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DESIGN FLOOD IMPACTS ON EVALUATING DAM FAILURE MECHANISMS

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Abstract

The implementation of the Probable Maximum Flood as the basis for the inflow design flood for evaluating dam safety has shown that existing analysis procedures and methods are inadequate. A collaborative team from the U.S. Bureau of Reclamation, Colorado State University, Pacific Gas and Electric Co., the Electric Power and Research Institute, and HDR Engineering, Inc., have identified three critical areas for additional dam safety research. Research programs are currently ongoing to investigate a) erosion protection and energy dissipation on embankment faces and spillways subjected to overtopping, b) erosion at the foundation and abutments of dams from overtopping, and c) embankment dam breach mechanics. Brief descriptions of each program are presented along with early project findings.

Introduction

There are presently more than 80,000 dams in use across the United States. These dams require continual care and maintenance to ensure that they remain operational and capable of performing all intended purposes, while minimizing the risk to people and property downstream if failure occurs. Dams provide a multitude of uses and benefits to society. Common uses include water supply, flood control, recreation, habitat preservation, power generation, and in some cases aesthetic value. Dam size, operations and safety are a function of the inflow design flood (IDF) deemed appropriate for the hazard potential. The philosophy of selecting the appropriate IDF (ICDS, 1994) has evolved over time as greater data and experience bases have been accumulated. The level of safety, or risk, associated with a specific dam is directly related to the IDF.

Before 1900, designers of dams had relatively little hydrologic data to indicate flood potential at a proposed dam site. Estimates of flood potential were selected by empirical techniques and engineering judgment based on high water marks or floods of record on streams being studied. Later, designers began looking at past regional flood peaks for basing their estimates of flood potentials. The concept of the safety factor was developed to compensate for the absence of hydrologic historic record.

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In the 1930s, the previous approaches to flood potential were abandoned because a greater hydrologic data base was being compiled. The previous approach was inadequate and there was not a consistent rationale for applying safety factors. The unit hydrograph approach was adopted for estimating flood potential as runoff could be directly related to the storm rainfall. Dam design became based upon the transposition of major storms that occurred within a region rather than from a generalized national rainfall pattern. It was recognized that flood peaks are dependent on topography, size of individual watershed, and chance placement of the storm's center over the watershed. Also, observed maximum rainfall values could provide a better indication of maximum flood potentials than data on flood discharges from individual watersheds.

During the 1940s and 1950s, hydrometeorologists were integrated onto the precipitation team to determine upper limits for rates of precipitation. The large scale features of the storm and measures of atmospheric moisture were considered as well as the rainfall depth-area values produced by these storms. The concept of the probable maximum precipitation (PMP) was developed that, in turn, introduced the concept of a physical upper limit to flooding that was later termed the probable maximum flood (PMF). The practice of setting inflow design flood standards based upon the size of a dam, its reservoir volume, watershed size and current downstream development has resulted in an inconsistent level of design.

In 1985, The National Academy of Sciences (NAS) published a study of flood criteria that contained an inventory of practices in providing dam safety during extreme floods. The inventory shows considerable diversity in the IDF approach by various government agencies, professional societies, and private firms. However, use of the PMF based on the PMP has become the predominate IDF for high-hazard dams.

Implementation of the PMF as the IDF required that all dams be reevaluated as to hazard evaluation and level of safety. Since more than 22,000 dams are classified as high and of significant-hazard (ICDS, 1994), an extensive effort has been expended to determine common deficiencies and potential modes of failure resulting from the IDF. Failures caused by hydrologic conditions can range from catastrophic (with complete breaching or collapse) to gradual (with progressive erosion and partial breaching). The most common modes of failure associated with hydrologic conditions (i.e., major "low-probability, high-consequence" events) address spillway adequacy, breach potential due to overtopping, and foundation stability during overtopping.

Overtopping of a dam occurs when the water level in the reservoir exceeds the height of the dam and flows over the crest. Failure depends on the type, composition, and condition of the dam and the depth and duration of flow over the dam. Embankment dams are usually the most susceptible to failure when overtopped because of erosion. If the erosion is severe, it can lead to a breach and failure of the dam. During overtopping, the foundation and abutments can be eroded leading to a loss of support and failure from sliding or overturning.

