation (FAVOR) method presented by Hirt
(1992) and Hirt and Sicilian (1985), is utilized to define the surfaces of obstacles in the path of fluid flow. The Volume-of-Fluid (VOF) method (Hirt and Nichols 1981) is used to compute and track the free surface.

The FAVOR method uses a porosity technique, assigning a porosity value to each cell of the computational domain based on the percentage of the cell consisting of a solid. Cells completely immersed in an obstacle are given a value of zero, whereas cells completely outside of an obstacle are assigned a value of 1. Cells that are partially filled by an obstacle are assigned a value between zero and 1 based on the percentage of the cell filled. These partially filled cells therefore constitute and define the surface of the obstacle. The location of the obstacle surface is defined as a linear approximation (a straight line in two dimensions and a plane in three dimensions), at the point where the obstacle crosses the cell faces. This method produces obstacles that are constructed of short, straight line segments or chords. The smaller each cell of the computational domain, the smaller the line segments used to construct obstacles, and therefore the more accurately the object is represented.

In order to compute and track the complicated free surface of fluid flow, Flow-3D® uses a VOF method. Like the FAVOR method of obstacle representation, the VOF method defines the free surface by assigning a value between zero and 1 to all computational cells, zero indicating a cell that contains no fluid and 1 indicating a completely filled cell. Again, partially filled cells are assigned a value between zero and 1 based on the percentage of the cell that is filled with fluid. The slope of the free surface within a cell is computed using surrounding cells to define surface angle and surface location. Like with the FAVOR method, the free surface is represented using a first-
order approximation, which uses lines (2-dimensional) or planes (3-dimensional) to approximate the computed free surface, and accuracy is improved with smaller cell size. Unlike the FAVOR method though, the VOF method allows for a changing free surface over time and space.

The general governing RANS and continuity equations are presented in (2) and (3). These equations include the FAVOR and VOF variables.

\[
\frac{\partial}{\partial x} (u A_x) + \frac{\partial}{\partial y} (v A_y) + \frac{\partial}{\partial z} (w A_z) = 0 \quad (2)
\]

\[
\frac{\partial U_i}{\partial t} + \frac{1}{V_f} \left( U_j A_j \frac{\partial U_i}{\partial x_j} \right) = \frac{1}{\rho} \frac{\partial P'}{\partial x_i} + g_i + f_i \quad (3)
\]

where \( u, v, \) and \( w \) are velocities in the \( x, y, \) and \( z \) directions; \( A_x, A_y, \) and \( A_z \) represent the fraction of flow through the face of a cell in the direction of the subscript with a value of 1 correlating to fully open flow and zero correlating to fully closed flow. \( U_i \) is the velocity in the \( i \) direction and \( U_j \) is the velocity in the \( j \) direction. \( V_f \) is the fraction of fluid in each cell with values of 1 and zero corresponding to full and empty cells respectively. \( \rho \) is the density of fluid, \( P' \) is pressure, \( g_i \) is the gravitational force in the \( i \) direction, and \( f_i \) represents the Reynolds stresses for which a turbulence model is required for closure. The turbulence model that was used to obtain this closure was the two-equation renormalized group theory model (RNG), as presented by Yakhot and Orszag (1986).
CHAPTER III
HAZARD CLASSIFICATION AT LOW-HEAD DAMS

Abstract

This study examines the dangerous countercurrent that can form at the downstream face of a low-head dam at certain flow conditions, utilizing a computational fluid dynamics software and laboratory observations. The objective of this project was to identify easily measured parameters that can be used to accurately distinguish between the possible high-risk and low-risk states of flow. The research was carried out on two common low-head dam shapes (ogee-crested and flat-topped), and three dam heights (0.61 m, 1.52 m, and 3.05 m). Simulations were performed at various upstream and downstream water depths. It was found that the combination of parameters \((h_u-h_d)/P\) (named the risk factor) was capable of showing clear transition points between the three main states of flow, and therefore the low-risk and high-risk scenarios. With regards to the ogee-crested dam simulations, it was found that the most dangerous flow conditions occurred at risk factors between 0.224 and 1.238. For the flat-topped dams tested, the high-risk conditions occurred at risk factors ranging from 0.248 to 0.974. Countercurrent length was also examined, with rollers from the ogee dams ranging from 2.05\(P\) to 5.95\(P\) in length, and from 2.60\(P\) to 5.45\(P\) for flat-topped dams.

Introduction

Low-head dams are very common open channel structures that can be found on rivers and canals or other waterways throughout the United States and the world.

\(^1\)Coauthored by Michael C. Johnson P.E., and Steven L. Barfuss P.E.
Through the years they have been constructed to serve several purposes. Today, the most common uses of low-head dams are to impound small volumes of water to be used for irrigation, industry, cooling power plants, use by municipalities, and simply to provide recreational activities. Some of these structures serve no other purpose than to house and protect utility lines such as sewers at river crossings, or to act as grade control structures. Others are built to enhance water quality downstream of the dam through the entrainment of air into the turbulent flow.

One aspect of these structures that is often overlooked or ignored during the design process is the potential hazard to the public that can occur under normal operating conditions. Depending upon the flow conditions present, a strong counterintuitive (reverse) current can form at the downstream face of the dam. This current, often referred to as a “hydraulic” by paddling enthusiasts or a “roller” by the engineering community, has been determined to be the main contributing factor in the deaths of many unsuspecting people throughout the years.

There have only been a few studies that have examined these deadly characteristics of low-head dams as well as possible remediation techniques, most notably Hotchkiss and Comstock (1992), Leutheusser (1988), Leutheusser and Birk (1991), and Leutheusser and Fan (2001). Although past studies have done fairly well at explaining the dangers and hydraulic conditions at low-head dams, little has been done when it comes to classifying the hazards created by these dams, especially using parameters easily observed and measured in the field.

This study addresses the issue of classifying the hazards found at low-head dams using a combination of parameters that are easily measured. These parameters include
upstream and downstream water depths, and the height of the structure. The analysis was undertaken using the computational fluid dynamics (CFD) software Flow-3D®, in which a significant number of simulations of flow over low-head dams were performed with varying dam sizes, headwater depths, and tailwater depths. The objective of this study was to be able to classify the dangers of the flow at low-head dams based on these easily measurable parameters.

**Background**

As water passes over a low-head dam, the flow regime smoothly transitions from subcritical to supercritical. As the supercritical jet impacts the subcritical pool downstream, the flow regime must transition back to subcritical. This transition requires the formation of a hydraulic jump in order to dissipate the excess energy possessed by the supercritical flow.

