The National Dam Safety Program

Research Needs Workshop: Dam Spillways

U.S. DEPARTMENT OF HOMELAND SECURITY

FEMA

Preface

One of the activities authorized by the Dam Safety and Security Act of 2002 is research to enhance the Nation's ability to assure that adequate dam safety programs and practices are in place throughout the United States. The Act of 2002 states that the Director of the Federal Emergency Management Agency (FEMA), in cooperation with the National Dam Safety Review Board (Review Board), shall carry out a program of technical and archival research to develop and support:

- improved techniques, historical experience, and equipment for rapid and effective dam construction, rehabilitation, and inspection;
- devices for continued monitoring of the safety of dams;
- development and maintenance of information resources systems needed to support managing the safety of dams; and
- initiatives to guide the formulation of effective policy and advance improvements in dam safety engineering, security, and management.

With the funding authorized by the Congress, the goal of the Review Board and the Dam Safety Research Work Group (Work Group) is to encourage research in those areas expected to make significant contributions to improving the safety and security of dams throughout the United States. The Work Group (formerly the Research Subcommittee of the Interagency Committee on Dam Safety) met initially in February 1998. To identify and prioritize research needs, the Subcommittee sponsored a workshop on Research Needs in Dam Safety in Washington D.C. in April 1999. Representatives of state and federal agencies, academia, and private industry attended the workshop. Seventeen broad area topics related to the research needs of the dam safety community were identified.

To more fully develop the research needs identified, the Research Subcommittee subsequently sponsored a series of nine workshops. Each workshop addressed a broad research topic (listed below) identified in the initial workshop. Experts attending the workshops included international representatives as well as representatives of state, federal, and private organizations within the United States.

- Impacts of Plants and Animals on Earthen Dams
- Risk Assessment for Dams
- Spillway Gates
- Seepage through Embankment Dams
- Embankment Dam Failure Analysis
- Hydrologic Issues for Dams
- Dam Spillways
- Seismic Issues for Dams
- Dam Outlet Works

In April 2003, the Work Group developed a 5-year Strategic Plan that prioritizes research needs based on the results of the research workshops. The 5-year Strategic Plan ensures that priority will be given to those projects that demonstrate a high degree of collaboration and expertise, and the likelihood of producing products that will contribute to the safety of dams in the United States. As part of the Strategic Plan, the Work Group developed criteria for evaluating the research needs identified in the research workshops. Scoring criteria was broken down into three broad evaluation areas: value, technical scope, and product. The framework adopted by the Work Group involved the use of a "decision quadrant" to enable the National Dam Safety Program to move research along to produce easily developed, timely, and useful products in the near-term and to develop more difficult, but useful, research over a 5-year timeframe. The decision quadrant format also makes it possible to revisit research each year and to revise research priorities based on current needs and knowledge gained from ongoing research and other developments.

Based on the research workshops, research topics have been proposed and pursued. Several topics have progressed to products of use to the dam safety community, such as technical manuals and guidelines. For future research, it is the goal of the Work Group to expand dam safety research to other institutions and professionals performing research in this field.

The proceedings from the research workshops present a comprehensive and detailed discussion and analysis of the research topics addressed by the experts participating in the workshops. The participants at all of the research workshops are to be commended for their diligent and highly professional efforts on behalf of the National Dam Safety Program.

Acknowledgments

The National Dam Safety Program research needs workshop on Dam Spillways was held on August 26-27, 2003, in Denver, Colorado.

The Department of Homeland Security, Federal Emergency Management Agency, would like to acknowledge the contributions of the U.S. Department of Interior, Bureau of Reclamation in organizing the workshop and developing these workshop proceedings. A complete list of workshop facilitators, presenters, and participants is included in the proceedings.

Abbreviations and Acronyms

ARS	Agricultural Research Service
ASCE	American Society of Civil Engineers
ASDSO	Association of State Dam Safety Officials
D/B	difficulty/benefit
ERDC	Engineering Research and Development Center
FEMA	Federal Emergency Management Agency
HB	high benefit
HD	high difficulty
HMR	National Weather Service Hydrometeorological Report
ICODS	Interagency Committee on Dam Safety
LB	low benefit
LD	low difficulty
NDSP	National Dam Safety Program
NDT	non-destructive techniques
NRCS	Natural Resources Conservation Service
O&M	operation and maintenance
PI	principal investigator
PMF	probable maximum flood
PMP	probable maximum precipitation
RCC	roller compacted concrete
Reclamation	Bureau of Reclamation
REMR	Repair, Evaluation, Maintenance, Rehabilitation
Review Board	National Dam Safety Review Board
SITES	Water Resources Site Analysis Program
strategic plan	National Dam Safety Program's 5-Year Strategic Plan
the Act	Dam Safety and Security Act of 2002
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
Work Group	Dam Safety Research Work Group

Table of Contents

Page

Tables

Page

Figures

Page

Overview

One of the key activities authorized by the Dam Safety and Security Act of 2002 (the Act) is research to enhance the Nation's ability to ensure adequate dam safety programs and practices throughout the United States. With the funding authorized by the Congress, the goal of the National Dam Safety Review Board (Review Board) and the Dam Safety Research Work Group (Work Group) is to encourage research in those areas expected to make significant contributions to improving the safety and security of dams throughout the United States. Although there are many worthwhile research projects that can be initiated, it was not intended by the Congress that the Act serve as the sole source of funding for research in the field of dam safety.

To guide decisions regarding the funding of specific research projects, the Work Group has developed a 5-Year Strategic Plan (strategic plan) that prioritizes research needs.[2] While the plan provides a snapshot of the priorities at one point in time, it is a living document that can be updated to reflect emerging needs and opportunities. The strategic plan also provides a blueprint for the Work Group to use in developing annual work plans. The goal of the Work Group in developing the 5-year strategic plan is to ensure that priority will be given to those projects that demonstrate a high degree of collaboration and expertise, and the likelihood of producing products that will contribute to the safety and security of dams in the United States.

Much of the input to this strategic plan originated with the results of a number of workshops sponsored by the Research Subcommittee of the Interagency Committee on Dam Safety (ICODS).[3] Funding provided under the National Dam Safety Act of 1996 enabled the Research Subcommittee to conduct the workshops, pursue highly valuable research that could be accomplished in a short period of time, and pursue several other opportunities to improve dam safety programs and processes. With many of the workshops completed or nearing completion, the Work Group determined that there was a need to develop a strategy for prioritizing the many research proposals being generated by the workshops.

The "Issues, Remedies, and Research Needs Related to Dam Service and/or Emergency Spillways" workshop was held to meet the requirements of the National Dam Safety Program Act of 1996. This act called for the Director of the Federal Emergency Management Agency (FEMA) to carry out a program of technical and archival research to develop: (1) improved techniques, historical experiences, and equipment for rapid and effective dam construction, rehabilitation, and inspection; and (2) devices for the

[2] "5-Year Strategic Plan (Draft)," National Dam Safety Program, Dam Safety Research Work Group, June 2003.
[3] Upon passage of the Dam Safety and Security Act of 2002, the ICODS Research Subcommittee was reformulated as the Dam Safety Research Work Group reporting to the National Review Board.

continued monitoring of the safety of dams. The recommended research from this workshop will be presented in the format developed in the strategic plan.

Workshop objectives were to:

- Document the state-of-practice concerning cost-effective techniques for enlargement, modification, inspection, monitoring, and maintenance of dam service and/or emergency spillways

- Access dam safety research needs: scope short-term and long-term needs of the Federal and non-Federal dam safety community

- Recommend course of action to address the identified research needs

Day one was dedicated to presentations of state-of-practice technologies by subject matter expects. Day two involved a facilitator, speakers, and invited participants who provided input on research needs related to the workshop objectives.

This document outlines the procedures used to accomplish the workshop objectives and provides the final documentation of the proceedings including:

- Topic presentations
- Topic discussions
- Research needs
- Research needs prioritization
    - Benefit/difficulty voting
    - Evaluation
- Research needs summary
- Appendices of supporting documentation

Workshop Organization

The 2-day workshop on Issues, Remedies, and Research Needs Relating to Service and/or Emergency Spillways was held August 26-27, 2003, at the Bureau of Reclamation, Technical Services Center, Denver, Colorado. The workshop steering committee met on the morning of the third day to capture and summarize the workshop results and determine final priorities of the research needs. The workshop steering committee was formed based on the advice of the Dam Safety Research Work Group to include a member of the Work Group; Federal, State, and private sectors; academia; and Association of State Dam Safety Officials (ASDSO). Table 1 shows the membership of the workshop steering committee and assistants.

Table 1.—Workshop steering committee members

Person	Position	Contact Info	Contact Info	Contact Info	Affiliation
		phone	fax	email	
Kathy Frizell	Team Leader	303-445-2144	303-445-6324	kfrizell@do.usbr.gov	Reclamation
Angela Medina	Secretary	303-445-2139	303-445-6324	amedina@do.usbr.gov	Reclamation
Nate Snorteland	Member	303-445-2395	303-445-6472	nsnorteland@do.usbr.gov	Reclamation/Denver Dam Safety Representative
Charles Tate	Member	601-634-2120	601-634-4158	Charles.H.Tate@erdc.usace.army.mil	USACE/ERDC
Darrel Temple	Member	405-624-4135 ext 226	405-624-4142	Darrel.temple@ars.usda.gov	ARS/Dam Safety Research Committee/ASDSO
Dave Campbell	Member	610-696-6066	610-696-7771	davec@schnabel-eng.com	Consultant/ASDSO
Eugene Zeizel	Program Manager	202-646-3187	202-646-3990	gene.zeizel@dhs.gov	FEMA
Tom Cook	Facilitator	303-445-3292	303-445-6475	tcook@do.usbr.gov	Reclamation's Value Engineering Group

The steering committee began by defining the workshop topics. Our goal was to define two major topics with subtopics that would encompass all aspects of dam spillway issues. The following topic areas were determined:

- **Topic 1**: Enlargement, modification, and retrofitting of dam service and/or emergency spillways including:
    - Labyrinth spillways
    - Fuse plug embankments and fuse gates
    - Crest parapets/dam raising including chutes and dissipaters
    - Gated spillways, both traditional and rubber gates
    - Earthen spillways
    - Dam spillway foundation erosion
    - Dam overtopping technologies with limits of applicability and long-term maintenance requirements

- **Topic 2**: Inspection, maintenance, and monitoring required to ensure proper performance of dam service and/or emergency spillways. Emphasis will be on economical maintenance of the state-of-practice regarding the following types of dam spillway structures:
    - Earthen spillways
    - Structural concrete spillways

The next task was to determine a well-rounded group of presenters and participants that were considered experts in the field of spillways. The group decided that a 2-day workshop could be conducted if the speakers were limited to 20 and if the second day of research needs development was well organized. The goal was to obtain a group of about 30 people that would provide a broad representation of individuals from the Federal, State, private, academia, and owner perspectives. Many participants had a broad background of expertise that would allow them to provide input on many research needs topics. The workshop had a total of 29 attendees. Of these, there were 14 representatives from 4 Federal agencies, 2 representatives from State dam safety agencies, 2 university professors, 1 dam owner, and 10 representatives from 7 different consulting agencies. Appendix A contains a complete list of speakers and participants.

Once the speakers had accepted, the workshop agenda was developed with the assistance of the facilitator, Tom Cook. The workshop agenda is shown in table 2. The first day was dedicated to the presentation of the state-of-practice with research needs outlined by each speaker. The second day was devoted to research needs development, voting, evaluation, and prioritizing. The speakers had all provided a list of research needs prior to the workshop. These research needs were listed on sheets of paper and attached to the wall to begin the second day of research needs discussion. All attendees then added additional ideas and spent a good deal of time coming to a consensus on how the needs should be grouped. Each research need topic was then voted on for difficulty and benefit, using a remote keypad with software provided by MH Events. The topics that made the cut were then evaluated by the group, using the form provided by the Work Group.

On the morning of the third day, the steering committee reviewed the results of the evaluations and summarized and prioritized the research needs.

