SPILLWAY AND FOUNDATION EROSION: ESTIMATING PROGRESSIVE EROSION EXTENTS

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Introduction

Causal estimates of the Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) are generally larger than a statistical estimate based upon historical records. Over the past thirty years causal methods have replaced statistical methods for estimating the PMP. These changes in estimating procedures have made dam owners aware of deficiencies in spillway capacity. Dam owners, faced with this new awareness, must show regulating agencies a plan for satisfying a deficiency. Allowing a dam to overtop is an alternative for satisfying a spillway deficiency. This alternative requires an analysis of the potential for erosion of the dam foundation and abutments. Current methods of evaluating erosion extents have limited applicability. Existing erosion prediction formulas do not track erosion as a function of time, and have limited application in hard-rock or cohesive foundation materials.

Spurr (6), in a discussion of a paper by Mason (4), summarizes the problems with current foundation and abutment erosion prediction schemes:

"Thus the disserter contends that time must be considered together with the unique hydraulic and geological processes existing at each site, the amount of surplus energy contained by a given jet at impact over and above the threshold resistance of the bedrock to scour, the shape of the sides of the scour hole, and the size of the downstream bar in order to determine the plunge pool's maturity before any meaningful comparison can be made. This is specifically true when predicting scour in any plunge pool which does not respond as though its bed material were essentially non-cohesive."

Mason (5) in response to Spurr writes,

"The quantification of plunge pool scour rates, in conjunction with varying rock types is an area where much useful research remains to be done."

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The discussion by Spurr and Mason relates to research needs of Reclamation and other dam owners. The need for better analytical tools for analyzing erosion in the foundation and abutment areas of dams is increasing as costly alternatives to overtopping come under consideration. Indeed, if erosion due to overtopping does not place the dam in jeopardy, then alternatives such as spillway enlargement and foundation armoring become unnecessary.

PG&E, EPRI, Reclamation, Colorado State University, and HDR Engineering are collaborating to improve technology for estimating the progressive extents of dam foundation erosion due to overtopping. The new technology couples hydraulic parameters and a geomechanical index system in a numerical model simulating progressive erosion in the foundation and abutment areas of overtopped dams. The collaborators intend to conduct investigations in both 1:3 scale and 1:1 prototype models. The 1:3 scale model provides an economy, while discounting material properties and aeration effects. The prototype model and specialized techniques are necessary for overcoming the limitations of other physical models. These limitations include scale effects associated with jet turbulence, jet coherence, jet air entrainment, and foundation material properties.

**Dam Foundation Erosion: Pre-Test Report**

This paper presents the collaborators' plans and progress for developing new technology. The investigation involves researching existing methods and data, conducting a systematic series of physical model tests, and developing a computer model for simulating the progressive extents of erosion. In a Pre-Test Report (8) and Survey of Literature (9), the collaborators review current technology and explain the basis for the development of new technology.

**Overview**

The primary objective of the study is to develop a numerical model for estimating the progressive extents of erosion. Numerical model developments with properly formulated boundary conditions, simulating physical processes rather than parametric empirical correlation's, may provide useful tools for estimating progressive extents of dam foundation erosion. Predicting flow patterns and air concentrations of plunging jets in prototype situations is largely beyond the capability of conventional physical and numerical modeling techniques. Numerous physical model studies described in the literature have limited application. These limitations are due to the uncertainty of scale effects associated with jet turbulence, jet coherence, jet air entrainment, and foundation material properties. Similar limitations are characteristic of existing numerical modeling techniques that omit the inherent complexities of both impinging jets and earth materials. The development of new technology to predict dam foundation erosion therefore requires application of specialized physical modeling and numerical analysis techniques.