Depending upon the headwater and tailwater depths present at a low-head dam, the hydraulic jump that is created can take one of three different forms, as presented by Leutheusser and Fan (2001). If the tailwater depth is sufficiently low, the hydraulic jump will be swept downstream from the face of the dam, creating what is known as a swept-out or repelled jump. However, as the tailwater depth is increased, the hydraulic jump will pass through its optimum state of energy dissipation occurring exactly where the overflowing nappe impinges into the downstream pool below. This state is known as the optimum or free form of the hydraulic jump. As the tailwater depth is increased further, the hydraulic jump is pushed up against the face of the dam and becomes drowned. This form of the jump is referred to as a submerged hydraulic jump. It is when the hydraulic jump is in the submerged state that a dangerous current can be formed.
downstream of the dam. It is this current that is the primary focus of this study. Figure 3 shows a definition sketch of the three possible hydraulic jump conditions occurring at a flat-topped low-head dam. They include: swept-out (a), optimum (b), and submerged (c) hydraulic jumps.

In their study, Leutheusser and Fan (2001) make use of a factor known as the submergence factor ($S$) of the hydraulic jump to predict what kind of jump will be present at varying tailwater depths. The submergence factor is calculated as $S = (Y_4 - Y_2) / Y_2$, where $Y_4$ is the downstream tailwater depth and $Y_2$ is the subcritical sequent depth of the free hydraulic jump obtained from the momentum equation.

Leutheusser and Fan (2001) found that if the submergence factor at a low-head dam is less than zero, the jump will be swept-out. When $S$ is equal to zero, the jump will be in its optimum form. It is when $S$ is greater than zero that the jump becomes submerged. As the tailwater depth continues to increase after becoming submerged, a point will be reached where the nappe will no longer plunge into the downstream pool, but will rather “flip” up to the surface and be entirely downstream directed. They found that nappe flip occurs at a headwater to tailwater ratio of approximately 1.10.

![Fig. 3. Definition sketch of possible states of flow at a low-head dam](image)
When the tailwater conditions at a low-head dam are such that the hydraulic jump takes the submerged form (excluding tailwater depths so excessive that nappe flip has occurred), a strong reverse or counterintuitive current is created at the downstream face of the dam. This current features a characteristic upstream directed surface velocity which can be strong enough to trap debris near the face of the dam for prolonged periods of time.

Another dangerous hydraulic factor that comes into play when a submerged jump is formed at a low-head dam is a result of the entrainment of air into the water due to turbulence. The addition of air into the water downstream of a low-head dam effectively reduces the density of the water, and therefore also reduces the buoyant force exerted on submerged objects. This includes debris as well as human beings.

Often times, fooled by the calm appearance of the cascading water present, recreational water users venture too close to a low-head dam and find themselves caught in the strong current, often struggling against the strong roller and decreased water density to the point of exhaustion, and many times drowning before being rescued or ejected from the unrelenting cycle.

When flow conditions are such that the hydraulic jump is swept downstream or at its optimum state of energy dissipation, the vast majority of the flow is directed downstream at high velocities. These high velocities allow debris and water users to be flushed through the jump without the risk of being caught by a current. Similarly, when the tailwater is so high that the nappe has flipped to the surface, the surface velocity is directed entirely downstream. This allows debris and users to continue downstream with
no risk from a roller. For the purpose of this study, only submerged scenarios displaying an upstream directed surface velocity will be examined in depth.

**Experimental Procedure**

As previously mentioned, the CFD software Flow-3D® was used for a significant portion of this study. This CFD software uses the volume of fraction (VOF) technique to model free surfaces and interfaces between two fluids, while a Fractional Area/Volume Obstacle Representation method (FAVOR) is used to model the complex geometries of obstacles in the path of flow. Using these fractional methods, it has been verified by several studies that the program can track free surfaces very accurately (Savage and Johnson 2001).

During a literature review of low-head dams, it was found that the majority of these structures consist of an ogee-crested or flat-topped shape. For this reason, it was decided that both of these dam shapes would be examined in this study.

Because much of this project was carried out on dams with an ogee-crest shape, several studies which used Flow-3D® to model flow over ogee-crested spillways were reviewed. This was done in order to verify that the program was capable of accurately modeling such flow conditions. One of these studies was conducted by Savage and Johnson (2001). In this study, they compared the discharge and crest pressures over an uncontrolled ogee-crested spillway using a physical model, a CFD model, and various design curves. Comparing their results, the authors found that numerical modeling of free flow over an ogee spillway using Flow-3D® yielded results very similar to those obtained through the other methods. From this, they concluded that CFD modeling is a reliable and cost effective tool for modeling such flow conditions.
In a subsequent study performed by the same authors (Johnson and Savage 2006), similar experimentation was performed on ogee-crested spillways under the influence of tailwater. This was done in order to investigate the ability of Flow-3D® to predict the pressures under this extremely complex case. Through comparison of the physical and numerical results obtained, the authors found that the flow rates predicted by the numerical solutions were within 3% of those obtained in the physical modeling. This led the authors to conclude that the CFD program was capable of reproducing the flow conditions present at an ogee-crested spillway with tailwater present.

**Numerical Model**

Each numerical simulation was set up identically in terms of physics models and boundary conditions in order to ensure that the results obtained were generated in the same manner, and could therefore be accurately compared. The only parameters that changed between simulations were the dam height ($P$), upstream water depth ($h_u$), and downstream water depth ($h_d$). Simulations were performed in groups, or series, with simulations in a particular series consisting of a constant $P$ and $h_u$, with only $h_d$ varying between simulations. Once an entire series had been completed, a new series was tested using different values of $P$ or $h_u$.

The physics models that were used in the CFD simulations included the Gravity model with a gravity component in the Z direction of -9.81 m/s², and the Viscosity and Turbulence model with the renormalized group model activated.