Spillway adequacy addresses the issues of capacity and of erosion resistance. Increased IDF flows have resulted in the inability of existing spillways to safely pass the peak inflow discharge. Spillway capacities have had to be modified to convey the increased discharges. Large flows through spillways adjacent to dams can result in erosion that progresses to the dam. Discontinuities in slope, nonuniformity in lining or bed materials, and concentrated flow can initiate headcuts and accelerate the erosion process. In many cases, the spillway must be reinforced to protect the embankment from increased shear stresses developed from increased flows.

Currently, three collaborative studies led by the U.S. Bureau of Reclamation and other interested entities are either ongoing or in a stage of development to assess the mechanics of dam failure resulting from the new IDF requirements. It is the objective of this paper to briefly describe these studies and present preliminary findings, where applicable. The three studies will focus on embankment and/or spillway erosion protection, estimating erosion at dam foundations, and breach mechanics due to overtopping flows.

Erosion Protection

The PMF design inflow has forced the owners of numerous dams to either expand the spillway capacity, increase the storage or upgrade the embankment to sustain an overtopping condition. Overtopping flows yield extremely high shear stresses resulting in a devastating potential for erosion that could lead to a breach condition. In an attempt to provide alternative methods for protecting embankments and spillways, a collaborative research program was established between the U.S. Bureau of Reclamation (Reclamation) and Colorado State University (CSU). The research program has, thus far, focussed on developing stepped overlay blocks and riprap as protective materials.

Overlay Blocks

Reclamation conducted a laboratory flume study simulating overtopping flow conditions utilizing tapered overlay blocks as the embankment and spillway protective system. The recommended overlay blocks were tested on a 2:1 slope with a 15-degree taper or slope as indicated in Figure 1 (Frizell, 1992; Frizell and Ruff, 1993). The prototype test blocks were 0.37 m long and 63.5 mm high with a maximum thickness of 0.11 m. The blocks are fabricated 0.61 m and 0.31 m wide with drains located through the block from the rise of the step to the underside. The blocks were installed shingle-fashion from the toe and are alternated so that there are no continuous seams in the flow direction except along the side walls. The blocks are placed over 15.2 cm of free-draining, angular, well-graded, gravel filter material.

In order to test the tapered overlay block system in near-prototype conditions, an outdoor facility was constructed at CSU to simulate overtopping. The test facility consists of a concrete headbox, chute, tailbox, and sump with a pump. Figure 2 presents the facility with the overlay blocks prior to testing and Figure 3 shows the overlay blocks during testing. The concrete chute, 2:1 (H:V) slope, has a maximum width of 3.05 m with a removable wall installed to reduce the chute width to 1.52 m. Water is supplied through a 0.91 m pipe from an adjacent reservoir. A portion of the flow can be recirculated by pumping back from the tailbox to increase the total discharge through the facility. Unit discharges up to approximately 2.94 $m^3/m/s$ have been tested.