Table 2.—Agenda for the workshop

Time	Tuesday - August 26, 2003
7:30 - 8:00	**The room is open - get through security & come get a cup of coffee/tea**
8:00 - 8:15	**Welcome**
8:15 - 10:10	Topic 1: Enlargement, modification, retrofitting of dam service and/or emergency spillways. Design guidances.
10:10 - 10:25	**Morning Break (15 min) – snack**
10:25 - 11:35	Topic 1: Enlargement, modification, retrofitting of dam service and/or emergency spillways. Design guidances. (Continued)
11:35 - 11:45	**Break (10 min)**
11:45 - 12:55	Topic 1: Enlargement, modification, retrofitting of dam service and/or emergency spillways. General discussion.
12:55 - 1:40	**Lunch – provided**
1:40 - 3:15	Topic 2: Inspection, maintenance, and monitoring required to ensure proper performance of dam service and/or emergency spillways. Emphasis on economical maintenance of dam spillway structures and the state-of-practice for earthen spillways and structural concrete spillways.
3:15 - 3:30	**Afternoon Break (15 min) – snack**
3:30 - 5:05	Topic 2: Inspection, maintenance, and monitoring required to ensure proper performance of dam service and/or emergency spillways. Emphasis on economical maintenance of dam spillway structures and the state-of-practice for earthen spillways and structural concrete spillways. Topic 2: Inspection, maintenance, and monitoring required to ensure proper performance of dam service and/or emergency spillways. General discussion.
5:05 - 5:15	Instructions/questions/Adjourn

Time	Wednesday - August 27, 2003
7:30 - 8:00	**The room is open - review research needs posted from Day 1**
8:00 - 8:15	**Ground rules for today's session**
8:15 - 9.25	Brainstorming session: Research needs added by group. Consolidate ideas.
9:25 - 9:45	**Morning Break (15 min)- snack**
9:45 - 11:45	Group rating of difficulty and benefit for each research idea. Compilation of rating and posting of decision quadrant.
11:45 - 12:30	**Lunch - provided**
12:30 - 2:30	Fill out evaluation forms for research topics in small groups.
2:30 - 2:45	**Afternoon Break (15 min) - snack**
2:45 - 3:45	Finish completing evaluation forms for research topics in small groups.
3:45 - 4:00	Results of evaluation.
4:00 - 4:15	Thank you and wrap-up.

State-of-Practice

Documentation of the state-of-practice was the first workshop objective. Per the agenda, the presentations were given on the first day of the workshop. Table 3 shows the presentations that were given to address the workshop topics with the presentation title, presenter, and presenter affiliation.

To ease the burden on each presenter, only an abstract, the presentation, and a list of pertinent references were required by the steering committee. Requiring a peer reviewed paper was viewed as too much work and would deter participation. Each presenter's abstract, with contact information, is given in Appendix B. The presentations are compiled in Appendix C. The reference list provided by each speaker appears in Appendix D, and it should provide a designer with the information needed to apply the technologies presented.

Table 3.—Summary of workshop presentations by title and presenter for each major workshop topic

Presentations	Presenters	Presenter's Affiliation
TOPIC 1		
Hydraulic Design of Labyrinth Weirs and Fuse Gates	Dr. Henry T. Falvey	Henry T. Falvey and Associates, Inc.
Fuse Plug Embankments—State of the Art and Practice, and Research Needs	Tony Wahl	Reclamation, Water Resources Research Laboratory
Crest Parapets and Dam Raising	Dwayne Fuller	USACE
Gated Spillways: Enlargement, Modification, and Rehabilitation—State of Practice	Elizabeth Cohen	Reclamation, Waterways and Concrete Dams
Earthen Spillways Design and Analysis—State of the Practice	Darrel Temple	U.S. Department of Agriculture, ARS
Spillway Foundation Erosion	Jim Ruff	Colorado State University
Dam Overtopping Protection Technologies—State of Practice and Research Needs	Kathy Frizell	Reclamation, Water Resources Research Laboratory
RCC Overtopping Protection for Increasing Spillway Capacity	Ken Hansen	Schnabel Engineering, Inc.
General Discussion—NRCS Designs and Research Needs	James Moore	NRCS, National Water Management Center

Table 3.—Summary of workshop presentations by title and presenter for each major workshop topic

Presentations	Presenters	Presenter's Affiliation
Spillways—An Owner's Perspective	Jim Weldon	Denver Water Board
General Discussion—Consultant's Spillway Design and Research Needs	Wade Moore	MWH Americas, Inc., and Chair, ASCE Hydraulic Structures Committee
TOPIC 2		
Vegetated Earth Spillways—Inspection, Maintenance, and Monitoring	Morris Lobrecht	NRCS
Earth Spillways—State of Practice and Research Needs	Greg Hammer	Colorado Division of Water Resources, Dam Safety Branch
Issues and Research Needs Related to Hydraulics for State Regulated Dams	Ed Fiegle	Georgia Department of Natural Resources, Safe Dams Program
Concrete Spillway Repairs	Jim McDonald	Private Consultant
Inspection of Concrete Spillways—Gated and Uncontrolled	Bill Bouley	Reclamation, Inspections and Emergency Management
Geophysics for Spillway and Seepage Evaluation	Mark Dunscomb (w/Dave Campbell)	Schnabel Engineering, Inc.
Inspection, Maintenance, and Monitoring of Service and Emergency Spillways	Dan Johnson	MWH Americas, Inc.
Unlined Spillway Erosion Risk Assessment	Joe Koester	USACE, Engineering Research and Development Center

Workshop Presentations

Each technical expert was asked to prepare a 20-minute-long presentation in their subject area that included:

- A short overview to orient the audience
- Current activities or the state-of-practice
- Long- and short-term research issues in your topic area

The goal was to provide the entire workshop group the background on the state-of-practice and research needs as viewed by the technical experts, so that the second day of the workshop dealing with research needs could be started on an equal footing.

The following paragraphs give a brief synopsis of the state-of-practice presentations.

Hydraulic Design of Labyrinth Weirs and Fuse Gates – *Henry Falvey*

This presentation focused on two ways to enlarge spillway capacity using the principle of increasing the length of the weir crest by folding it into a given width. Labyrinth weir technology has been around a long time, but until recently, the hydraulic design criteria have not been well established. A fuse gate is a labyrinth weir shape that is formed in individual pieces and designed to fail or tip over, lowering the hydraulic control when a certain flow depth over the gate is attained. In this way, the fuse gate provides increased controlled flow using a labyrinth shape, then a controlled failure down to a given sill elevation, to accommodate extreme floodflows.

Modeling results were presented with recommended design guidance provided for both the labyrinth weir and fuse gate.

Fuse Plug Embankments—State of the Art and Practice, and Research Needs – Tony Wahl

This presentation focused on the design concept for fuse plug embankments in spillways and the testing that has been conducted. Fuse plug spillways have undergone extensive laboratory testing and a full-scale field test that has confirmed the design concepts and added to the comfort level for use. The state-of-practice is that many have been designed and constructed, but few, if any, have operated. This leaves some uncertainty with regard to their ability to function after years of weathering and settlement.

Crest Parapets and Dam Raising - Dwayne Fuller

This presentation discussed the recent hydraulic modeling performed by the USACE ERDC regarding methods to increase spillway capacities. Three studies were presented where several alternatives, including raising the dam to increase storage, were combined with spillway modifications to provide successful passage of increased flows.

Gated Spillways: Enlargement, Modification, and Rehabilitation—State of Practice - *Elizabeth Cohen*

This presentation discussed the use of gated spillways to provide increased flow capacities in a spillway. The presentation focused on the importance of determining the function of the gate and the design data that must be obtained prior to selection of a gate type for increased capacity. Gated spillways offer flexibility in function and may be operated remotely if needed. There was then a brief presentation of the types of gates available and the pros and cons regarding their operation and maintenance.

Earthen Spillways: Design and Analysis—State of the Practice – *Darrel Temple*

This presentation stressed the state-of-practice for design tools for earthen spillway channels. The design goal is to pass the flood without breaching, although damage may occur. There are three basic tools for design:

- Stable exit channel
- REMR (USACE) Erosion Prediction Method
- SITES (USDA) Spillway Erosion Analysis

The presentation focused on the three phases of the erosion process, as dealt with in the SITES analysis of vegetation erosion, bare earth or concentrated flow erosion, and erosion by headcut advance.

Spillway Foundation Erosion – *James Ruff*

Scour from spillway and outlet jets can cause undermining of chutes and structural damage that is expensive to repair. This presentation focused on large-scale testing and subsequent development of tools to predict the rate of scour from high-velocity jets impacting earth and rock materials below both flip bucket or orifice outlet spillways and outlet valves. Colorado State University performed large-scale testing to investigate the properties of water jets traveling through the air, pool of water, and impact on cohesionless beds and on simulated rock material. The water jets attempted to simulate waterflow from orifice outlets, flip buckets, or outlet valves. The objective of the study was to investigate the depth and rate of scour caused by the jets on the various foundation materials. Results provided a method to calculate scour hole formation and dimensions. A brief discussion was presented of spillway rock channel and concrete block protection systems for earthen channels that were covered in more detail by another presenter.

Dam Overtopping Protection Technologies—State of Practice and Research Needs – *Kathy Frizell*

This presentation focused on providing a very brief synopsis of the technologies available to protect embankment dams and earthen spillway channels during flood events that would cause overtopping or flow in the channels. Providing protection over the earthen slope is often economical compared to other techniques used for spillway enlargement. The hydraulics of high-velocity flow over an embankment were discussed. Basic guidelines for each technology were given regarding the limitations of their use based upon testing, small and large scale, and actual installations. The large-scale testing and design guidance developed for riprap and stepped spillways was emphasized.

RCC Overtopping Protection for Increasing Spillway Capacity – *Ken Hansen*

This presentation emphasized the use of RCC to increase spillway capacity by providing many examples of actual installations. Each installation provided insight into a construction technique or aspect of the placement where lessons were learned and the technology was advanced. Basic guidelines for construction and RCC compaction were discussed with the need for understanding the flow forces that the surfaces will be subjected to as an important feature.

General Discussion—NRCS Designs and Research Needs – *James Moore*

This presentation focused on the hydrologic events used to design service and auxiliary spillways within the NRCS. Hydrologic criteria for auxiliary spillways are determined based upon the hazard classification of the dam and are a function of the Probable Maximum Precipitation (PMP). Examples of the typical intake tower used by NRCS as a service spillway were discussed. Examples of the three most common auxiliary spillway designs utilized by NRCS (vegetated earthen, straight drop, and RCC spillways) were also shown.

Spillways—An Owner's Perspective – *Jim Weldon*

This presentation focused on revisiting the issue of the design hydrologic events for spillways and the use of the PMP and Probable Maximum Flood (PMF). The current practice has been to use the National Weather Service Hydrometeorological Reports (HMR) to derive the PMP and then compare spillway capacity to the flood determined from the PMP. The presenter contended that while this level of conservatism may be appropriate for large Federal facilities, most dam owners, including some Federal owners, do not have the funding to comply. The presentation outlined several problems with using HMRs. In addition, questions were raised regarding the appropriateness of the zero risk approach, inconsistent application from State to State, new computer capability that should allow revisiting the procedures, and whether or not a smaller frequency event, such as the 5,000-year or 10,000-year storm, would be adequate.

General Discussion—Consultant's Spillway Design and Research Needs – *Wade Moore*

This presentation focused on two organizations that the presenter is affiliated with and their spillway design issues. First, the efforts by ASCE to address research, analysis, design, construction, operation, and maintenance of state-of-the-art methodology associated with hydraulic structures were discussed. The presenter then discussed the types of spillway expansion projects that Harza has completed over the last decade. Finally, methods to determine dam failure analysis were given.

Vegetated Earth Spillways—Inspection, Maintenance, and Monitoring—
Morris Lobrecht

This presentation focused on inspection, maintenance, and monitoring performed by the NRCS Fort Worth Office when dealing with earth auxiliary spillways. Many examples of well maintained and poorly maintained spillways were shown. The types of the problems encountered on the spillways and the expected result of the problems were discussed. Several spillways were shown during or after flows had been passed. Steeper slopes experienced more damage than flatter slopes when both had good vegetative cover and maintenance.

***Earth Spillways—State of Practice and Research Needs** – Greg Hammer*

This presentation discussed the popularity of using an earth channel spillway because of economical design and simple construction. However, these same properties are the basis for the limited resistance to hydraulic loading, as is evidenced by eroded channels after flows occur. The dilemma for the engineer regarding the design of an earth channel thus becomes not only how large the spillway must be to pass a given design flow, but also how to keep the channel intact during flow, and how to be sure that the spillway will be clear, particularly of snow and ice, when it is needed to pass flow.