The collaborators intend to conduct experiments in two physical models at the Hydraulic Laboratories of Colorado State University. The first model will have a scale of 1:3 and follows Froude criteria. The second model is prototype scale. The 1:3 scale model provides an economy of scale, accurately modeling hydraulics, with scale effects distorting material properties and aeration effects. Accurate simulation of air-water and water-material interaction without scale effects requires a prototype scale model. The 1:3 scale model is in place at the Hydraulics Laboratory, Colorado State University Engineering Research Center. The prototype scale model requires moderate modification of an existing overtopping facility at Colorado State University.
Facility Plans
The 1:3 scale model facility was completed in the spring of 1994. Figure 1 shows the plan of the facility. An orifice in the side wall of the delivery pipe discharges water into a basin ten feet long, seven feet wide, and six feet deep. An extensive set of configurations resulted in similitude between the orifice and a free trajectory jet. The orifice is 3.33 feet wide, and two inches tall, and discharges up to six cubic feet per second. The orifice assembly rotates about the delivery line, allowing the jet to issue from vertical to horizontal. The objective is to simulate a free trajectory jet like that overtopping a concrete dam. Material may be placed in the facility at varying levels and with various tailwater levels. Instrumentation will be designed and prototyped in the scale model before operation in the prototype facility.

Figure 1. Area plan of 1:3 scale model facility. Note water supply system; wasteway; walkways, platforms, & stairs; basin; orifice.

Facility Plans
The prototype scale facility is adjacent to an existing overtopping research facility at Colorado State University. Construction of the prototype facility requires additions and modifications to the overtopping facility. The prototype facility will utilize many of the components of the overtopping facility. Figure 2 shows the plans for the prototype scale model. The prototype facility is three times as large as the scale model. The basin dimensions are roughly forty-five feet long, thirty-two feet wide, and fifteen feet deep. The support for the ten feet wide orifice and delivery line is ten feet above the top of the basin. Discharge capacity is one-hundred and fifty cubic feet per second, or a unit discharge of fifteen cubic feet per second per foot width. Material will fill the basin to a depth of up to ten feet, leaving up to five feet for tailwater. Plans include instrumentation channels and bulkheads.

Overview of Experiments
There are two parts to this study: Hydraulic Experiments and Material Experiments. The purpose of the hydraulic experiments is to identify the hydraulics of plunging, dissipating jets. The purpose of the material experiments is to identify the processes of erosion of earthen materials caused by a plunging dissipating jet. Each part contains plans for several series and types of experiments. Series refer to experiments intended to illuminate the physical processes of erosion, while types refer to the use or non-use of earthen materials in the experiments.
Figure 2. Plans for the prototype scale facility.

The scale model facility offers economy, performing many series and types of experiments rapidly, with scale effects. The prototype facility offers an unprecedented opportunity for incorporating the effects of aeration and material properties without scale effects into erosion technology. Both facilities have plans for experiments with and without earthen materials in place. Table 1 summarizes the experimental program.

The Hydraulic experiments include measuring flow variables such as velocity, discharge, pressure, rate of energy dissipation, turbulence intensity, angle of incidence, and others. The Material experiments include measuring material variables such as mass strength, particle size, relative orientation and interparticle strength. The material variables also include fundamental geotechnical and geomechanical properties.

Hydraulic Experiments

There are two facets to the hydraulic experiments, instrumentation design and the clear water experiments. Measuring the hydraulic properties of a plunging dissipating jet requires new and unique instrumentation. We anticipate utilizing ground penetrating radar, air concentration probes, and high velocity Pitot tubes in various combinations to measure and track the progressive extents of erosion. The clear water experiments include measurement of the requisite hydraulic parameters such as velocity, aeration, discharge, etc. The majority of the clear water experiments will occur in the scale model facility due to the economy of operating that facility. Experiments that require the most accurate simulation of physical processes will occur in the prototype facility. The scale model facility will serve as a screening facility wherein multiple configurations and experiments will assess the potential value of a prototype scale experiment.
Table 1. Summary of tasks.

<table>
<thead>
<tr>
<th>Scale Model</th>
<th>Prototype Model</th>
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<tr>
<td>1. Instrumentation design</td>
<td>1. Clear water correlation experiment</td>
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<tr>
<td>2. Clear water experiments</td>
<td>2. Granular correlation experiment</td>
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<td>3. Granular media experiments</td>
<td>3. Cubical slabs</td>
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<td>5. Temporal effects experiments</td>
<td>5. Upstream oriented slabs</td>
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<td>6. Downstream oriented slabs</td>
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<td>7. Cohesive material</td>
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<tr>
<td></td>
<td>8. Cohesive material in slab joints</td>
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<tr>
<td></td>
<td>9. Noncohesive material in slab joints</td>
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<td></td>
<td>10. Other experiments as resources allow</td>
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A rectangular sharp-edged orifice near the terminus of a delivery pipe, discharging through the pipe wall, simulates the overtopping phenomenon. Placing an orifice near the terminus of a pipe, issuing through the side wall, presents a complex design problem. A jet issuing from the orifice must be coherent and uniform and the jet must issue perpendicular, in the horizontal plain, from the pipe. Achieving these design goals requires model study to produce precise design specifications.