The computational domain in Flow-3D® is represented by a Cartesian mesh. The boundary conditions of this mesh were held constant for each of the simulations.
performed throughout the study. These boundaries were specified as follows, in order to model as closely as possible actual physical conditions at a low-head dam:

- **Upstream boundary** ($X_{\text{min}}$): Specified pressure boundary with a stagnation pressure left blank and a specified fluid height
- **Downstream boundary** ($X_{\text{max}}$): Specified pressure boundary with a stagnation pressure left blank and a specified fluid height
- **Bottom boundary** ($Z_{\text{min}}$): Wall boundary (no slip)
- **Top boundary** ($Z_{\text{max}}$): Symmetry boundary (no influence on model due to open channel)
- **Side boundaries** ($Y_{\text{min}}$ and $Y_{\text{max}}$): Wall boundaries (no slip)

At the completion of a numerical simulation, the flow rate ($Q$), minimum surface velocity in the direction of flow ($V_{x,\text{min}}$) (negative indicating upstream directed and therefore the presence of a roller), and water surface elevations at a distance of $2P$ upstream and $3P$ downstream from the upstream face of the dam, were extracted from the results. A distance of $2P$ was used as the standard location for upstream depth measurement in order to avoid the effects of drawdown as water flows over the dam. A distance of $3P$ was used as the downstream measurement location in order to minimize the error associated with turbulence directly downstream of the dam. A three-dimensional animation representing the magnitude of the $X$-velocities based on color were also created for each simulation. A definition sketch of the numerical model setup of a flat-topped dam simulation is shown in Figure 4.
Numerical Model Verification

In order to verify that the CFD models created would accurately reproduce flow conditions at a low-head dam, a physical model was built at the Utah Water Research Laboratory. This was done so that the numerical results could be compared with physical data to ensure that results obtained were accurate. The physical model consisted of a flat-topped weir that was 0.61 m high, 0.15 m thick and 1.83 m wide. The weir was installed in a rectangular laboratory flume (1.83 m wide by 9 m long and 1.22 m deep). Eight physical model tests were performed using four different upstream water depths. Downstream water depths were adjusted using various sizes of stop logs. As with the numerical models, the upstream and downstream flow depths were measured at locations of 2P and 3P from the upstream face of the dam, respectively, using piezometers installed along the bottom of the flume.

Once a desired upstream water depth had been achieved, a flow meter was used to measure the flow rate, the downstream water depth was recorded from the downstream piezometer, and video and pictures were taken. Also, flow depths were measured with a
ruler at 1.52 m beyond the designated depth measurement locations to aid in the setup of the corresponding CFD models.

Once the physical model tests had been completed, the corresponding CFD simulations were created using the same procedures and parameters as the aforementioned numerical models. The models were constructed so that the computational mesh extended 1.52 m beyond the designated depth measuring locations in both the upstream and downstream directions. The specified pressure boundaries at these ends of the computational domain were set accordingly with specified fluid depths of the values obtained at the same locations in the physical models. Table 1 shows the comparison of results between the numerical and physical model tests described above.

As can be seen, the largest percentage error encountered in any of the models tested was that of comparison four in flow rate, with a percent difference of 7.5%. This model also had the largest percentage difference in downstream water depth at 5.9%. The relatively small discrepancies in the data presented in Table 1 have been deemed acceptable for this study. It has therefore been concluded that the numerical setup being used accurately reproduces the desired physical flow conditions at low-head dams.

Figures 5 and 6 show an animation of the numerical model and a photo of the physical model, respectively, of the tests shown in comparison 6 of Table 1. Notice the similar nappe shape and downstream roller characteristics including the upstream directed surface velocity.

Figures 7 and 8, respectively, show the tests from comparison 3. These tests showed the ability of the CFD program to model flow conditions when the tailwater depth was sufficiently high to cause the nappe to flip to the surface.
Table 1. Numerical and physical model comparison data

<table>
<thead>
<tr>
<th>Comparison</th>
<th>$Q$ (m$^3$/s)</th>
<th>$h_u$ (m)</th>
<th>$h_d$ (m)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Comparison 1</strong></td>
<td><strong>CFD</strong></td>
<td>0.064</td>
<td>0.686</td>
<td>0.305</td>
</tr>
<tr>
<td><strong>Physical Model</strong></td>
<td>0.062</td>
<td>0.686</td>
<td>0.290</td>
<td></td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td><strong>3.7</strong></td>
<td>0.0</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td><strong>Comparison 2</strong></td>
<td><strong>CFD</strong></td>
<td>0.064</td>
<td>0.686</td>
<td>0.387</td>
</tr>
<tr>
<td><strong>Physical Model</strong></td>
<td>0.062</td>
<td>0.686</td>
<td>0.381</td>
<td></td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td><strong>3.7</strong></td>
<td>0.0</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td><strong>Comparison 3</strong></td>
<td><strong>CFD</strong></td>
<td>0.062</td>
<td>0.686</td>
<td>0.646</td>
</tr>
<tr>
<td><strong>Physical Model</strong></td>
<td>0.062</td>
<td>0.686</td>
<td>0.649</td>
<td></td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td><strong>0.0</strong></td>
<td>0.0</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td><strong>Comparison 4</strong></td>
<td><strong>CFD</strong></td>
<td>0.200</td>
<td>0.762</td>
<td>0.274</td>
</tr>
<tr>
<td><strong>Physical Model</strong></td>
<td>0.186</td>
<td>0.762</td>
<td>0.259</td>
<td></td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td><strong>7.5</strong></td>
<td>0.0</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td><strong>Comparison 5</strong></td>
<td><strong>CFD</strong></td>
<td>0.194</td>
<td>0.762</td>
<td>0.652</td>
</tr>
<tr>
<td><strong>Physical Model</strong></td>
<td>0.186</td>
<td>0.762</td>
<td>0.634</td>
<td></td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td><strong>4.4</strong></td>
<td>0.0</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td><strong>Comparison 6</strong></td>
<td><strong>CFD</strong></td>
<td>0.303</td>
<td>0.805</td>
<td>0.375</td>
</tr>
<tr>
<td><strong>Physical Model</strong></td>
<td>0.295</td>
<td>0.808</td>
<td>0.369</td>
<td></td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td><strong>2.8</strong></td>
<td>0.4</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td><strong>Comparison 7</strong></td>
<td><strong>CFD</strong></td>
<td>0.303</td>
<td>0.814</td>
<td>0.716</td>
</tr>
<tr>
<td><strong>Physical Model</strong></td>
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<td>0.817</td>
<td>0.686</td>
<td></td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td><strong>2.7</strong></td>
<td>0.4</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td><strong>Comparison 8</strong></td>
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<td>0.723</td>
<td>0.671</td>
</tr>
<tr>
<td><strong>Physical Model</strong></td>
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<td>0.726</td>
<td>0.671</td>
<td></td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td><strong>3.0</strong></td>
<td>0.4</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>

In addition to verifying the accuracy of the numerical models, the physical model was also used to observe the ability of the roller to catch a one-fifth Froude scale human dummy. The dummy used for this purpose was cut out of a sheet of high density polyethylene. The prototype height of the dummy was 1.75 m, which corresponds to a model height of 0.35 m. The desired weight and buoyancy of the model was achieved through a trial and error process that involved cutting material from the chest and head of the model, placing bolts through its ankles, and filling the empty chest cavity with
polystyrene foam. The bolts and polystyrene foam were primarily used to achieve an upright floating orientation that would most closely approximate that of an individual wearing a life preserver. The final weight of the model was 0.68 kg, which corresponds to a prototype weight of 85 kg.