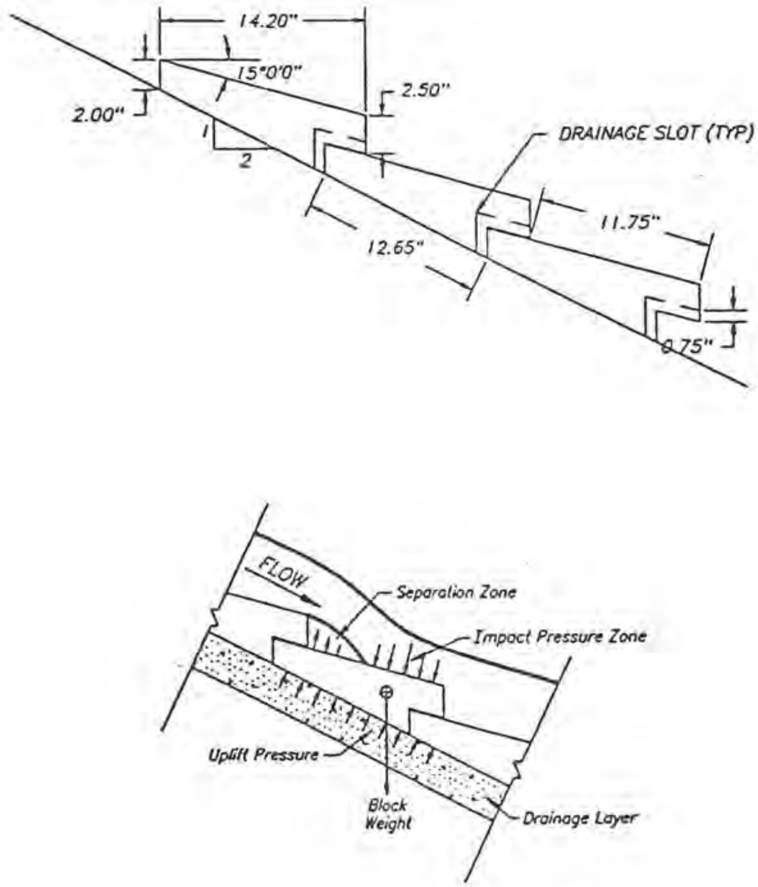

Figure 1 Schematic of the Overlay Block

The tapered overlay blocks were tested over a variety of discharges and flow conditions. Fines and dirt were flushed from the bedding material during the initial flows. Localized settlement of the blocks was observed after extensive testing, however, there were no sliding or noticeable failures (Frizell and Ruff, 1993). The test data indicated that the built-in slots relieved the uplift pressure that develops in the drainage layer. In addition, the block weight, impact pressure, and the downward slope keep the blocks in position. The combination of the downward forces in conjunction with the uplift pressure relief resulted in an extremely stable protection system. In general, Frizell and Ruff (1993) reported 30 to 170 pounds of force per foot of width in the downward direction holding the blocks on the slope. The stability attributed to the overlapping of the blocks was not included in these measurements. Upon conclusion of the tests, the tapered overlay blocks had interlocked and could not be removed without demolishing at least one block.