Earth spillway design procedures were discussed, and concern was expressed over what the appropriate method is to compute the spillway capacity. The method for controlling the flow in the spillway must be recognized, and the appropriate method for design must be chosen, such as the broad-crested weir formula, uniform flow conditions using Manning's equations, or backwater analysis techniques (HEC-RAS, HEC-2). Spillway capacities can be determined to be markedly different, depending on the method of computation. Snow and ice buildup was also a particular problem discussed.

***Issues and Research Needs Related to Hydraulics for State Regulated Dams** –
Ed Fiegle*

This presentation provided the results of a survey that had been performed by Mr. Fiegle regarding hydraulic issues faced by State dam safety representatives. Thirty State dam safety representatives responded to the questionnaire that dealt with a wide range of hydraulic design issues. The following particular problems were presented as top concerns of the State dam safety community: snow and ice, RCC step design and durability, siphon spillway design, articulated concrete block system performance, understanding of hydraulic coefficients, irregular spillway shape performance, and drop structure designs.

***Concrete Spillway Repairs** – Jim McDonald*

This presentation focused on the current practice relating to concrete repair techniques in spillways. The primary problem with concrete repairs is cracking, due to incompatibility between the repair material and the original concrete surface. Results of extensive laboratory and field performance testing that now provide a basis for selection and specification of dimensionally compatible cement-based repair materials were presented. Performance criteria regarding minimum tensile strength and elasticity, shrinkage, and thermal expansion were also discussed.

***Inspection of Concrete Spillways—Gated and Uncontrolled** – Bill Bouley*

This presentation focused on the important aspects to investigate when performing inspections on concrete spillway surfaces. Particular emphasis is placed on visual inspection and the importance of a good technical background for the inspector. Many examples were given of poor concrete surfaces or poor maintenance leading to potential problems during passage of flood events. Emphasis was placed on inspecting when the spillway is in operation or when the reservoir water levels are high. Inspection and monitoring techniques include visual above ground, underwater diving and remotely operated vehicles, climbing, surveying, crack monitoring and mapping, and non-destructive evaluation where the extent of a suspected problem must be known. Expensive non-destructive techniques and monitoring with instrumentation must be paid for by the dam owner, and it is often difficult to obtain the appropriate services.

Geophysics for Spillway and Seepage Evaluation – *Mark Dunscomb (w/Dave Campbell)*

This presentation outlined the advantages of using geophysical noninvasive and non-destructive techniques to characterize subsurface risk on a project. These should be used in combination with intrusive methods to improve the understanding of subsurface voids or waterflow. Several examples were given to show the capability of geophysical techniques and how they can be used to save money by preventing problems before they become insurmountable.

Inspection, Maintenance, and Monitoring of Service and Emergency Spillways – *Dan Johnson*

This presentation focused on what components were necessary to have a successful inspection, maintenance, and monitoring team. Development of a successful team begins with understanding the owner's and public's perception, and relating important historical events to the current timeframe. Inspection must include knowledge of the potential failure modes. Maintenance is often infrequent and directed primarily at the service spillways. Owners must be aware that older structures need attention, but that new rehabilitation techniques may not have the redundancy built in that the older, more traditional techniques did. Monitoring is vital, but the information gathered must be evaluated and is of no use if not reviewed and understood.

Unlined Spillway Erosion Risk Assessment – *Joseph Koester*

This presentation provided a methodology to assess the probability of damage to unlined spillway channels and a tool to prioritize remediation of unlined spillway channel projects. Risk assessment deals with answering these questions: what can go wrong, what is the likelihood it will go wrong, and what are the consequences? Event trees are used to assess the issues with probabilistic techniques to produce hard numbers for comparisons. An example of how risk assessment techniques are used on an unlined spillway channel was presented.

Summary

The presentations were all very well received and provided the entire group of participants with the topic state-of-practice and each expert's thoughts on further research needs. The workshop participants each were selected because they had a specific expertise; however, each participant also had a broad base of experience that allowed them to participate in evaluating research needs in other areas. All workshop participants were instructed to think about other points of research that they felt were important to include during the next day's research needs session.

Research Needs

This section will discuss the research needs developed from the workshop. Each presenter provided a list of research needs related to their topic prior to the workshop. The workshop organizers compiled the research needs by listing main topic headings on large sheets of paper and attaching them to the wall of the room before the second day of the workshop. This provided an organized starting point for the development of research needs by the entire group on the second day. At the conclusion of the first day of the workshop, everyone was encouraged to come early the second day to add their personal thoughts on research needs, as all the participants had a broad experience base that allowed input on several topics.

This section does not distinguish between research needs topics provided by the presenters or state-of-practice experts and other participants, but it gives all the topics developed by the entire group. The presenters' specific research needs are given in their abstracts or slides (shown in Appendices B and C). The following discussion describes how the research need topics were compiled to facilitate overall understanding, grouping of like ideas, and voting.

Topic Development and Discussion

The initial sheets had main topic headings with research needs topics listed below them. There were initially 76 separate topics, if each topic were to stand alone as a research need. The group then began the process of rearranging and compiling what were judged to be similar topics under main heading categories. During this phase, quite a bit of overlap was discovered between topics, and even main topic headings were modified. This process was fairly time consuming, but the result was an organized list of main headings, each with several topics and related tasks grouped beneath each topic. There were finally 10 main headings with 32 topics listed beneath them that were agreed upon by the group. Table 4 shows the entire list of topics with letters assigned to the compiled topics. These 32 topics were then voted on for difficulty and benefit by the group. The compiling process contributed to a certain amount of 'narrow scope' bias in the voting because singular topics were generally rated as less difficult to accomplish, whereas topics with many tasks were generally rated as more difficult to accomplish (as would be expected). Unfortunately, we found no way to successfully amend this process. Topics that have numerous tasks generally were of high benefit but were viewed as much more difficult to achieve in terms of time and cost.

Table 4.—Compilation of research needs topics with letter designations under main category headings
(The decision quadrant results are also given which are discussed in the next section of this report.)

	Topics	Difficulty	Benefit	Kept for evaluation based upon D/B results	Final list for evaluation (after final group consensus)
	Flow Through Spillway Chutes				
A	Develop guidelines for chute hydraulics by compiling existing information on: • Influence of chute roughness • Curved spillway chutes • Converging walls • Supercritical transitions • Flow downstream from spillway aerators	5.8	4.8		
B	Test operating spillways at heads that create supercavitation (test crest shapes beyond design heads).	5.5	3.6	X	
C	Develop spreadsheet to identify discharge coefficients for spillway crests.	4.3	5.2	X	X
D	Develop design guidelines for siphon spillways including: • Hydraulic for multiple intakes • Rating curves • Joint integrity • Maximum height and maximum diameter • Material types	4.1	5.5	X	X
E	Develop a manual on rock spillway chutes for small spillway application to meet technology transfer needs.	2.9	5.2	X	X
	Dam Spillway Foundation Erosion				
F	Enhance existing physically based models by performing additional large-scale tests and site inventory under various flow (and geologic conditions) that determine scour depth over time.	7.9	6.1	X	X
G	• Characterize jet properties at impact with plunge pool free surface and in plunge pool. • Determine concrete plunge pool thickness and drainage criteria. • Evaluate effects of jet entry angle on plunge pool performance and scour.	5.8	6.0	X	X

Table 4.—Compilation of research needs topics with letter designations under main category headings (The decision quadrant results are also given which are discussed in the next section of this report.)

	Topics	Difficulty	Benefit	Kept for evaluation based upon D/B results	Final list for evaluation (after final group consensus)
	RCC and Other Dam Overlays				
H	Develop a guideline document to be used by designers and review agencies that includes: • Design criteria for groin flow, constriction areas, and energy dissipation. • Design criteria regarding drainage blanket/filter criteria and foundation uplift pressure. • Long-term effects of differential settlements on RCC stability under flow conditions.	6.4	8.3	X	X
I	Develop design guidelines for alternate materials for overlays on small dams such as: • Damage of block protection due to debris flow. • Evaluation of systems under hydraulic loading. • Soil cement and geomembrane use. • Gabions etc.	6.8	8.4	X	X
L*	• Develop guidelines for the following aspects of RCC overlays: • Determine energy dissipation characteristics of weathered RCC steps. • Research hydraulic issues associated with RCC overlay thickness based on unit discharge. • Define upper limit for unit discharge with stepped spillways. • Dynamic effects of water pressure transmitted to the foundation through cracks in the RCC. • Determine design criteria for stepped spillway energy dissipater. • Determine flow characteristics and energy dissipater with stepped spillway. • Side wall convergence. • Determine relationship of various height and shaped steps and energy dissipation. • Determine flow conditions upstream of the point of inception for high discharges and for a wide range of dam heights. • Effects of slope on air entrainment and energy dissipation.				

Table 4.—Compilation of research needs topics with letter designations under main category headings (The decision quadrant results are also given which are discussed in the next section of this report.)

	Topics	Difficulty	Benefit	Kept for evaluation based upon D/B results	Final list for evaluation (after final group consensus)
N*	Compile historical information on performance of spillways on nonrock foundations or spillways on embankment dams (how have they failed, uplift/seepage/foundation—how have they operated)	4.0	6.8	X	X
	Gated Spillways				
J*	Investigate spillway flow due to seismic or security related gate failures.	7.1	2.2		
K*	Develop/Verify rubber gate discharge performance with and without submergence.	4.6	4.0	X	X
	Stepped Spillway Design				
M*	Document and finish research, where needed, for hydraulic design criteria, including limitations or step effectiveness for typical formed RCC stepped embankment slopes.	4.5	7.4	X	X
O	Determine crest profiles for gated stepped spillway.	4.8	3.2	X	X
P	Determine cavitation potential and designs for artificial aeration.	6.1	3.3		
Q	Determine model/prototype scale effect.	6.8	4.4		
	Earth Spillways				
R	Enhance capabilities of SITES computer model to include: • Brush vegetation • Headcut advance (present model with limited data). • Determine relationship between detachment coefficient and headcut erodibility index.	6.8	7.8	X	X
S	Investigate breach formation and peak discharge releases.	5.8	5.4	X	

Table 4.—Compilation of research needs topics with letter designations under main category headings (The decision quadrant results are also given which are discussed in the next section of this report.)

	Topics	Difficulty	Benefit	Kept for evaluation based upon D/B results	Final list for evaluation (after final group consensus)
T	Improve the erodibility index to include material description factors for erosion of very low plasticity soils and rock.	6.2	5.6	X	X
U	Determine methods to mitigate erosion at: • The outlet and/or contact with abutments. • Spillway sections that have curved or narrowing spillway geometries. • The location of the hydraulic jump on an earthen spillway slope.	6.3	5.6	X	
V	Research grass design criteria, including cool weather grass and reinforced grass, in terms of flow capacity and/or performance longevity. (Model studies needed).	4.9	5.4	X	X
W	Determine most appropriate method (i.e., HECRAS, HEC-2, or weir formula) for determining earth spillway crest discharge coefficients.	4.5	4.8	X	X
X	Determine design criteria for sill wall spacing and foundation in earth spillways.	5.0	5.7	X	X
Y	Determine effects of ice and snow and ways to prevent ice and snow buildup on earth spillway channel performance.	6.3	4.4		
	Spillway Design Capacity - Hydrologic Concerns				
Z	Update and develop computer model that replaces HMRS-Use latest technologies. Is PMF the appropriate design flood loading condition for high and significant risk structures?	7.4	8.1	X	X

Table 4.—Compilation of research needs topics with letter designations under main category headings
(The decision quadrant results are also given which are discussed in the next section of this report.)

	Topics	Difficulty	Benefit	Kept for evaluation based upon D/B results	Final list for evaluation (after final group consensus)
	Labyrinth Spillways				
AA	Investigate the following: • Crest shape design effectiveness. • Investigate need for aeration splitters on crest. • Design to optimize approach flow conditions. (Example: weir placement, raised inverts). • Investigation of downstream Nappe interference, downstream submergence, and head loss. • Research flow distribution and residual energy in straight of converging chutes downstream. • Performance of smaller plan form with low width to crest height ratio shapes.	5.7	3.8	X	
	Fuse Plug Spillways				
AB	Investigate the following aspects of fuse plug spillways: • Investigate clay cores in terms of long-term stability including effects of freeze/thaw effects. • Other design materials (Concrete/Membranes). • Create Inventory of Designs and operational history. • Develop erosion model. • Guidance on trigger mechanisms. • Design and testing of Homogeneous Sections. • Understand the aging behavior of decades old fuse plugs and their ability to function. • Develop method to test the ability to operate after decades of service. • Foundation erosion prevention measures (downcutting).	6.4	5.5	X	X

Table 4.—Compilation of research needs topics with letter designations under main category headings (The decision quadrant results are also given which are discussed in the next section of this report.)