Measurement of hydraulic factors requires complex instrumentation and measurement schemes. The purpose of the measurements is to gain an understanding of the hydraulics of a plunging dissipating jet of water, and then to be able to predict the hydraulics in specific situations. This study calls for development of various instruments and measurement schemes in the scale model facility. Variables requiring measurement include discharge, head, tailwater depth, velocity profiles and pressure distributions along numerous non orthogonal axes and at many sections, and other factors. Plans for these aspects are under preparation.

Material Experiments

There are two facets to the material experiments. First are screening experiments in the scale model facility and second, primary experimenting in the prototype facility. Fractured rock, slabs of rock, and mixed materials with widely varying size fractions, are not specifically treated by formulas by Mason (4) or Veronese (7). Therefore it is difficult to anticipate the erosion characteristics of these materials and configurations.

Preliminary experimenting in the scale model facility will provide a frame of reference for the behavior of non-homogeneous, non-heterogeneous material. The intent is to screen a significant number of material configurations in the scale model facility, discounting the scale effects. The screening provides a basis for evaluating materials and material configurations for experimenting in the prototype facility. Since resources limit the number of experiments in the prototype facility, insight from experiments in the scale model facility will assure optimum value of data from the prototype facility.

The number, type, and combination of materials constituting the foundation of a dam are very numerous. It is imperative that limiting assumptions aimed at reducing the number of permutations of combinations be logical. This study is adopting a geomechanical index system by Moore, Kirsten (3), and Annandale (1)(2) for describing the type, number, combination, orientation, and other properties of foundation materials. The Erodibility index, $K_n$, is the product of four factors quantifying fundamental properties of earthen materials.
The four factors are the Mass Strength Number, $K_m$, Relative Ground Structure Number, $K_s$, Block Size Number, $K_b$, and the Interparticle Strength Number, $K_d$. The basis of this study is the correlation between the Erodibility Index and the rate of energy dissipation.

Most materials of interest to this study have relatively similar mass strength. Similarly, interparticle strength does not appear to be the primary focus area of this study. Therefore for the purpose of this study the mass strength number and interparticle strength numbers are considered constant. The particle block size and the relative orientation are the primary material variables for this study. Preliminary calculations [See Wittler, Pre-Test Report (8), Facilities section] indicate that the proposed prototype facility has the capacity to erode two to ten inch material to a depth of roughly ten feet. The relative orientation will vary from dipping into the flow, vertical with respect to the flow, and dipping away from the flow.

**New Technology**

A single equation cannot adequately represent changing field conditions, and is therefore ineffective for calculating the extents of erosion. The analysis of scour problems in rock and other earth materials, such as detritus and cohesive soils, is complex. The reason for this is that succinct representation of the variables that determine the resistance of such materials to erosion is difficult, as is the calculation of the erosive power of water. Annandale (1) proposes a new technology, based on the analysis of more than 100 field observations from the SCS data base on the erodibility of emergency spillways. The basis of the technology is a relationship between a geomechanical index and the erosive power of water. The geomechanical index summarizes the most important variables into a single number, known as the erodibility index, and the erosive power of water is expressed as the rate of energy dissipation at a point of interest.

**Erodibility Threshold - Fundamentals**

Modern thinking pertaining to the scour of earth materials separate the concepts of hydraulic erodibility and extent of erosion. Hydraulic erodibility is a threshold condition that can be expressed as a graphical relationship or an equation. At the erodibility threshold the agitating agent and the capacity of the material to offer resistance to erosion are related in the following functional manner:

$$P = f(K_n)$$  \hspace{1cm} (1)

$P$ = the magnitude of the agitating agent

$f(K_n)$ = the capacity of the material to resist erosion.