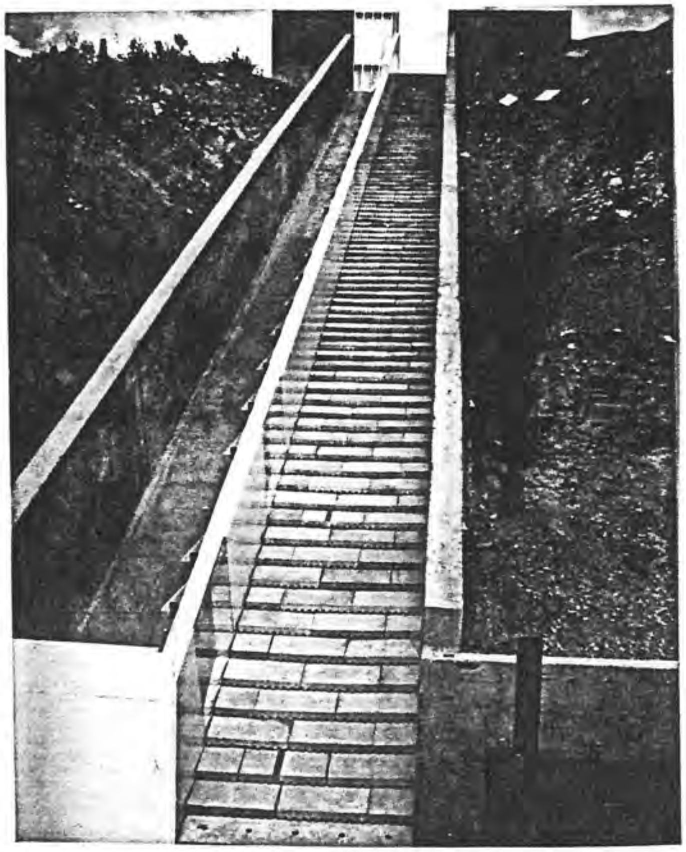

Figure 2 Overtopping Test Facility with Overlay Blocks

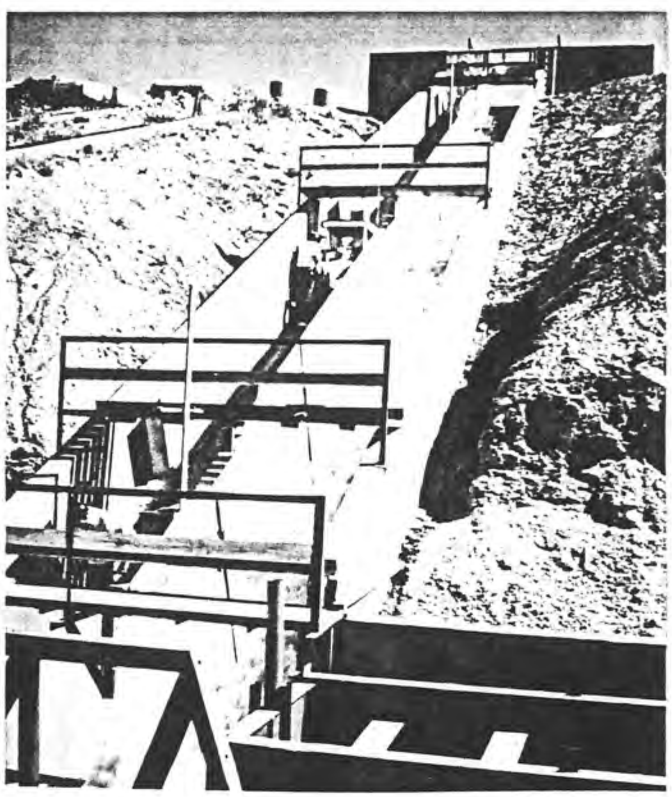

Figure 3 Overtopping Test Facility during Testing

Riprap

One alternative to providing erosion protection on the downstream dam face is by placing a riprap layer on the embankment slope. However, little information exists to properly size the rock to resist the overtopping flow. Reclamation, in conjunction with Colorado State University, utilized the near-prototype overtopping facility to evaluate the overflow and through flow capacity of riprap placed on a steep slope. It is anticipated that these test results combined with the findings of Abt et al. (1991) and Abt and Johnson (1991) will provide an enhancement of the rock sizing criteria previously developed.

A series of overtopping tests was conducted in the 2:1 slope facility by placing a 0.2 m layer of bedding into the test chute (3 m wide and 18.3 m long). A riprap layer 0.61 m thick with median stone size of 0.4 m was placed atop of the bedding. A series of overtopping flows was conveyed through the facility as shown in Figure 4. Instrumentation was installed to measure the through flow velocity, flow depth and discharge in and above the riprap.

Figure 4 Testing of Riprap in the Overtopping Facility

Preliminary test results (Ward, 1994) indicate that the riprap layer conveyed approximately 0.03 m^3/s (unit discharge of 0.01 $m^3/s/m$) of through flow. The rock atop of the riprap layer began to move at a total discharge of 0.07 m^3/s (unit discharge of 0.02 $m^3/s/m$). However, only 0.04 m^3/s (unit discharge of 0.013 $m^3/s/m$) flow at or above the rock surface. It appears as if a large median rock (much greater than 0.4 m) will be required to adequately protect the embankment face from overtopping.

Dam Foundation Erosion

The magnitude of the IDF in conjunction with the inadequacy of the spillway capacity may result in overtopping of the dam crest. One aspect of designing for dam overtopping requires an analysis of the potential for erosion of the dam foundation and abutments. Existing methods of evaluating the extent of erosion have several short-comings because of a limited data base in prototype (current approaches are based on scale models), because current prediction approaches do not track erosion as a function of time, and because the limited data bases disregard hard-rock and cohesive foundations materials. In addition, it is difficult to predict flow patterns and velocity distributions from the impinging jet created as a result of overtopping. The prediction of erosion at dam foundations is as much an art as a science and is dependent on the designer's experience.