	Topics	Difficulty	Benefit	Kept for evaluation based upon D/B results	Final list for evaluation (after final group consensus)
	Inspection Maintenance and Repair				
AC	Investigate tools to reduce O&M cost and extend functional life of infrastructure: • Sustainable repair technology. • Innovative repair materials that satisfy compatibility requirements. • Underwater concrete repair. • Inspection techniques.	5.8	6.5	X	X
AE*	Evaluate instrumentation that may be installed for remote monitoring of spillway structural features that are inaccessible.	4.2	5.3	X	X
AF*	Develop procedures to do better geophysical exploration to detect voids, defects, and seepage.	3.8	6.1	X	X
AG*	Investigate new reliable NDT equipment/procedures to evaluate gate anchorage systems and other infrastructure components.	6.0	5.3		
	32 topics			26 topics	22 topics
AD	Missing. Was voted on, but then discussed for better understanding and re-voted as AE.				

* listed out of alphabetical order

Evaluation of Research Needs

The Dam Safety Research Work Group has published draft guidelines for use in evaluating the research needed, as determined by all the workshops that are being conducted. They requested that we follow this procedure when developing the results from this workshop. The procedure was to vote on difficulty and benefit for each topic, then plot the results on a decision quadrant. Worthwhile topics, based upon the Work Group criteria, were then evaluated further using the form developed by the Work Group and utilized in this workshop.

Voting

The next step in the workshop was to vote on the difficulty and benefit for the 32 topics. For this purpose, MH Events was contracted to provide remote keypads for assigning a difficulty and benefit score from 1 to 10 for each topic. The information was instantly recorded and graphed for evaluation of the result. If the result did not look appropriate, the facilitator would ask for the topic to be clarified so that perhaps the voting would be better distributed. The participants did not see this graph so they were not influenced by other opinions. The graphical result from this individual topic voting is shown in Appendix E.

Decision Quadrant

The ultimate goal of the voting process was to develop the decision quadrant as requested by the Dam Safety Research Work Group. A decision quadrant is typically used in these types of situations with the axes defined as needed. In this case, the quadrants were developed based upon a rating scale of difficulty and benefit as shown in figure 1.

Based upon the Work Group goals, only those topics that were rated low difficulty/low benefit (LD/LB), low difficulty/high benefit (LD/HB), and high difficulty/high benefit (HD/HB) would be considered for requests for future research proposals and funding. The quadrant of LD/LB is often termed the "low hanging fruit," topics that are not of high benefit but are easy to accomplish and somewhat useful. These topics may be just one remaining task from a larger project or a task that, when completed, could lead to a future program or project. The LD/HB quadrant is obviously desirable because the results are perceived to have broad application and be very important, whereas low difficulty implies that the tasks can be completed with relatively little short-term effort. In addition, low difficulty also implies that the tasks should be completed with less funding. Therefore, the LD/HB quadrant is termed "short term research" and would be attractive to the Work Group. The HD/HB quadrant is defined as long-term research and might require a fairly lengthy and expensive research program to complete; however, the benefit is perceived as worth the investment with broad application and essential guidelines received from the program. Difficulty/benefit voting was essential to determining whether topics were carried forward for further evaluation by the group and possible research funding as per the Work Group directive.

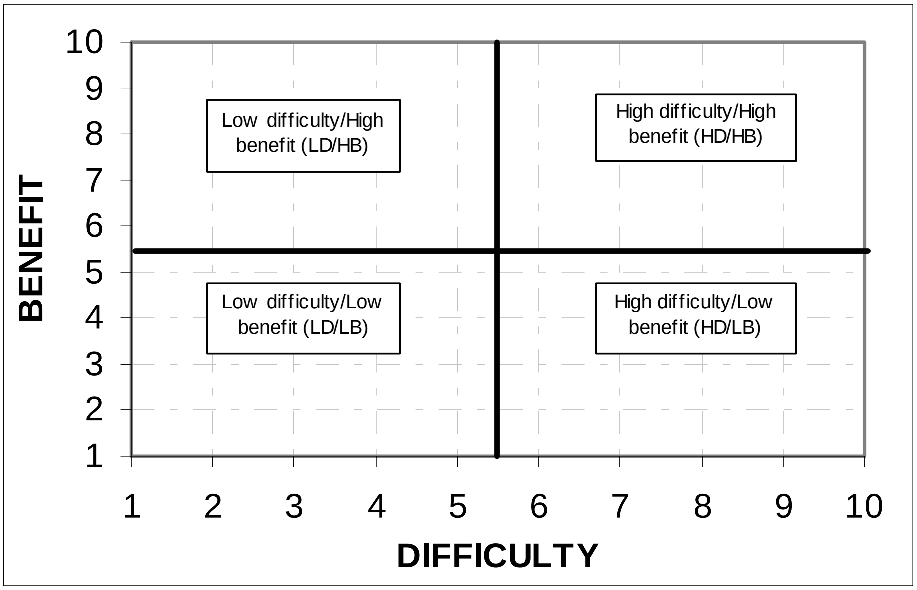

Figure 1.—Research needs decision quadrant definition.

Figure 2 shows the result of the voting on all the topics from table 4, including the topic letters. Twenty-six topics remained after eliminating topics that clearly fell into the HD/LB quadrant. Topics that fell on the dividing lines bounding the HD/LB benefit quadrant (topics that would not be carried forward) were then voted on (with a show of hands) by the entire group to determine if they would be further evaluated. Topics B, S, T, U, AA, and AB fell on the line separating the LD/LB and HD/HB quadrants from the HD/LB quadrant that would not be kept for further evaluation. The group voted to keep topics T and AB. The final list of research needs topics, as voted by the workshop attendees, is shown in the last column of table 4. At the end of the difficulty/benefit voting, there were 22 topics left to be evaluated using the form developed by the Work Group.

Evaluation

Completion of the voting and the results from the decision quadrant led to the evaluation phase of the workshop. All the research topics from the decision quadrant, except for those in the high difficulty/low benefit quadrant, were retained for evaluation scoring. The Dam Safety Research Work Group has developed scoring criteria for evaluating research needs identified in the various workshops against three broad evaluation scoring areas: value, technical scope, and product. The research evaluation form was forwarded to the workshop steering committee to use during this phase of the workshop. Table 5 is the research evaluation form that was used by the workshop attendees after a couple of minor modifications to the original form forwarded by the Work Group. The workshop committee added the research topic title and a section for a brief topic description.

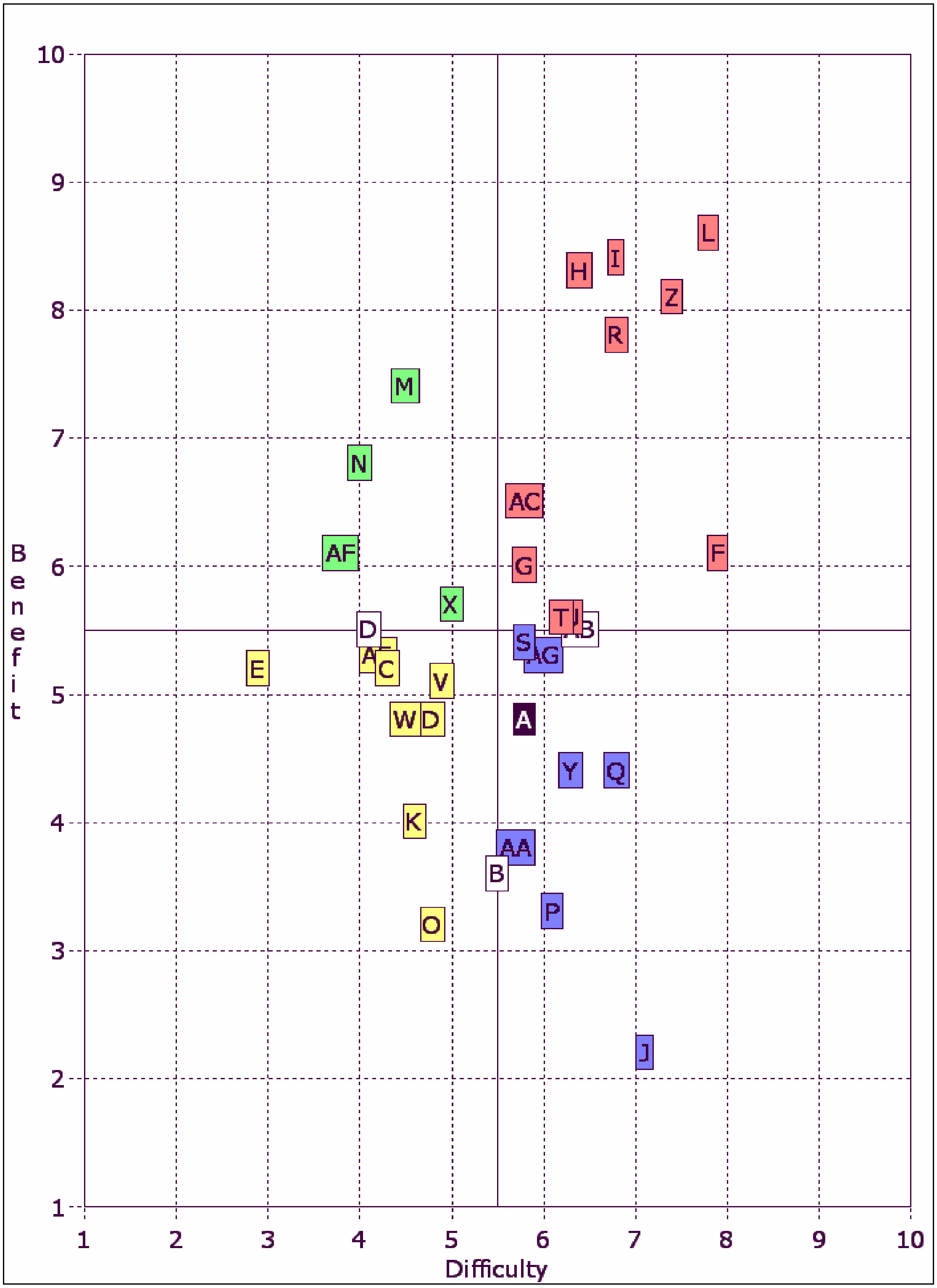

Figure 2.—Decision quadrant results for each topic developed during the brainstorming session. Each lettered topic is shown in table 4. The blue topics were not voted on with the evaluation criteria. The topics on the lines between quadrants were re-voted (by a show of hands) by the group as to whether to retain for further evaluation.