![Animation of CFD results from comparison 6](image)

**Fig. 5.** Animation of CFD results from comparison 6

![Photo of physical model test from comparison 6](image)

**Fig. 6.** Photo of physical model test from comparison 6
The laboratory flume used for the scaled physical model was relatively narrow compared to an actual river that this size of dam would most likely be found in. For this reason, sidewall effects played a significant role on the actions of the dummy as it traveled over the dam. In most instances, the dummy would get caught in the roller
momentarily, but almost inevitably would end up being sucked to one of the sidewalls
due to a lateral current created by the vertical sidewalls. Although this did hinder
attempts to observe how long a person would stay trapped by the roller, several runs did
successfully manage to trap the dummy in the roller for several minutes, before the
sidewall effects took over. For this reason, it was determined that physical models tested
were capable of catching and holding a person.

Results

The minimum X-component of surface velocity \( V_{x,\text{min}} \) directly below the dam
was used to compare roller strengths among the models tested. For the purpose of
simplifying the analysis of the results, a \( V_{x,\text{min}} \) of +3 was assigned to all simulations
observed to display a swept-out hydraulic jump. All simulations that had a flipped nappe
were assigned a value of +1 for \( V_{x,\text{min}} \). This was done because these cases did not create
the dangerous roller with upstream directed surface velocities that is the primary focus of
this study. The value of \( V_{x,\text{min}} \) for all other simulations was extracted from the numerical
results.

Once the data from the CFD models had been collected, the next step was to
identify a combination of parameters that could accurately be used to distinguish between
the conditions of the roller, swept-out jump, and flipped nappe. For this analysis, \( V_{x,\text{min}} \)
was used to calculate a dimensionless velocity factor \( V^* \) as presented in Equation 4,
where \( g \) is the acceleration due to gravity and equals 9.81 m/s\(^2\).

\[
V^* = \frac{V_{x,\text{min}}}{\sqrt{2g(h_u - h_f)}}
\]  

(4)
This velocity factor was used to represent the strength of the roller, with a negative value indicating an upstream directed surface velocity, and therefore the presence of a roller.

The ability to distinguish between the different states of flow at a low-head dam was examined using several factors made up of different combinations of parameters. Some of these factors included \( h_u - h_d \), \( (h_u - h_d)/P \), \( h_u/h_d \), and \( Fr_u/Fr_d \) (where \( Fr_u \) is the Froude number at the upstream measurement location, and \( Fr_d \) is the Froude number at the downstream measurement location). These factors were plotted on the X-axis against the corresponding \( V^* \) from each of the simulations.

After examining the resulting plots, it was observed that the only factors that displayed any type of clear relationship were those utilizing the non-dimensional factors of \( (h_u - h_d)/P \) and \( Fr_u/Fr_d \). Because of the difficulty of measuring the parameters required to calculate the Froude number in the field, it was determined that using the latter of the two factors would defeat the purpose of this study, which is to utilize only easily measured parameters. Therefore, the factor chosen for this classification system was that of \( (h_u - h_d)/P \), which has been named the risk factor. The plot of risk factors versus \( V^* \) for the ogee shaped dams is shown in Figure 9. The plot of risk factor versus \( V^* \) of the simulations consisting of a flat-topped dam is shown in Fig. 10.

The roller length ratio \( (L_r/P) \) was calculated for every simulation as the roller length \( (L_r) \) divided by the dam height. The length ratios were then plotted against the risk factor in Figure 11.
Fig. 9. Ogee-crested simulation results

Fig. 10. Flat-topped simulation results
Discussion

Ogee-Crested

As depicted in Figure 9, the transition between simulations with a roller and those with a flipped nappe occurs between risk factors of 0.224 and 0.231. It was decided that in order to be conservative, the maximum value of the risk factor for the flipped nappe simulations (0.224) would represent this transition point.

The transition zone between the simulations featuring a swept-out hydraulic jump and those with a roller is much wider. The maximum risk factor encountered in simulations with a roller was 0.950, whereas the minimum value for the swept-out cases was 1.238. No simulations fell into the boundary region encompassing values between 0.950 and 1.238 because values within this range are physically unattainable due to the conservation of momentum and flow conditions involved. If the tailwater depth at a low-head dam featuring a swept-out jump is increased, it will reach a point where the jump is
no longer positionally stable. Beyond this point, the hydraulic jump must retreat to the face of the dam to become stable again, at which point the jump becomes submerged.

The actual transition point used to discern between the presence of a roller and a swept-out hydraulic jump for ogee-crested dams was determined to be the minimum risk factor for simulations featuring a swept-out hydraulic jump. This value of 1.238 was again used to be on the conservative side.

Therefore, if a risk factor at an ogee-crested low-head dam is calculated to be between the values of 0.224 and 1.238, it should be assumed that a roller is present and the associated drowning risk is high. On the other hand, if a risk factor of less than 0.224 is encountered, it can be assumed that the nappe has flipped and there is no roller present. Likewise, if a risk factor of greater than 1.238 is encountered, the hydraulic jump has been swept-out and there is no roller present. For these two cases the drowning risk associated with roller formation can be considered low.

**Flat-Topped**

For the simulations consisting of a flat-topped dam shape, the transition zone between the flipped nappe simulations and those with a roller occurred at noticeably higher risk factor values than those for the ogee-crested shape. This difference in risk factors which make up the transition zone is due to flow separation at the downstream edge of the flat-topped dam. Flow separation does not occur with ogee-crested dams because the flow stays attached to the ogee profile as it flows over the crest. For this boundary, the definition of the transition point was again taken to be the conservative maximum value of the risk factor for the flipped-nappe simulations, which was 0.248.
Therefore, low-head dams with a risk factor of less than 0.248 should be assumed to have a flipped nappe and would be considered low-risk.

For the flat-topped shape, the transition zone between roller formation and the swept-out state of the hydraulic jump occurred between risk factors of 0.920 and 0.974. Again, to be conservative, the definition transition point for this study was taken to be the minimum risk factor of the swept-out hydraulic jump simulations, or 0.974. Therefore, if a low-head dam is known to have a risk factor of greater than 0.974, it should be assumed that no roller exists and hazards are minimal in that respect.