A collaborative study is ongoing with the Electric Power Research Institute (EPRI), the Pacific Gas and Electric Company (PG&E), Reclamation, CSU, and HDR Engineering, Inc. to enhance the information base for predicting erosion at dam foundations and abutments due to overtopping (Wittler et al., 1993). The collaborative team formulated a study approach to analyze the mechanics of the impinging jet into the stilling pool, to develop an approach for determining material erodibility, to conduct a laboratory scale model study for evaluating the jet and erodibility hypotheses, and to perform near-prototype evaluations where appropriate. The final objective is to develop a numerical model for simulating overtopping and predicting the extent of foundation and abutment erosion.

One key element of the study attempts to convert the power of the overtopping jet into an expression of energy that initiates and propagates the erosive process at the dam foundation. The rate of energy dissipation (RED), defined as

$$RED = \gamma Q \Delta E \tag{1}$$

where γ is the unit weight of water, Q is the discharge, and ΔE is the energy dissipation selected as the measure of erosive power of discharging water. The higher the RED, the greater the magnitude in pressure fluctuation and turbulent energy loss, and the greater the erosive impact. The erosive power of the plunging jet can be calculated as determined by Annandale and Kirsten (1993).

The erosion process entails the jacking, dislodgement and displacement of material. The capacity of earthen material to resist erosion is determined by its mass strength, particle/block size, interparticle bond strength, relative shape and orientation. The study team adapted geomechanical index methodology developed by Kirsten et al. (1993). The Erodibility Index, K_n, that indicates the ability of earth material to resist erosion is expressed as

$$K_n = K_m \times K_b \times K_d \times K_s \tag{2}$$

K_m is the mass strength factor, K_b is the particle/block size factor, K_d is the interparticle bond strength factor and K_s is the relative shape and orientation factor. Extracted examples of the Erodibility Index factors for mass strength are presented in Table 1.

Table 1 Extended Erodibility Index Values for K_m

Soil	Consistency/Hardness	Mass Strength Number
Granular	Very loose Dense Very Dense	0.02 0.04 0.41
Cohesive Soil	Soft Stiff	0.04 0.19
Rock	Soft Hard	4 - 8 17.7
Detritus	Loose Dense	0.05 0.21

from Annandale and Kirsten, 1993.

In order to refine the mechanics of the jet as it impacts the plunge pool and foundation material, a model facility was constructed for simulating the overtopping jet and characterizing the erosive process. An orifice slit 1.0 m long was fabricated into the side wall of a delivery pipe that was elevated above a stilling/impact basin as presented in Figure 5. The orifice is 50 mm high and is capable of conveying up to 0.18 m^3/s. The orifice assembly rotates about the delivery line allowing the jet to issue at a variety of angles from vertical to horizontal. The stilling/impact basin is 3.05 m wide, 1.52 m deep, and 6.1 m long. Figure 6 presents the model in operation. Initial tests will be conducted to characterize the issuance jet at the orifice and the velocity distribution (and rate of energy dissipation) in the plunge pool.

A near-prototype facility will be constructed three times larger (Froude scaling) than the model. The proposed orifice will be approximately 3.05 m in length with a discharge capacity of 2.83 m^3/s. The stilling/impact basin will be 4.6 m in depth, 9.1 m in width and 16.8 m in length. The near-prototype facility will be used to verify model test findings and to test prototype size materials. Construction of the facility is scheduled to begin in the summer of 1995.