Table 5.—Evaluation criteria for research topics developed by the Dam Safety Research Work Group. *(Note: The form was slightly modified for use by these workshop participants by adding the research topic title and the brief description.)*

Research Topic:

Brief topic description:

Scoring Area:	Subtitle:	Criteria	Subscore (circle one)	Evaluator's Score (transfer circled score)
Value			40	
	Usefulness		11	
		Broad federal/state support in addition support from NDSP Research workgroup	11	
		Proposal from any source addressing a need identified by the NDSP Research workgroup	8	
		Identified need with limited support (Federal/State/Academic/Private)	5	
		Unsolicited proposal with independent validation	2	
		Unsolicited proposal	1	
	Cost		8	
		Total Project Cost <$50,000	8	
		<$100,000	6	
		<$250,000	4	
		<$500,000	2	
		>$500,000	0	
	Probability of Success		6	
		Useful product virtually certain	6	
		Identified interim products for progress and long term direction	4	
		Significant technical challenges to overcome	2	
		Unlikely to obtain a useful product	0	

Table 5.—Evaluation criteria for research topics developed by the Dam Safety Research Work Group *(Note: The form was slightly modified for use by these workshop participants by adding the research topic title and the brief description.)*

Scoring Area:	Subtitle:	Criteria	Subscore (circle one)	Evaluator's Score (transfer circled score)
	Transferable to the Public:		4	
	(General, Engineering, regulators, Owners)			
		Proposed format of products meets needs of sectors	4	
		Proposed format of products meets needs of 2-3 sectors	2	
		Proposed format of products meets needs of 1 sector	1	
		No identified transfer of benefits	0	
	Timeliness		2	
		Products developed within 1 year	2	
		Products developed over multiple years with interim products identified	1	
		Products developed over multiple years with no interim products identified	0	
	Leverage		6	
		Part of NDSP workgroup plan with >80% cost share or in-kind service	6	
		Part of NDSP workgroup plan with >50% cost share or in-kind service	4	
		Part of NDSP workgroup plan with all NDSP research funding with federal or state/ASDSO sponsor	2	
		All NDSP Research funding	0	
	Societal Benefits		3	
		Relevant to current events/societal concerns (promotes additional state/federal funding)	3	
		Promotes general societal awareness	1	
		Targeted to specific interests	0	
Value total				

Table 5.—Evaluation criteria for research topics developed by the Dam Safety Research Work Group *(Note: The form was slightly modified for use by these workshop participants by adding the research topic title and the brief description.)*

Scoring Area:	Subtitle:	Criteria	Subscore (circle one)	Evaluator's Score (transfer circled score)
Scope			40	
	Audience		5	
		General (Lay)	1	
		State	1	
		Federal	1	
		Private	1	
		Research (future impact)	1	
		(One point for each group whose need are addressed)		
	Facilitate decisions		6	
		Does scope include or address:		
		Facilitation of day to day dam safety decisions	2	
		Development, documentation, or modification of practices	2	
		Regulatory activities or decisions	2	
		(Max of 2 points for each issue covered)		
	Sound science		12	
		Is proposed work based on sound scientific principles:		
		Is scope and/or product consistent with resources available or proposed	4	
		is data available or to be acquired to address issue as intended	4	
		Is data or approach consistent with quality and nature with identified end product	4	
		(Maximum of 4 points for each issue)		
	Staff resources		12	
		Are appropriate staff resources available?:	12	
		Recognized experts are PI's		
		Recognized experts are collaborators		

Table 5.—Evaluation criteria for research topics developed by the Dam Safety Research Work Group *(Note: The form was slightly modified for use by these workshop participants by adding the research topic title and the brief description.)*

Scoring Area:	Subtitle:	Criteria	Subscore (circle one)	Evaluator's Score (transfer circled score)
		PI's are new to area		
		Primarily new scientists or grad students		
		No qualified technical staff	0	
		(Rated 0 to 12 based on appropriateness of available staff)		
Scope total				
Product			25	
	Output		15	
		Produce a process, tool, or technique (guideline, computer program, equation, etc)?	15	
	State of technology		3	
		Define or summarize an entire state of technology or practice for a dam safety audience	3	
	Safety lessons		2	
		Extract important dam safety lessons from case histories	2	
	Innovative technology		2	
		Produce product with new, novel, or innovative technology	2	
	Tech Transfer		3	
		Develop products or technology that can be easily transferred for use by dam safety interests	3	
Product total				
Research topic total*				

*Sum of all scoring areas.

On the evaluation form, each main evaluation scoring area has several subtitles or subcategories with possible scores designated. The value scoring area has seven subcategories, with usefulness and cost having the most importance or the highest point values. The scope scoring area has four subcategories, with sound science and staff resources having the highest point value. The product scoring area has five subcategories with the final output far outweighing the others in point value. A total score of 100 is possible (value = 40 points, scope = 35 points, and product = 25 points). The understanding of these categories and their weighted importance played a role in the group topic scoring.

To perform the evaluations, the workshop participants were divided into small groups of four or five people, with an effort to blend Federal, private consultants, State, and academia in each group. The facilitator then went around the room and asked each group which topic they would like to evaluate until all the topics were selected. Each small group evaluated three to four topics. Instructions were then given to the groups regarding the value, scope, and product scoring areas and how to fill out the form. It was beneficial to have Darrel Temple, from the Work Group, at the workshop to provide an overview of the thinking behind the form and to answer questions. Each small group then completed their evaluation forms for each of their topics. The evaluation forms for each topic are attached in Appendix F of this report.

The end result is a scoring document for identifying valuable and cost-effective research needs to be addressed in the 5-year strategic plan. As additional research needs are identified from other sources, they can be prioritized and included in the priority listing. The scoring system will enable the National Dam Safety Program to move research forward to produce easily developed, timely, and useful products in the near-term and to develop more difficult, but useful, research over the 5-year timeframe. It also will be possible to revisit research each year and to revise priorities based on current needs and knowledge gained from ongoing research and other developments.

Results

Twenty-two topics were evaluated using the form provided, after eliminating the HD/LB topics using the decision quadrant tool. The evaluation sheets were gathered after the groups completed them. After a short break that allowed the workshop facilitator to compile the evaluation scores, the workshop members were told which topics had the highest evaluation scores. Table 6 and figure 3 show the compiled results of the difficulty/benefit voting and the evaluation scores. All the numeric values are shown together in table 6 so that the highest scoring topics and their relationship to the difficulty/benefit rankings can easily be seen.

Table 6.—Tabulated results of the difficulty/benefit voting and the group evaluations for each research topic (See table 4 for the topic title that matches the topic letter.)

Topic Letter	Difficulty	Benefit	Evaluation Score
C	4.3	5.2	75
D	4.1	5.5	79
E	2.9	5.2	85
F	7.9	6.1	60
G	5.8	6	76
H	6.4	8.3	94
I	6.8	8.4	81
K	4.6	4	36
L	7.8	8.6	80
M	4.5	7.4	89
N	4	6.8	72
O	4.8	3.2	55
R	6.8	7.8	79
T	6.2	5.6	64
V	4.9	5.4	82
W	4.5	4.8	81
X	5	5.7	88
Z	7.4	8.1	85
AB	6.4	5.5	76
AC	5.8	6.5	84
AE	4.2	5.3	68
AF	3.8	6.1	88

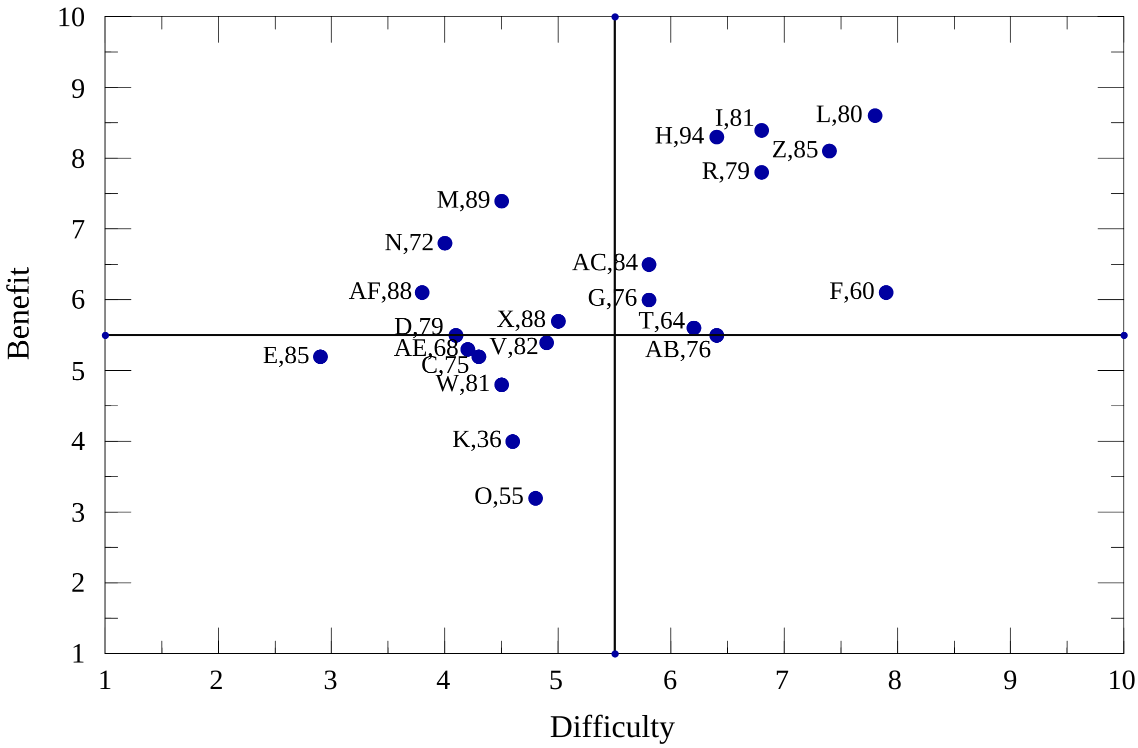

Figure 3.—Results of the evaluation ratings for each topic shown on the decision quadrant for reference. The labels are the topic identifying letter and the evaluation scores developed by the small groups (i.e. H,94 is topic H with a score of 94).

As a wrapup to the workshop, the evaluation scores were discussed in relation to the topic placement within the decision quadrant. A hard copy of the decision quadrant had been distributed to the group and evaluation scores could be jotted down as they were read by the facilitator. Figure 3 shows the positioning of each lettered topic on the decision quadrant, and the evaluation score is listed next to the lettered topic.

The importance of the three evaluation factors (value, scope, and product) can be seen on figure 3. In theory, a high-value project with a well-defined scope and useful product would produce the highest priority project. Because the evaluation contained cost estimates, if the proposed research topic had a high cost, which generally occurred when physical modeling was thought to be required, the value score could be significantly lower. Therefore, the most beneficial topic in each quadrant did not always have the highest evaluation score. Thus, some of the evaluation rankings in the HD/HB, or long-term research area, did not score as high as they potentially might have.

In a brief discussion of the results, the group felt that, in general, the evaluation scores did not contradict the difficulty/benefit results. When asked about the usefulness or applicability of the form, the general comments from the workshop participants regarding the evaluation form were:

- The evaluation elements were, in general, easy to understand and fair.
- Funding was, at most, a "best guess." Most workshop participants did not feel comfortable putting down a dollar figure for topics if the program was viewed as complex.
    - For some topics, if program cost was ranked as high, then the overall topic score was low, even though the group evaluating it felt that it was an important topic (i.e., Topic E had a relatively low cost at $75,000 and obtained a high total evaluation score; topic N had relatively high cost at $250,000 and obtained a lower total evaluation score; even though the group felt that topic N was perhaps more valuable technically).
- It was difficult to determine the amount of leverage that would be provided under the value scoring area.
- It was difficult to determine whether or not staff resources would be available under the scope scoring area.

The group also felt that State Dam Safety opinions were lacking, based upon not enough representation from the State dam safety community. In general, this was felt to be due to a lack of funding for travel for State representatives, not due to a lack of interest.

Final Prioritization of Research Needs

The steering committee convened the day after the workshop to discuss the workshop process and findings. The committee reviewed the decision quadrant results with the rankings from the evaluation criteria. The Dam Safety Research Work Group will not be interested in funding the LB/HD quadrant topics at this time. Therefore, those topics were not evaluated by the group and not considered in the final prioritization conducted by the steering committee.

The steering committee initially agreed that we should prioritize and forward what we considered the top 10 research topics from the workshop results to the Work Group. After further consideration, we agreed to use the information shown in the decision quadrant (shown in figure 3) developed from the workshop results. It seemed logical to take 4 topics from the HD/HB quadrant, 4 topics from the LD/HB quadrant, and 3 topics from the LD/LB quadrant for a total of 11 topics. The highest scoring topics from the three quadrants were then selected by consensus of the committee and are shown in figure 4 and listed in table 7 in descending order, based upon the highest evaluation score.

The steering committee debated what other factors could be used to prioritize the topics, and cost seemed to be an important factor. The cost of doing the research was also added to table 7 from the evaluation sheets because the cost played a role in the evaluation process and in the selection of the highest priority research by the steering committee. The steering committee also thought that the cost of the proposed research would play an important role in determining whether or not the Work Group would fund the recommended research. The bar chart in figure 5 shows the cost of the recommended research topics from table 7.