**Conclusion**

In this study, computational fluid dynamics in conjunction with a physical model were used to simulate flow over two common shapes of low-head dams, ogee-crested and flat-topped. The objective was to identify a risk factor which consists of parameters that are easily measured in the field, that could be used to distinguish between high-risk and low-risk states of flow that are possible at these dams. These different states of flow include a swept-out hydraulic jump, submerged hydraulic jump (and the presence of a roller), and a flipped nappe.

When a swept-out or flipped nappe scenario is encountered, it is considered a low-risk situation for the purpose of this study. This is due to the fact that when these flow conditions occur, the dangerous roller is not created, and a person would be flushed past the dam with no chance of being recirculated through a roller. On the other hand, when flow conditions are such that a roller is formed, the drowning risk is assumed to be high. This is due to the upstream directed surface velocity associated with the roller that
can trap a victim for prolonged periods of time, in combination with the decreased density of the water found there.

The combination of easily measureable parameters that was found to best identify key transition points between these states of flow was \((h_{w}-h_{d})/P\), and was named the risk factor. For the ogee-crested dams tested, the high-risk zone consisted of risk factors ranging from 0.224 to 1.238. Risk factors of less than 0.224 can be assumed to be of the flipped-nappe state and therefore low-risk. Risk factors greater than 1.238 can be assumed to consist of a swept-out hydraulic jump, and therefore low-risk as well.

For low-head dams with a flat-top shape, the dangerous zone consisting of a roller was found to range from risk factors of 0.248 to 0.974. If the risk factor at a dam is found to be less than 0.248, the flow conditions are probably that of a flipped nappe. If it is greater than 0.974 there is probably a swept-out hydraulic jump present. Both of these conditions can be assumed to be low-risk with regard to rollers for the reasons mentioned earlier.

By establishing the easily obtainable risk factor and identifying ranges that predict high-risk flow conditions in regard to roller formation, it is anticipated that low-head dam owners and recreational water users will be able to make more informed decisions. More informed decisions will be based on a greater understanding of the hydraulic conditions creating increased risk associated with low-head dams. The author’s greatest desire is that the results of this study may save one and hopefully many lives.

**Revised Data**

As already mentioned, the current chapter was submitted to the Journal of Hydraulic Engineering for publication. As part of this process, the manuscript was peer
reviewed by three experts in the field of dam and spillway hydraulics and sent back for revisions before being published. One of the concerns of the reviewers was the location for upstream and downstream measurement of the water depth. It was felt that $2P$ upstream from the dam was too close to the structure, and would therefore pick up the effects of drawdown as water approaches the crest of the dam. The $3P$ downstream measurement location was a concern because, in many cases this location fell within the length of the roller, therefore effecting the results.

In order to eliminate the possible source of inaccuracy associated with these measurement locations, the data was recollected using measurement locations further away from the structure. The new upstream measurement location used was $3P$, because at this distance no effects due to drawdown were discernable in the data. After reviewing the simulation results and noting that, of the scenarios tested, none produced rollers that extended further than about $5.9P$ downstream, $6P$ was chosen as the new measurement location since this was beyond the boil line for all simulations.

The results obtained using these updated measurement locations produced data that looked very similar to the original data, therefore leading to the same conclusions, but with slightly different limiting values for the different risk levels identified. Figures 12 and 13 show the revised ogee and flat-topped results, respectively, with the limiting risk factors for the scenarios with a roller labeled.

These revised results were used for the procedures described in the next chapter.
Fig. 12. Revised ogee-crested results

Fig. 13. Revised flat-topped results
CHAPTER IV
LOW-HEAD DAM REVERSE ROLLER REMEDIATION OPTIONS

Abstract
This study examines possible remediation options to mitigate dangers found at low-head dams. The objective was to identify at least one remediation option that would be relatively simple to implement and effective over a range of flows. Two remediation configurations were identified to this end, and consisted of either ramps, or platforms protruding from the downstream face of the dam, spaced along the width of the channel downstream of the low-head dam. The consistent hydraulic element among the configurations identified was their ability to disrupt the roller, preventing it from creating an entrapment hazard. Three different designs were tested for each of the configurations (R1, R2, R3, P1, P2, and P3). Effectiveness of the options was evaluated based on entrapment times of human dummies introduced upstream of the dams. The P2 design was shown to be the most effective option tested on both dam shapes, with an overall average entrapment time of 17.4 seconds. The R3 and P3 designs produced smaller entrapment times, but were only tested on flat-topped dam shapes.

Introduction
Low-head dams have been used for over a century all over the United States and the world to impound small volumes of water and to serve other various purposes. Although these structures are relatively small, usually standing between 3 and 5 m in height (Tschantz and Wright 2011), and having a relatively calm and quiescent

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1Coauthored by Michael C. Johnson P.E., and Steven L. Barfuss P.E.
appearance, they have proven to be literal “drowning machines.” This is due to a reverse roller that can form at the downstream face of the dam when the hydraulic jump there is in a submerged state, as described by Leutheusser and Fan (2001).

This countercurrent can be attributed to several factors. First, as the overflowing nappe impacts the downstream water surface, nearby water is entrained into the submerged jet that is formed. Also, as a result of the impact and the associated turbulence, air is entrained into this flow, therefore decreasing the density of the mixture. The jet is deflected downstream by the channel bottom, and begins to rise toward the surface as a result of the reduced density. The point where the jet resurfaces is known as the boil line. It is called the boil line because of the surfacing air bubbles and a slightly higher surface elevation, which give it the appearance of boiling water. The increased surface elevation creates an elevation gradient which causes water to flow back towards the face of the dam. At this point, the water is also beginning to feel the draw created by the entrainment of surface water by the impinging nappe discussed earlier. Another danger created by this process is a reduced buoyant force exerted on submerged objects in the area upstream of the boil line due to the decreased density of the water. This buoyant force can be as low as thirty percent of the normal buoyant force on an object (Tschantz and Wright 2011), and therefore causes life preservers to lose their effectiveness and makes it more difficult for victims to stay afloat.

The upstream directed surface velocity that can be created by this process can be so excessive that it can exceed the swimming velocity of some of the world’s fastest trained college swimmers (Leutheusser 1988). As a victim that has been trapped by the
roller struggles against this strong current, they can quickly become exhausted and drown before being ejected or rescued.