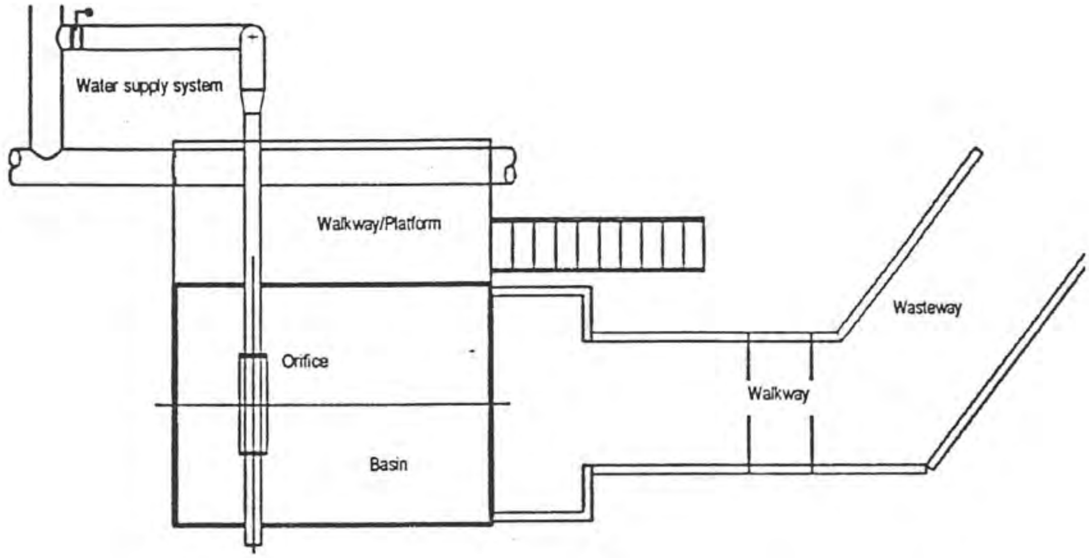

Figure 5 Schematic of the Scale Model Facility

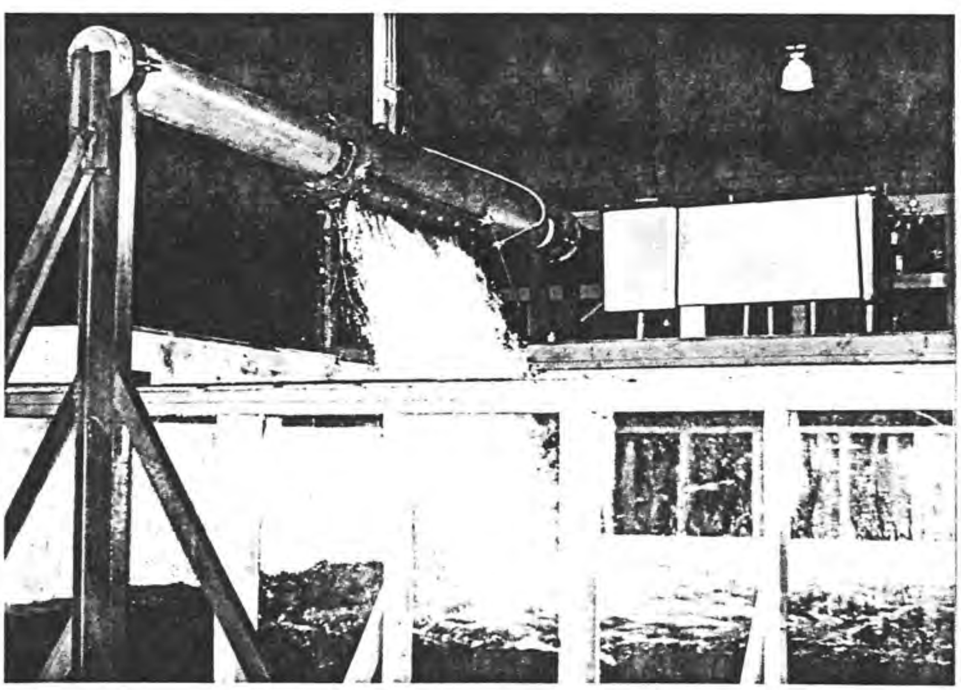

Figure 6 Jet Impacting into Stilling Basin

Breach Mechanics

The PMP based IDF requires that many dams convey the peak discharge through the reservoir and/or over the dam crest. One concern is the impact to persons and property downstream of the dam should the embankment breach due to overtopping. Numerical codes have been developed (i.e., NWS DAMBRK [Fread, 1984], NWS BREACH [Fread, 1988], etc.) to simulate the breaching process. Although boundary conditions are usually known just prior to the breach and upon conclusion of the breach, little is documented concerning the breach parameters during the breach. Reclamation is planning a collaborative research effort to more fully develop the breach parameters that will improve the understanding of the mechanics of embankment dam breach.