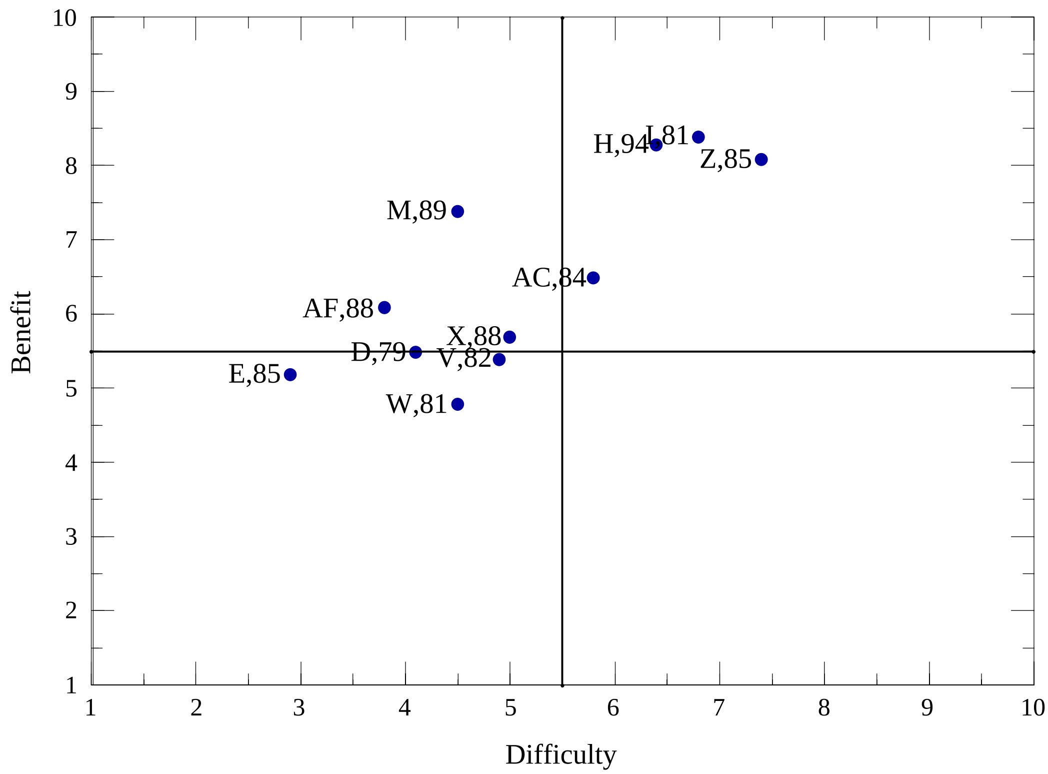

Figure 4.—Final research needs prioritization from steering committee recommendations, based upon the decision quadrant location and evaluation scores developed by the workshop participants.

Overall, the highest priority research topic is topic H, verifying the structural design and integrity of RCC embankment dam overlays. This topic had the highest evaluation score and the third highest benefit of all the topics. Topic H is in the HD/HB (or long-term) research category. In addition to the benefit and evaluation, the cost to perform the research outlined in topic H was far less than the others (Z, AC, I) in the long-term (HD/HB) quadrant, making it a logical choice.

Topic M, developing hydraulic design guidelines for embankment stepped spillways, had the highest evaluation score and the highest benefit in the LD/HB quadrant. This is probably because it is also the lowest cost of the four topics recommended from that quadrant.

Table 7.—Prioritized research needs topics developed by the workshop steering committee from the workshop results

Topic Letter	Ranking	Topic Title	Difficulty	Benefit	Evaluation Score	Cost $1,000
H	1	Develop RCC design document – structural aspects	6.4	8.3	94	100
M	2	Document hydraulic design criteria for embankment stepped spillways	4.5	7.4	89	100
AF	3	Develop procedures to perform better geophysical exploration of foundation voids and seepage	3.8	6.1	88	50
X	4	Determine criteria for sill wall spacing and foundation needs in earthen spillways	5.0	5.7	88	100
E	5	Develop a design manual for rock spillway chutes or steep riprap slopes	2.9	5.2	85	75
Z	6	Update or develop computer models to replace HMR and possibly PMF design requirements	7.4	8.1	85	250
AC	7	Investigate tools to reduce O&M costs and extend life of infrastructure (i.e., repairs or inspections)	5.8	6.5	84	500
V	8	Research grass design criteria for cool weather grass and reinforced grass	4.9	5.1	82	500
W	9	Determine best method for determining earth spillway crest discharge coefficients	4.5	4.8	81	50
I	10	Develop design guidelines for alternative materials for small embankment dam overlays	6.8	8.4	81	1,000
D	11	Develop design guidelines for siphon spillways	4.1	5.5	79	250
High difficulty/high benefit quadrant						
Low difficulty/high benefit quadrant						
Low difficulty/low benefit quadrant						

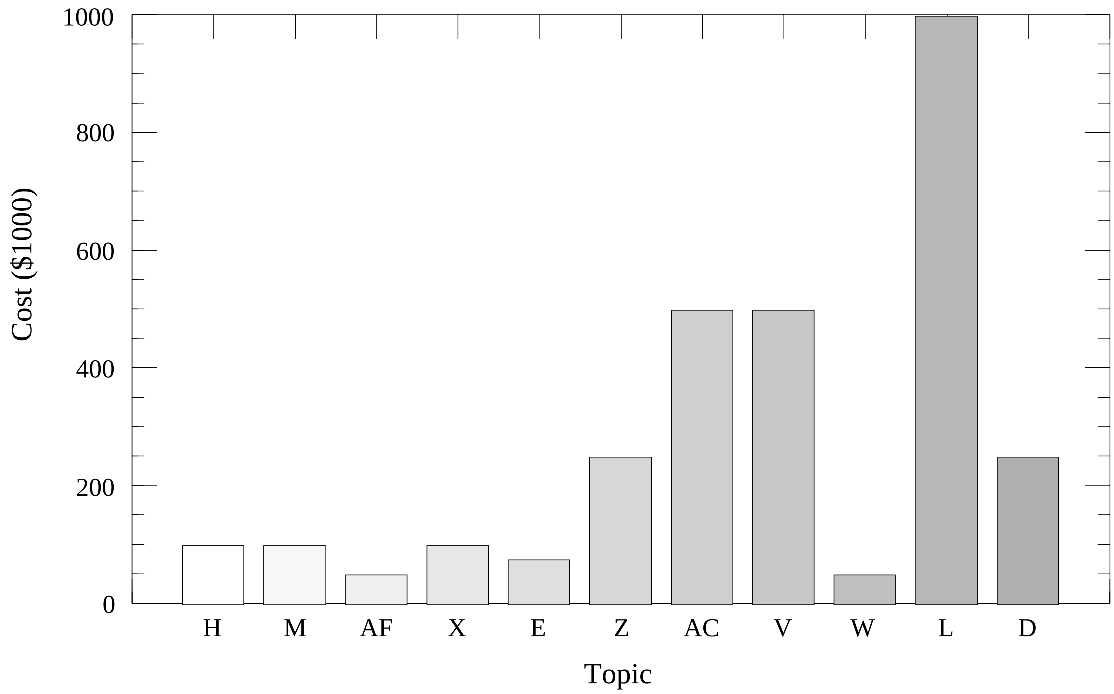

Figure 5.—Cost of the recommended research topics from the workshop.

Topic E, developing a design manual for rock spillway chutes or flow over riprap slopes, had the highest evaluation and the lowest difficulty among the three topics recommended from the LD/LB (or low hanging fruit) quadrant. The benefit of the three topics selected was very similar, and the evaluators felt that minimal effort would be involved with documenting existing research to produce a valuable output.

These three topics are the highest priority for each of the individual quadrants in the decision quadrant, and each topic had the highest evaluation score based upon the workshop rankings.

The steering committee generally concluded that technical merit and cost were the most important qualities of any research topic or proposal. The committee felt that the evaluations aligned with the intuitive feelings of importance by the group in that high benefit was not given to topics of relatively narrow usefulness. However, there was a bias introduced when several similar topics were combined under a research topic heading that generally produced a highly beneficial, but expensive, topic. An example of this is topic I, developing design guidelines for alternative protective materials during overtopping of small embankment dams. This topic was recommended by the steering committee as a worthwhile project, but because this research will most likely involve some modeling using many materials, the cost will most likely be high to complete the entire program. In contrast, if each individual protective material had been rated separately, then the topic most likely would be less costly and even possibly moved to another quadrant or given a higher quadrant rating in the current quadrant.

The steering committee agreed that cost played a fairly major role in the total evaluation scores and it was, therefore, listed separately in the final table of prioritized research topics.

Appendix A

Workshop Attendees

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Kathy Frizell	USBR P.O. Box 25007 Denver, Co 80225	303.445.2144	kfrizell@do.usbr.gov
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Appendix B

Abstracts

Hydraulic Design of Labyrinth Weirs and Fusegates

Henry T. Falvey[1]

Most spillways consist of some form of a weir. The weirs are normally placed perpendicular to the flow direction. The most significant parameters in determining the capacity of a weir are its height relative to the upstream depth, the crest shape, and the crest length. Here, capacity refers to the flow rate or discharge for a given depth of flow over the crest of the weir. Of these parameters, the crest length has the greatest influence on the spillway capacity.

As the emphasis in dam safety has increased, many spillways must be rehabilitated to increase their capacity without changing the reservoir storage. However, for many spillways, the width of the approach channel or the downstream chute cannot be widened. To increase the crest length but keep the spillway width constant, the crest is often placed at an angle to the centerline of the chute. The length can be increased further and can still keep the downstream dimension constant by folding the weir into several sections. These sections can be rectangular, triangular, or something in between.

The key points are

- Increased spillway capacity
- Research needed for crest shape, interference, splitters, approach flow conditions and raised invert.
- Preliminary design hydraulics and economics can be estimated easily with available computational methods.
- Model tests of specific installation recommended.

Fusegates are a proprietary device that is sold by Hydroplus in France. Lempérière invented them as a method of increasing spillway capacity or reservoir storage. They consist of a series of metal or concrete gates that when placed together have the shape of a labyrinth weir. As the flood rises, the gates tip as a function of the reservoir level.

The base of the each gate contains a block-out that fills with water when the reservoir rises above a specified elevation in a well. The well is located on either the gate or on the sidewalls of the spillway chute. When the block-out fills, the water pressure in the space creates an overturning moment that causes the gate to tip. The flowing water washes the gate downstream.

Research has been conducted on the effects of waves, downstream blockage, and ice on the performance of the gates. The key points of the fusegates are:

- Used to increase spillway capacity
- Used to increase reservoir storage
- Extremely predictable tipping as a function of reservoir elevation

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- Ice loadings, waves, seismic, and downstream plugging of stream have been studied
- Model studies of specific installations is required

Fuse Plug Embankments – State of the Art and Practice, and Research Needs

Tony L. Wahl[2]

The state of the art in fuse plug embankments is the design concept first described by Tinney and Hsu (1961). This approach utilized an inclined clay core underlain by a non-cohesive shell material. When the shell material is eroded away, the core fails as a cantilevered structural element, leading to rapid, reliable breach initiation. Laboratory and field testing by Tinney and Hsu and later testing by the Bureau of Reclamation (Pugh, 1985) confirmed acceptable performance and provided a means for estimating the lateral erosion rate of an embankment. Since the completion of the tests by Pugh, Reclamation has constructed four spillways with fuse plug embankments. None of these spillways has operated. Application of fuse plug embankments outside of Reclamation is thought to be relatively widespread on small dams, but there has been no comprehensive investigation. Many small dams are believed to be equipped with so-called fuse plug embankments that do not incorporate the design features described by Tinney and Hsu. Documented operational experience is extremely limited. During May of 2003 a fuse plug embankment operated in northern Michigan, causing damaging floods on the Dead River. Erosion of this embankment apparently continued to a deeper elevation than intended.

Three primary research needs are identified. First, long term performance of the thin clay core has been a concern on many projects. Cracking due to dessication and/or differential settlement and maintaining good contact between the core and floor/abutments are issues. Some have proposed use of alternative materials to address these issues, so a second research need is for development of designs that use impermeable goetextiles or concrete core walls designed to fail in a controlled manner. Finally, an inventory of fuse plug spillways is needed, so that the performance of different past and future design concepts can be evaluated.