Several studies were found that explain and classify the various flow conditions that are possible at low-head dams. Some of these studies include those performed by Govinda Rao and Rajaratnam (1963), Leutheusser (1988), Leutheusser and Birk (1991), Leutheusser and Fan (2001), Mossa et al. (2004), Ohtsu and Yasuda (1991), and Tschantz and Wright (2011).

A risk factor was identified in the previous chapter that is calculated as \((h_u-h_d)/P\), where \(P\) is the height of the dam, \(h_u\) is the upstream water depth at a distance of \(3P\) from the upstream face of the dam, and \(h_d\) is the downstream water depth at a distance of \(6P\) from the upstream face of the dam. This factor can predict the risk of entrapment by a roller below a low-head dam based on these parameters. It was found that for the ogee shaped dams tested, the risk of entrapment by a roller was present between risk factors of 0.09 and 0.80. For flat-topped dams, the risk of being trapped by a roller was highest between risk factors of 0.34 and 0.71. It was also found that the entrapment zone below 3.05 m tall low-head dams can be up to \(6P\) downstream from the dam.

Studies that examine possible solutions to the effects of the “drowning machine” seem to be few and far between. One possible remediation option that has been proposed by Leutheusser and Birk (1991) is to install baffled chute spillways at low-head dams to break up the roller through the use of continuous energy dissipation by cascade effects, rather than through a hydraulic jump. Hotchkiss and Comstock (1992) countered the proposal of baffled chute spillways as a blanket solution to drowning machines, claiming that these structures have the potential to create more danger for the public than the
original structure. Other solutions that have been suggested include complete dam removal, placement of large diameter boulders downstream of the dam, placement of grout bags at the base of the dam, and the installation of a stepped spillway on the downstream face of the dam, all of which are discussed briefly by Schweiger (2011).

Another solution discussed by Schweiger (2011) and Garcia et al. (2005) to mitigate the dangers at low-head dams, as well as to promote natural fish passage at these structures, is the use of a rock arch rapid as developed by Aadland (2010). This solution consists of a gradual boulder and cobble ramp built in a U-shaped configuration nearly up to the crest of the dam. One primary disadvantage of most of these proposed solutions is that they can potentially be very costly to implement effectively. Also, depending on the purpose and function of the dam in question, some of these options are simply not feasible.

The computational fluid dynamics (CFD) software, Flow-3D®, was used in conjunction with physical model tests in this study to identify several possible remediation options that could be fairly inexpensive and straightforward to implement. Two such configurations were found for flat-topped and ogee-crested low-head dams 3.05 m in height, that were capable of breaking up the reverse roller throughout a range of risk factors proven to be associated with high risk of entrapment, as discussed in the previous chapter.
Experimental procedure

Numerical Models

Studies by Savage and Johnson (2001), Garcia et al. (2005), and Johnson and Savage (2006) were used as verification that the CFD package Flow-3D® was capable of accurately reproducing the flow conditions over ogee-crested spillways and low-head dams in general. Each of these studies performed CFD simulations and verified the results with physical model tests.

Within the numerical models, the longitudinal and lateral dimensions of the computational domain used in each simulation were 3.05 m and 27.43 m, respectively, with only the height and the mesh cell size varying between simulations. The upstream and downstream boundaries were set at a distance of 3P and 6P from the upstream face of the dam, respectively, the distances at which $h_u$ and $h_d$ were measured in the previous chapter. All computational domain boundary conditions were as follows:

- Upstream boundary ($X_{\text{min}}$): Specified pressure boundary with a stagnation pressure left blank and a specified fluid depth $h_u$
- Downstream boundary ($X_{\text{max}}$): Specified pressure boundary with a stagnation pressure left blank and specified fluid depth $h_d$
- Bottom boundary ($Z_{\text{min}}$): Wall boundary (no slip)
- Top boundary ($Z_{\text{max}}$): Symmetry boundary (no influence on model due to open channel)
- Side boundaries ($Y_{\text{min}}$ and $Y_{\text{max}}$): Symmetry boundary
The upstream flow depths \((h_u)\) and tailwater depths \((h_d)\) used for the simulations were chosen so as to produce risk factors proven to create a roller, as determined in the previous chapter. It was desired to determine whether a particular remediation option would be effective throughout the entire range of risk factors identified as high risk of entrapment, for both the flat-topped and ogee-crested shape. Therefore, an \(h_u\) and \(h_d\) combination was chosen from the upper, middle, and lower end of this danger range for both dam shapes. The scenarios and the associated headwater/tailwater combinations tested in this study are shown in Table 2.

In order to evaluate the effectiveness of possible remediation options, three human dummies were introduced into the CFD simulations upstream of the dam at lateral spacings that placed them at different locations in relation to dam modifications. The dummies represented a person that was 1.83 m tall and weighing of 84.1 kg with a density of 0.84 g/cc. The desired densities and weights were achieved by modeling each dummy as two stacked 0.91 m tall cylinders of 0.27 m diameter. The density of the bottom and top cylinders were 1.29 g/cc and 0.38 g/cc, respectively, giving an average density of 0.84 g/cc.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>(P) (m)</th>
<th>(h_u) (m)</th>
<th>(h_d) (m)</th>
<th>Risk Factor ((h_u - h_d)/P)</th>
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</thead>
<tbody>
<tr>
<td><strong>Flat-Topped</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Lower Limit</td>
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<td>5.18</td>
<td>0.400</td>
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<td>4.88</td>
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<tr>
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<tr>
<td><strong>Ogee-Crested</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>3.05</td>
<td>3.66</td>
<td>0.702</td>
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</table>
Simulations were performed in series, with each series corresponding to a different headwater/tailwater scenario, as listed in Table 2. Each series consisted of a pair of simulations for each of the remediation options tested, as well as for a base run with no modifications installed. The first simulation in a pair was used to establish steady state conditions, in which the dummies were held in a fixed location 1.83 m upstream from the dam. Once the initial simulation in the pair had reached steady state, a restart simulation was created in which the initial conditions were taken from the final time step of the previous simulation, and the dummies were given coupled motion, allowing them to be influenced and carried by the flow. The base run in each series was used to show the ability of the modeled conditions to trap the dummies with no remediation option applied. Figure 14 shows a CFD animation of one of the simulated base runs in which the dummies were trapped by the roller.