A portion of the input into numerical codes that solve the simulation equations is the upstream boundary conditions and the initial conditions at overtopping. The upstream boundary conditions are the physical aspects of the site specific conditions to include the width, breadth and side slopes of the breach as it forms. Breach characteristics are dependent upon the embankment material and hydraulic properties of the dam. In addition, the breach is influenced by the reservoir inflow, reservoir storage characteristics, spillway outflows, and downstream tailwater conditions.

The proposed study would focus on describing hydraulic breach scenarios for large and small reservoirs subjected to overtopping flow conditions. The small reservoir breach is where the reservoir area to dam height ratio results in the outflow peak coinciding with the breach depth reaching the bottom of the dam. The large reservoir breach is where the reservoir head remains marginally unchanged at the time the breach depth reaches the bottom of the dam, and the peak outflow subsequently occurs. Breach parameters will include surface area to dam height, overtopping depth, dam height and material compaction. The monitoring of the temporal aspects of material removal in the breach will also be attempted.

Scale modeling of embankments (i.e., embankments less than 1 m in height) in controlled laboratory conditions has produced questionable results in defining appropriate breach parameters due to the inability to scale the embankment soils and their properties. Therefore, it is proposed to construct a "full" scale facility for breach and failure testing. The constructed facility will be capable of:

- Maintaining a variable upstream water surface,
- Providing tailwater conditions that may be controlled between 0 depth to one-half the embankment height,
- Providing sufficient area to allow a breach width 4 times the height of the planned embankment,
- Allowing for a flow capacity of not less than 4.3 m^3/s, and
- Allowing for prototype embankment heights of up to 2.5 m.

Figure 7 presents a concept for the prototype facility. A minimum of 8 tests would serve as the foundation for the research program.

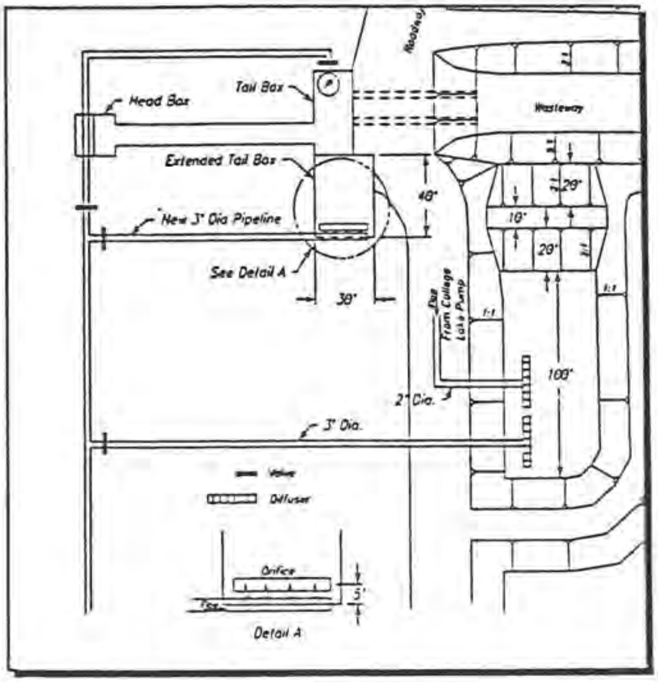

Figure 7 Conceptual Schematic of Prototype Dam Breach Facility

Summary

The use of the Probable Maximum Flood as the inflow design flood for determining reservoir and dam safety has resulted in a re-analysis, and in some cases modification, of the constructed dam. Three critical areas in evaluating dam safety have been identified by the study team that warrant further research; embankment face and spillway protection from overtopping, erosion at dam foundations and abutments from overtopping, and breach mechanics. The two ongoing and proposed research programs were briefly described. It is anticipated that each program will provide an enhancement in the evaluation and design of proposed dams and in determining the safety of existing dams.

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