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Crest Parapets and Dam Raising

Dwayne Fuller[3]

In 1956, the National Weather Service (NWS) published generalized estimates of probable maximum precipitation (PMP) for areas of the United States east of the 105th meridian in Hydrometeorological Report (HMR) no. 33. Later, at the request of the U.S. Army Corps of Engineers, the NWS published HMR No. 51, dated June 1978, which revised and expanded PMP estimates. The dam safety assurance analysis used HMR No. 51 to derive the probable maximum flood (PMF) and subsequent hydrologic deficiencies of several dams. Two of these dams were Tygart Dam near Grafton, West Virginia and Bluestone Dam near Hinton, West Virginia.

Because of hydrologic deficiencies these dams would not safely pass the PMF. This presentation discusses the model studies used to evaluate alternative actions or designs for remediation of these deficiencies.

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Gated Spillways - Enlargement, Modification and Rehabilitation - State of the Practice

Elizabeth Cohen[4]

The design of a dam with gates provides greater flexibility in the operation and management but also require specific operation and maintenance plans while posing potential risks due to mis-operation. The design of a gated spillway should address the function and needs of the project. A dam with a gated spillway operates to its full potential capacity only when the gates are open to discharge floods. Gate failures are not an uncommon phenomenon whether due to structural, power supply interruption or general miss-operation. If any gate fails to open during a flood, the safety of the whole dam is at risk. If any gate opens in error during normal operation, the artificial flood generated may endanger life & property downstream. Reclamation requires that any redesign or modification be a risk neutral design or that the risks do not increase for the downstream population.

The determination of function and needs should involve an evaluation of high head vs. low head, river flow, potential for storage of large floods (>100 Yr), maintenance, and attendance issues. The design and data should evaluate and address the river flow (normal, minimum, maximum, or bypass needs), storm storage, climatic conditions (temperature changes, winter conditions), reservoir fluctuations, vandalism, security issues, debris, controls and automation - operate remotely or onsite, emergency power, and flow measuring capability.

The types of gates available for consideration include Slide Gate, Wheel Gate, Radial Gate (or Tainter Gate), Drum Gate, Crest Gate (i.e. Obermeyer Gate or Rubber Dam), Fusegate, and Flashboards. Additional research needs could address development of information for the discharge; submergence effects on discharge, extrapolations to other situations, flows released during failure, seismic and security modifications, cost, maintenance, and durability. Other areas to be addressed may include air supply downstream of gates, orifice properties of submerged gates, transitions from open channel flow to submerged gates, discharge coefficients, and degree of accuracy of flow at rubber dams.

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Earthen Spillways Design and Analysis – State of Practice

Darrel Temple[5]

Earth channels have been widely used for auxiliary or emergency spillways to convey major flood flows around dams. These spillways are normally designed to flow infrequently and are generally considered have operated successfully if erosion experienced during a given event does not threaten the integrity of the dam and reservoir. For watershed flood control reservoirs, the typical earth spillway consists of a vegetated channel with an inlet reach, a level crest section, and one or more exit channel reaches designed to flow supercritical at design discharge. Larger structures may incorporate concrete weirs or sills to provide improved hydraulic control characteristics, including more uniform flow conditions over the width of the spillway. Energy dissipaters and erosion barriers of various forms may also be integrated into the design, but this discussion focuses on the behavior of the earth spillway channel itself.

Historically, earth or vegetated earth spillways designs were based on stable channel design criteria described in publications such as the USACE "Hydraulic Design of Flood Control Channels" or on an empirical bulk length as described in USDA TR-52. Although failure of these spillways has been rare, erosion observed during spillway flows has led to refinement of design and analysis procedures in recent years. The United States Society on Dams is presently developing a bulletin describing the history and the present state of the science in the area of erosion of earth spillways in more detail. Publication of this bulletin is expected during 2004.

The methods presently being used for the design and analysis of earth spillways tend to be semi-empirical, based on flows and erosion observed during the past 25 years. The REMR erosion prediction method developed by the US Army Corps of Engineers consists of a classification system that allows comparison of an erosion risk class with an erosion potential class. The approach predicts whether erosion is or is not expected.

The vegetated earth spillway erosion model developed by USDA and incorporated into the NRCS Sites software divides the erosion process into three sequential phases: 1) failure of the vegetal cover, if any, and development of concentrated flow; 2) surface detachment in the area of concentrated flow leading to development of a vertical or near vertical headcut; and 3) deepening and upstream advance of the headcut. Each phase of the process is described by different threshold-rate relations reflecting the physics of that phase. The model is applied iteratively to various potential points of initiation to determine the scenario with the greatest potential for spillway breach.

The USDA model represents a first attempt at quantification of the dominant spillway erosion processes. The potential exists for refinement of the relations describing all phases of the overall process. The US Army Corps of Engineers has applied the general approach with modified equations and ongoing research is expected to result in improved relations describing the processes. Research is also underway to refine the three-phase

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approach for application to prediction of dam breach due to overtopping flows. There is a need for continued study to develop improved parameters for describing the resistance of geologic materials to erosion and for improved means of identifying pertinent characteristics of materials that may be exposed during the erosion process. Other identified research needs include expanding the current breach prediction model to include spillway erosion that occurs after the initial breach and identification of conditions where modes of failure other than headcut formation and advance dominate the process.

Spillway Foundation Erosion
James F. Ruff, Ph. D., P.E.[6]

Spillways consist of control, conveyance, and terminal structures. There is not a high incidence of damage or of catastrophic failure of dams or of spillways as a result of spillway foundation erosion. The primary reasons are because spillways are constructed mainly on abutments, are founded on and anchored to rock, and have drainage systems. However, scour can occur downstream from chutes and stilling basins discharging to earth or rock exit channels or in plunge pools and basins impacted by water jets from flip buckets, orifice spillways, or outlet valves. Undermining of concrete chutes and floor slabs can cause structural damage that results in more foundation erosion and/or undermining and the cycle can continue. . Foundation erosion of one of the components affects operation of the structure and of the reservoir and forces repairs under time constraints at high costs.

Changes in design flood criteria have resulted in spillways with inadequate discharge capacity requiring different solutions for spillway improvements and enlargements. Most research has assumed the foundation was satisfactory and has focused on performance of the spillway components using small-scale models.

At Gibson Dam on the Sun River in Montana, flow over the dam eroded rock at the foundation and in the downstream channel in 1964. Although spillway failures have not caused catastrophic failures of dams, repairs have been expensive and have affected dam operations.

Testing of innovative methods to protect downstream slopes of earth embankments, earth spillways, and terminal channels began at Colorado State University in 1990 when the Bureau of Reclamation contracted with Colorado State University to conduct large-scale tests of riprap and Reclamation designed concrete wedge blocks. These tests indicated the blocks were a viable covering for embankment slopes and provided design criteria for riprap on slopes as great as 2:1 (H:V).

In 1995, Colorado State University began a second series of large-scale tests for Reclamation relating to water jets impacting on cohesionless beds and on simulated rocks. The water jets attempt to simulate water flow from orifice outlets, flip buckets or outlet valves. The objective of the study was to investigate the depth and rate of scour caused by the jets. Results provided a method to calculate scour hole dimensions.

Additional research is needed to investigate:

- riprap performance for different slopes at near- prototype scale
- mechanism of rock erosion because of overtopping flow and plunging jets

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- evolution of jet velocity and air concentration at surface and within plunge pool
- jet entry on plunge pool performance and scour

Prototype data is needed to improve scour prediction formulas.

Dam Overtopping Protection Technologies – State of Practice and Research Needs
Kathy Frizell[7]

Thousands of embankment dams across the US could be severely damaged or fail due to overtopping events predicted by increases in design flood amounts. Many embankment dam projects must then ensure the existing embankment would survive the flood, enlarge an existing spillway, add an adjacent spillway, or allow overtopping of the dam and provide protection. Often protecting the dam and allowing overtopping is the most economical solution; however, confidence in the protective system must be high.

Of primary importance when selecting an embankment dam overtopping protection method is the durability of the material that is chosen for the hydraulic loading conditions that are expected. Many technologies are available. Some have been adequately tested and proven to work in the field. Others have been tested and installed in the field, but not yet had flows to prove whether or not the method will work. Others have not been tested adequately under the high velocity, steeply sloped flow regime that exists on an embankment dam and should not be utilized until adequate testing has been performed. Some methods have been adequately tested, but not applied on a real dam.

This presentation will outline the available techniques that are available for use in protecting embankment dams during overtopping events:

- Earthen embankments, grass-covered earthen embankments, geotextiles and membranes, gabion or Reno mattresses, riprap, concrete blocks (cable-tied, interlocking, overlapping), soil cement, reinforced smooth concrete slab, RCC (formed or not) or reinforced conventional concrete formed into steps.

Each is dependent upon knowledge of the flow hydraulics or forces that act on the protection system and the underlying embankment for the given flood event. Basic guidelines for each overtopping protection method will be reviewed to give dam owners the current state-of-the-practice and research so that they can choose a reliable protection system based upon the loading requirements of the flow that must be passed. Examples of site specific applications are given when available.

Research needs mostly are left to documenting the current research on stepped spillway design for embankment dams. Then expanding the knowledge of energy dissipation of small dams under high flow discharges where the expected rate of energy dissipation is probably less than may currently be expected. All technologies need to have flow events occur over field installations to improve the acceptability and reliability of the methods.

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RCC Overtopping Protection for Increasing Spillway Capacity

By Kenneth D. Hansen, P.E.[8]

The use of roller-compacted concrete (RCC) to increase the spillway capacity and thus, the hydraulic safety of existing dams is now more than two decades old. In that time, RCC has gained the widest acceptance of all the methods available to design engineers for providing overtopping protection for embankment dams. The number of dams that have been upgraded with RCC overlays now exceeds 80 projects in the USA. The main reasons for this widespread acceptance is that an RCC overlay is easily designed, easily and rapidly constructed, has a relatively low cost and has had a very good performance record in the cases where flows have overtopped the RCC. In addition, all this remedial work can be accomplished without lowering the reservoir.

There is no accepted method for determining the minimum thickness of the overlay consistent with the maximum head of water flowing over the RCC. The minimum RCC thickness has been based on construction equipment considerations rather than any mathematical calculations. In order to place the RCC in 1-ft. thick, horizontal lifts in stair-step fashion up the embankment slope, a minimum layer width of about 9 feet has been found to work well from both a construction and stability standpoint. For a 3H:1V downstream slope, the minimum thickness thus produced is about 1.9 feet.

Projects in service have shown no hydraulic or structural problems when designed as noted above. The biggest problem noted over the years has been due to weathering of the outer exposed edges. Deterioration of the RCC surface has been noted in areas subject to many freeze-thaw cycles. This situation has been improved upon with greater strength RCC mixes (higher cement content) and by greater compaction of the outer edges of the RCC.

Recently, many RCC overtopping protections have been designed with 1 to 2-ft. deep, formed steps. The steps are visually attractive, hydraulically efficient and the forms provide a means for increasing the compaction at the outer edge. The hydraulic efficiency of steps for embankment slopes has not received as much laboratory study as those for the steeper gravity dam slopes. Additional research could be accomplished on this subject as well as the hydraulic efficiency of steps that have deteriorated a little due to weathering.

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General discussion - NRCS Designs and Research Needs

Jimmy Moore[9]

The presentation presents the hydrologic criteria used by the Natural Resources Conservation Service (NRCS) for the design of principal and auxiliary spillways. It includes the storage criteria to determine the crest elevation of the auxiliary spillway and the freeboard hydrologic criteria to determine the top of the embankment. Examples of various spillways constructed by NRCS are included in the presentation.

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Spillways – An Owner's Perspective

Jim Weldon[10]

None submitted.

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General discussion – Consultant's Spillway Design and Research Needs

Wade Moore[11]

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Vegetated Earth Spillways - Inspection, Maintenance and Monitoring

Morris Lobrecht[12]

NRCS experience with earthen spillways suggests that they generally perform well for infrequent flows. However, problems have been encountered when spillways are not properly designed or maintained. Performance examples from NRCS experience range from good to bad. Properly designed and maintained spillways with good vegetal cover have withstood large flows with minimal damage. Other spillways that were properly designed, but lacked uniform vegetal cover protection, have suffered damage with relatively low flows. In many cases maintenance was a problem. Maintenance, vegetation, and soil characteristics determine the performance of earthen spillways for a given flow event.