The agitating agent in the case of the hydraulic erodibility of earth material is the erosive power of water discharging incident to or over the material. The capacity of the material to resist erosion can be described by means of an index that accounts for the relative contribution of the important elements determining the strength of the material. If $P > f(K_n)$ the erodibility threshold has been exceeded and the material will erode. Conversely, if $P < f(K_n)$ the erodibility threshold is not exceeded, and erosion will not occur.

Annandale (2) assembled the data shown in Figure 3 from roughly one-hundred cases of erosion or overtopping in SCS dams. The data clearly show a threshold relationship between erosion and no erosion. Note that the relationship shown in Figure 3 implies nothing about the rate of erosion. The relationship indicates only the state of erosion, eroding or not eroding. Therefore a major objective of experiments in both model facilities is to establish a similar function between rate of energy dissipation and rate of erosion.
New Technology Algorithm
The collaborators created this algorithm as a prototype for the numerical model. Certain steps utilize existing technology and other numerical models such as HEC 6 and HEC 2. Other steps employ existing technology. The target platform for the numerical model is Microsoft Windows 3.x, and the numerical model will be a Visual Basic application. The steps listed are in sequential order.

1. Express geomechanical properties as an erodibility index. Determine the erodibility index via field and laboratory investigations. Combine the index into a material database.
2. Fit a three-dimensional (3-D) grid to known geology and topography. A 3-D grid creates a computational grid that is cubic in nature.
3. Assign a radial vector to each face of each cube, where the vector magnitude and direction represents the erodibility index on that face for all directions of flow impingement.
4. Create an accounting system for fluid and material continuity.
5. Create a global timer.
6. Correlate hydraulic agitation to dislodgement, or the threshold of dislodgement characterized by the erodibility index. Figure 3 represents the threshold relationship for a variety of earth materials, including jointed and fractured rock, weathered rock, detritus, cohesionless granular material, and cohesive material. The erosive power of water is represented by the rate of energy dissipation, and the relative ability of earth material to resist erosion is represented by the Erodibility Index. The rate of energy dissipation is a good measure of turbulence intensity, with turbulence intensity in turn being a good measure of the relative magnitude of pressure fluctuations [Annandale (2)].
7. Correlate displacement and hydraulic agitation. In most formulae, displacement is a function of particle size and hydraulic agitation. Many procedures that correlate displacement and hydraulic agitation already exist.

8. Start the global timer

9. Calculate boundary conditions such as the ODF (Outflow Design Flood) and tailwater.

10. Predict the flow patterns.

11. Determine hydraulic agitation based upon flow patterns.

12. Predict dislodgement.

13. Predict displacement. Dislodgement and displacement multiplied by the time step gives the volume of material removed per time step.

14. Calculate the remaining geometry.

15. Treat structural causes of erosion separately. Weaker materials may erode and undermine zones of highly resistive materials. Mass wasting is a different phenomenon than dislodgement. The treatment of cases involving mass wasting necessitates a different methodology than that for dislodgement.

16. Optimize dislodgement predictors for varying geology. Identify the optimum or appropriate method of quantifying hydraulic agitation for material categories and matrix configuration.

17. Combine dislodgement prediction techniques by applying to the geology exposed during scouring. Apply the optimum dislodgement predictor to the appropriate face of each cubic element.

18. Use the resulting topography as feedback to hydraulic agitation and erodibility. The new geometry is the input into the analysis of the flow patterns. The flow patterns determine the direction and magnitude of the hydraulic agitation at every point in the computational and physical grid. This updated flow field is input into reevaluating the erodibility of the newly exposed faces.

19. Increment the global timer and return to step 9.

**Summary**

The key aspects influencing the accuracy and precision of this algorithm are the performance of the Erodibility Index and the displacement function. Other factors influencing the outcome of the algorithm include the resolution and celerity of the computational grid, the sensitivity of the erodibility index to the accuracy of flow pattern predictions, temporal effects, and mass wasting. The design of the experiments planned in the scaled and prototype facilities will yield direct information on these factors. As the investigations continue and information becomes available, the process simulations will become more complex, more accurate, more precise, and more dependable.
References