Fig. 14. CFD animation of dummies trapped in a roller
Physical Models

The primary purpose of performing physical model tests in addition to CFD simulations was to verify the numerical results. This was done by constructing a one-fifth Froude scale flat-topped low-head dam model in a 1.38 m wide rectangular laboratory flume at the Utah Water Research Laboratory. Similar to the CFD models, the upstream and downstream water depths were measured at a distance of $3P$ upstream and $6P$ downstream from the upstream face of the dam, using piezometer tubes installed near the floor of the flume. Due to limited capacity of the flume used, only flat-topped scenarios 2 and 3 could be verified with the physical model. Headwater/tailwater combinations between these two scenarios were also verified with the physical model.

In order to observe a remediation options ability to break up the roller and flush the dummy through the normal entrapment zone, a one-fifth Froude scale human model was constructed out of high density polyethylene. The desired scaled weight was obtained by removing material from the head and chest area of the model, while adding ballast to its legs. This gave the model an upright floating orientation that resembled that of a person wearing a personal flotation device.

It was also desired to verify that the modifications made to the dams would not affect upstream flow characteristics so as to preserve the functionality of dams used for flow measurement and other functions sensitive to headwater depth. This was done by calculating $C_d$ values from the weir equation (5), in which $Q$ is the flow rate, $W$ is the width of the dam, $g$ is the acceleration due to gravity ($9.81 \text{ m/s}^2$), and $H_t$ is the total head above the crest of the dam at the upstream measurement location. The calculated $C_d$
values were then compared to that of the base run in which no modifications were present.

\[ Q = \frac{2}{3} C_d W \sqrt{2gH} \]  

(5)

**Results**

Several low-head dam remediation options were simulated to test their ability to break up, or at least significantly reduce the size and strength of the roller. All of these tests were performed on 3.05 m tall low-head dams of the flat-topped and ogee-crested shape. Some of the unsuccessful options included half circle baffles spaced at regular intervals along the width of the channel, the same half circle cross-sectional geometry except spanning the whole channel width with no gaps, downstream facing ramps spaced across the width of the channel and positioned against the downstream face of the dam, the same downstream facing ramp design without spaces and therefore spanning the whole channel width, and an upstream facing ramp placed against the downstream face of the dam and spanning the width of the channel. These options, which are shown in Figure 15, were not effective at significantly changing the flow patterns, and retained the vast majority of the dummies introduced into the flow.

Two options were identified that were proven to be effective at allowing the dummies to be flushed past the low-head dam more consistently than the other options specified. The next sections discuss these options in more depth.

**Upstream Facing Ramps**

*Flat-Topped.* The first of the options that showed potential at eliminating the reverse roller were upstream facing ramps positioned with the low end placed against the
downstream face of the dam, and spaced at regular intervals along the channel width as shown in Figure 16. Three variations of this design were tested in this study and are referred to as R1, R2, and R3 throughout the remainder of this paper.

The first ramp design (R1) consisted of a ramp height ($h_r$) of $0.5P$, ramp width ($w_r$) of 0.61 m, ramp spacing ($s_r$) of 0.61 m, and ramp length ($L_r$) of $P$. The R2 ramp design had the same $L_r$, $w_r$, and $s_r$ as R1, but with the ramp heights increased to $0.75P$, increasing the slope of the ramps to 0.75 (V:H). The final ramp design tested (R3) had the same cross sectional ramp geometry as the R2 configuration, but with altered ramp widths and spacing. This design consisted of a $w_r$ and $s_r$ of 1.83 m. The latter design was tested to determine if the roller could effectively be broken up or reduced at larger ramp spacings, making passage by recreational water users safer at lower flows.

The ramp configuration R1 was tested only using CFD. R2 was tested using CFD and verified with the physical model. The R3 configuration was primarily tested in the physical model, with the only CFD simulation being that of the highest headwater and
Fig. 16. Flat-topped ramps definition sketch

tailwater depth (scenario 1) since it could not be tested in the physical model due to the limited capacity of the flume.

*Ogee-Crested.* The ramp configurations R1 and R2 tested on the flat-topped dams were also tested on the ogee-crested dam shape using the numerical model. The dimensions of the ramps and associated spacings in both of these designs were identical to that of the respective flat-topped tests, but with the ramps positioned so that the downstream ends were flush with the end of the flip bucket of the dam, as depicted in Figure 17.
Protruding Platforms

*Flat-Topped.* The second remediation option identified as a potential solution to the drowning machine was spaced platforms protruding from the downstream face of the dam, as depicted in Figure 18. Three variations of the protruding platform design were tested using the aforementioned methods, and are referred to as P1, P2, and P3 throughout this paper.

The first platform design (P1) consisted of platform widths \((w_p)\) and spacings \((s_p)\) of 0.61 m. The height of the platforms \((h_p)\) for this design was 0.8\(P\) and platform lengths \((L_p)\) were 0.75\(P\). The P2 design had similar dimensions to the P1 design, with the only exception being \(L_p\), which was increased to 0.85\(P\). The P3 design used the P1 cross sectional platform dimensions, but \(w_p\) and \(s_p\) were both increased to 1.83 m. Like the R3 design, the P3 configuration was tested in order to determine its effectiveness at larger spacings, allowing for safer and easier passage to water users passed over the dam.
The P1 and P2 configurations were tested solely using the numerical model. P3 was primarily tested using the physical model, with the only CFD simulation again being that of scenario 1.

*Ogee-Crested.* The P1 and P2 designs tested on the flat-topped dam shape were also tested on ogee-crested dams numerically. The definition sketch of the ogee platform configuration is shown in Figure 19. Similar to the flat-topped simulations discussed earlier, $h_p$ for the ogee simulations was $0.8P$ for both designs. $L_p$ was $0.5P$ for the P1 tests and $0.6P$ for P2 tests. The platform widths ($w_p$) and spacings ($s_p$) were $0.61$ m for both P1 and P2.
Remediation option effectiveness was evaluated based on dummy entrapment time, or the time that passed between entrance of the dummies into the entrapment zone to when the last dummy exited the computational domain of the restart simulations (6P downstream from the dam). All restart simulations were allowed to run until the last dummy exited the computational domain or the dummies had been inside the entrapment zone for at least 50 seconds, whichever was shortest. Any remediation option simulation which still had dummies within the entrapment zone after 50 seconds of entering, was considered an ineffective option. Entrapment times were then averaged for each
remediation option to determine the best solution to reduce the danger of entrapment by a roller.

Comparison of the numerical results to those of the physical model tests showed close correlation, and therefore verified that the numerical setup of the CFD software was accurate and produced results that were trustworthy.

The entrapment times determined for each of the six remediation options tested are shown in Table 3. Scenarios in which the dummies introduced into the flow were flushed through the entrapment zone in less than 50 seconds are shown in green, whereas those in which the dummies remained trapped for longer than 50 seconds are shown in red. An asterisk indicates a test that was only tested using the physical model.

The entrapment times for flat-topped and ogee-crested tests shown in Table 3 were then averaged separately for each of the different remediation options. An overall average entrapment time was also calculated incorporating both dam shapes. These averaged times are shown in Table 4. Figure 20 provides a graphical representation of this averaged data.

<table>
<thead>
<tr>
<th>Table 3. Individual remediation option entrapment times</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario</strong></td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>Flat-Topped</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Ogee-Crested</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

* Physical model only
Table 4. Averaged remediation option entrapment times

<table>
<thead>
<tr>
<th>Remediation Option</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat-Top Average</td>
<td>44.3</td>
<td>22.2</td>
<td>12.2</td>
<td>36.3</td>
<td>18.2</td>
<td>10.8</td>
</tr>
<tr>
<td>Ogee Average</td>
<td>48.1</td>
<td>31.8</td>
<td>-</td>
<td>15.8</td>
<td>16.5</td>
<td>-</td>
</tr>
<tr>
<td>Overall Average</td>
<td>46.2</td>
<td>27.0</td>
<td>12.2</td>
<td>26.0</td>
<td>17.4</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Fig. 20. Average remediation option entrapment times

A plot of the calculated $C_d$ values for flat-topped and ogee-crested scenario three tests is presented in Figure 21.

Discussion and Conclusion

From the data presented in the previous section, the remediation option that was tested on both the flat-topped and ogee-crested dam shapes that had the lowest overall entrapment time and therefore showed the best performance, was that of the P2 configuration. This option demonstrated its ability to flush dummies with human characteristics through the normal entrapment zone below a low-head dam for a range of
risk factors proven to present a roller capable of trapping an average human, as discussed in the previous chapter.

The R3 and P3 options resulted in the absolute lowest entrapment times among the flat-topped tests performed, and are therefore considered the most effective options. However, due to time constraints associated with this project, these configurations were physically tested only on flat-topped dams. Therefore, it is not known for certain how they would perform in conjunction with an ogee-crested dam, although based on the good agreement between the CFD model and the physical model, the authors are confident that these options would perform well.

The design of the remediation options were such that they are located downstream from the control section of the low-head dam. The purpose for this was to enable installation and operation of the original structure without influencing the upstream flow depths. In order to verify this, a comparison of $C_d$ values was performed between a base
run simulation and several remediation option simulations for both the flat-topped and ogee-crested low-head dams. This comparison showed that the discharge coefficient was not influenced by the introduction of the modifications.
CHAPTER V

CONCLUSION

The CFD program Flow-3D® was used to model flow conditions over oggee-crested and flat-topped low-head dams. These structures have come to be known as “drowning machines” because of their tendency to trap recreational water users and rescue personnel in a reverse roller formed under submerged conditions. The numerical models created were used in conjunction with physical model tests to identify a risk factor consisting of easily retrieved measurements in the field, that could predict the presence of a roller, and therefore a high risk of entrapment.

The parameter that was identified to perform this function is calculated as 
\[
\frac{(h_u - h_d)}{P},
\]
where \( h_u \) and \( h_d \) are the upstream and downstream flow depths, respectively, and \( P \) is the height of the structure.

Through graphical analysis of the data shown in Figures 12 and 13 for oggee-crested and flat-topped dams, respectively, transitions from low-risk to high-risk conditions with regard to risk of entrapment by the roller were clearly visible. The results showed that for oggee-crested dams, the risk of entrapment was high between risk factors of 0.093 and 0.798. For the flat-topped simulations, risk of entrapment was highest between risk factor values of 0.348 and 0.708. Outside of these ranges, risk of entrapment is considered low because the hydraulic jump has either been swept downstream, or the nappe has flipped to the surface inducing entirely downstream directed surface velocities below the dam.

The next phase of the project involved using Flow-3D® to model several possible remediation options capable of eliminating or significantly reducing the size of the roller.
By doing this, debris and water users passed over the dam are more likely to be flushed past the dam without the risk of being trapped by a reverse roller. In order to assess a remediation option’s ability to perform this function, human dummies were introduced into the simulation or physical model upstream of the low-head dam. The time that the dummies were trapped within the entrapment zone below the structure was timed and compared with the other tested options.

Two general configurations were identified that showed promising performance based on averaged entrapment times for various flow scenarios. The first configuration consisted of upstream facing ramps spaced at regular intervals across the width of the channel. The second configuration consisted of platforms protruding from the downstream face of the dam and spaced at regular intervals along the width of the channel. Each of these configurations were tested with three design variations. The ramp variations were designated with an “R” (R1, R2, and R3), while the platform configurations were designated with a “P” (P1, P2, and P3).

Various configurations of the ramp and platform designs were proven to either hydraulically eliminate or reduce the roller downstream of a low-head dam and therefore reduce risk making them safer from a hydraulic standpoint. However, it should be noted that some of the designs may induce physical injury (versus death) to water users passed over the structure, most notably the R2 design because of the orthogonal nature of the intersection of the ramp surfaces and the overflowing nappe.

Based on the observed entrapment times for remediation options tested on both dam shapes, the P2 design was shown to be the most effective option at eliminating the roller and allowing the human dummies to be flushed through the entrapment zone. The
averaged entrapment time (measured from when the dummy passed the crest of the dam to when it left the entrapment zone) for this design was 17.4 seconds. The R3 and P3 designs were only tested on flat-topped dams, but showed exceptional results with average entrapment times of 12.2 seconds and 10.8 seconds, respectively.

By identifying the risk factor for entrapment at low-head dams, as well as identifying possible options that can be implemented to reduce this risk to the public, it is hoped that at least one life can be saved, and that dam owners, recreational water users, and other concerned individuals will be able to more accurately assess and mitigate the dangers created by low-head dams.
CHAPTER VI
RECOMMENDATIONS FOR FURTHER RESEARCH

One potential area from this study that would benefit from further research is examination and expansion of the identified remediation options. Due to time constraints associated with this project, every possible variation of the two configurations could not be tested. Therefore, it is likely that by altering a single or multiple parameters of the described designs, comparable or smaller entrapment times can be attained with less construction and material requirements, therefore optimizing the designs.

Another possible area of interest for further research could be the application of the risk factor to other dam shapes and sizes not examined in this study. This would potentially allow the factor to be used more broadly.
REFERENCES