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Earth Spillways- State of Practice and Research Needs

Greg Hammer[13]

Introduction

The choice to use an earth channel spillway is typically driven by the economics of design, and its simple construction. However, as the low cost is a product of the ease of excavation and material placement, these same properties are the basis for the limited resistance to hydraulic loading, as is evidenced by eroded channels after flows occur. The initial process of design of the spillway may dictate the dimensions to safely route the inflow design flood (IDF), but the final design phases are driven by how to prevent, or at least limit the erosion that will inevitably occur after operation of the channel. The dilemma for the engineer regarding the design of an earth channel thus becomes not only how large the spillway must be to pass a given design flow, but also how to keep the channel intact during flow, and how to be sure that spillway will be clear and available when the occasion for flow presents itself.

State of Practice

In current practice it has been my observation that earth channels are immensely popular because construction requires no "high-tech" tools, or high-cost products. Concrete structures require forming, and quality control to assure that the final product is as designed. Earth channels however are created with little more that excavation by any simple means, followed by final grading to dress-up the appearance of the channel. Based upon evaluation of the material within which the channel was excavated, some remedial measures may be necessary to lessen the erosion attack, either by the use of rip-rap or a sill wall.

A typical design for an earthen spillway will include the process of sizing to route the IDF, then consider what armoring requirement will be necessary. The NRCS procedures based upon the "bulk length" are commonly used to evaluate erosion attack, and identify velocities that may be excessive. It may be necessary also to use a concrete sill wall to provide a measure of protection against the anticipated head-cutting. No clear guidance has been identified however as to where and when a sill wall may be required, or to provide a proper design.

Research Needs

Spillway capacities: Typically the capacity of a spillway will be calculated based upon either the broad-crested weirs formula, or uniform flow conditions using Manning's equations. Backwater analysis techniques (HEC-RAS, HEC-2) are often utilized, but can give results that differ markedly from the more popular formulas. Recent evaluation studies of spillways in Colorado have been found to give varied and unexpected results for channel spillways. Typical references (Brater & Street) depict values in the range of

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2.5 –2.7 for a typical earth channel spillway configuration, however HEC-RAS analyses have yielded values as low as 1.5. Conversely, there have been some instances where the flow coefficient has been found to be much higher than is reasonably expected.

Once the design flow has been identified, the channel must be evaluated for erosion. This requires an assessment of velocities and soil properties of the channel. NRCS has conducted much research in this arena based upon generalized soil conditions. On a micro scale, erosion occurs due to irregularities in soil properties or the channel. A common protective measure is a sill wall to retard the advance of head-cutting of the channel. Development of design techniques for sill walls would enhance our confidence in the ability of the channel to defend against erosion. This should include how frequently to space sill walls, and how deep to construct them when they cannot be placed on bedrock.

For the spillway to function as designed, another consideration is the aspect of keeping the channel open and unobstructed. Floating debris is a typical concern, but proper attention to maintenance can resolve that concern. In Colorado, we face the problem of snow and ice settling into the spillways. We have become aware of some research in Scandinavian countries, but little information has as yet been disseminated to engineer community. This concern is typically recognized at existing structures, and in many cases requires owners to venture to the dam before the snowmelt period begins to excavate the blockages and clear the spillway. On a case-by-case basis, some work has begun to design service spillways that can limit reservoir levels until natural melting will clear the emergency channel. Another method is to provide for a cover to create a low flow channel that can pass flows to encourage melting.

Issues and Research Needs Related to Hydraulics for State Regulated Dams

Ed Fiegle[14]

There are over 75,000 dams listed in the National Inventory of Dams. Ninety percent of these dams are regulated by state dam safety programs. They range in size from very small run of river dams all over the country to very large storage and flood control projects in the West. A survey was prepared and sent out to all ASDSO state representatives to prepare information on design and research needs for the workshop. The following questions were asked:

- Types of spillways?
- PVC siphon spillways?
- Ice and snow effects on hydraulics?
- Skimming flows on stepped spillways?
- Questions about hydraulics of spillways?
- Adequate training?
- What are the hydraulic issues with spillways that need further research?

Responses were received from 30 states. The responses will be summarized and presented at the workshop. The primary research needs as compiled from the state responses were in the following categories:

- Snow and ice issues (16 states)
- Stepped spillway design and longevity issues (7 states)
- Siphon design and integrity issues (6 states)
- Concrete block system issue (5 states)
- Hydraulic designs relating to spillway coefficients (5 states)
- Irregular spillway shapes (4 states)
- Drop structures (3 states)

The most important factor in performing research was that it must be relevant and reliable and the results needed to be proven in the field in long-term applications.

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Concrete Spillway Repairs
Jim McDonald[15]

The unacceptably high failure rate for concrete repairs is a major problem in repair of water-resource infrastructure and the overall concrete repair industry. It is generally acknowledged that the primary problem is cracking of repair materials - typically the result of dimensional incompatibility between the repair material and the concrete substrate. To achieve durable repairs, it is necessary to consider the factors affecting the design and selection of repair systems as parts of a composite system. Compatibility between repair material and existing substrate is one of the most critical components in the repair system. Unfortunately, information on material properties that affect dimensional compatibility, how the various properties interrelate, and values that should be specified as performance criteria for individual properties is very limited.

To address this need, the Corps of Engineers initiated a two-phase program of research in 1994 to develop performance criteria for dimensionally compatible cement-based repair materials that will provide durable crack-free repairs. Results of laboratory and field performance tests were correlated to provide a basis for development of performance criteria for the selection and specification of dimensionally compatible cement-based repair materials. Performance criteria include a minimum value for tensile strength and maximum values for modulus of elasticity, drying shrinkage, and coefficient of thermal expansion. Also, resistance to cracking in restrained shrinkage tests is a requirement. A data sheet protocol was developed for cement-based repair materials that will provide reliable, standardized information on pertinent material characteristics. Results of the overall investigation are summarized in Technical Report REMR-CS-62. Also, a summary paper is available on the High-Performance Materials & Systems (HPM&S) Website (http://www.wes.army.mil/SL/HPMS/bulletins.htm).

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Inspection of Concrete Spillways – Gated and Uncontrolled

Bill Bouley, P.E.[16]

The inspection of spillways requires qualified technical staff able to recognize satisfactory performance and to identify developing problems. The inspection techniques are similar for gated and uncontrolled spillways and can be also be applied for outlet works inspections. Earth-lined spillways are evaluated similar to embankment dams, but with special consideration given to approach (inlet) and discharge areas.

For the various spillway gates, an exercise or testing program should be established. A partial opening cycle of less than a ten percent opening should be used at least annually to ensure the hoist equipment and gates can operate in a satisfactory manner. Full cycle operation is desired to verify that there are no obstacles to releasing floods from the dam. These tests are conducted less frequently than the ten percent opening cycle due to the concerns about releasing large amounts of valuable water supply and impacting downstream residents. These full cycle tests are generally conducted at the end of an irrigation season or other periods of low reservoir elevations. Debris booms are needed where the potential for flow obstruction exists. Innovations to the original gate design that improves performance and reduces maintenance should be identified.

Uncontrolled spillway crests should be examined during discharge conditions and when not in use to determine if any deficiencies are present. Latent construction defects can appear during high reservoir conditions such as leakage through lift lines. Glory hole spillways should be isolated from public access by buoys or booms from the reservoir. The ideal inspection opportunity for these spillways is during reservoir conditions when the water surface approaches the spillway crest. This allows the examiner to identify possible shifting of the crest structure foundation.

Chutes, tunnels, stilling basins are the most critical features of the spillway, as they must pass discharges safely past the dam without eroding the abutments or foundation. Deflections and offsets in the walls and chute floor should be noted as they pose an impediment to flows and could lead to future damages. Patterns of flow should be observed either at the time of discharge or by observing water stains on the chute to ensure flow patterns are acceptable. Trees and brush should be removed and kept clear of the structure for a distance where such growth will not impact the structure or impede flows, usually a minimum clearance zone of 15 feet. In tunnel sections, offsets have led to cavitation damage at Glen Canyon Dam that required air slot installation. Drains constructed to prevent back pressure from groundwater should be cleared on a periodic basis.

Stilling basins are vulnerable to damage from excess surcharge to the walls or freeze/thaw cycles that can weaken the concrete. With basins that are constantly

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underwater, hidden defects can go unrecognized until they become more serious as can be the case with ball milling action when rocks become drawn into the basin.

Inspection techniques employed vary from the visual above ground evaluations for the majority of the spillway structure that are conducted with the overall facility examinations (conducted by local staff monthly, area staff annually, and regional staff and Technical Service Center staff alternating on a three year basis) to the more specialized examinations that are performed less frequently. Climbing and underwater inspection services are needed for areas that are difficult to access. These specialized services should be aware of any inherent hazards associated with examining water storage features. Whether for climbing or underwater services, in manned teams, there is a requirement for at least three team members, two conducting the actual structural examination, and a third member to be in communication with the team and to be in reserve should problems arise. Climbers are limited to their endurance and equipment constraints. Divers have limitations imposed by altitude and depth, restricting their duration underwater. Remote-operated vehicles are useful in visually monitoring underwater conditions, but physical conditions of structures cannot be adequately determined without the ability to check concrete and metalwork soundness.

Monitoring has consisted of survey measurement point installed along the spillway walls and chute floor. Surveys of smaller structures that show little movement over a 30-year period may be curtailed until a significant event (flood or earthquake) occurs in the area. Crack monitoring and mapping is used where needed. Other instrumentation is installed depending on site conditions and failure mode concerns.

Concrete repair methods and materials are being analyzed constantly by Reclamation's laboratory personnel to better assist the field staff. Non-destructive evaluation techniques are used to identify the extent of problem areas. In-place concrete strength tests, ultrasonic, x-ray, infrared, and several other processes are used to conduct non-destructive evaluations. Unfortunately, to obtain the services of these specialists, field personnel need to provide the funding for such advice, as there is not an agency infrastructure fund.

Geophysics for Spillway and Seepage Evaluation

Mark H. Dunscomb, P.G.[17]

Geophysics arguably has a greater ability to lower subsurface risk on a project for every dollar spent than any other investigative technique. It can not and should not totally replace intrusive methods but, in combination with these methods, it can used to reduce the number and cost of intrusive probes by helping to locate them more effectively, use probes to calibrate geophysical findings, and vastly improve overall subsurface understanding. Geophysics is non-invasive and non-destructive. It can help characterize the subsurface over broad areas and depths both quickly and cost effectively. It can "screen" an area for specific objects (e.g. voids, pipes) and provide in-situ estimations of some key physical properties. Specifically, with regard to dams, we have used geophysics to trace seepage through a variety of embankment and gravity dam configurations; test concrete arches for weathering and deterioration of concrete; locate abandoned diversion pipes; and "look" inside of and underneath concrete spillway slabs to map voids, trace seepage and locate steel reinforcing.

Research Needs

While geophysical techniques and applications continue to develop, there appears to be little need for basic research into the principles and applications of geophysical applications for dams and spillways. What does appear to be needed is the development of a State of the Practice document for application to dams. There are numerous tools available for geophysical exploration and each has its strengths and weaknesses. In addition, significant advantages can many times be gained through the overlapping application of two or more techniques. Development of a document that provides a clear and concise overview of geophysical applications for evaluating dams would have broad application and would bring significant value to the dam safety community.

[17] Mark H. Dunscomb, P.G., Associate, Schnabel Engineering, Inc., 510 E. Gay St. West Chester, PA 19380, phone: 610-696-6066, Mdunscomb@schnabel-eng.com

Inspection, Maintenance and Monitoring of Service and Emergency Spillways

Dan Johnson[18]

Introduction

There is an old dam Owner's mentality that is slowly changing from one that the dam did not need observation and upgrading to one where more attention is taken to ensure long, safe operation. This change involves more attention to maintaining the ability of a dam's components to perform as designed. At the same time, however, the costs of upgrading projects are more than Owners can afford. Modern technology has created less expensive upgrades for spillways that may have less redundancy than those prior "in-the-abutment-concrete-spillways".

As always, the general public has short memories and does not believe that significant events do occur. Who remembers the 1913 snowstorm in Denver that dumped 7 feet of snow? Very few, and so Denverites were ill prepared for the 2003 March snowstorm which dumped 4 feet. There is a general lack of good prototype experience; because design events occur so rarely that we do not get to evaluate the real conditions and behavior. We attempt to model with scale physical and digital models, but they may fall short in evaluating the behavior of water flow on designed earth and concrete spillway structures during the real event. We need to be observing the real events as they occur and the ability of spillways to perform as designed.

Inspection

Prior to an inspection an understanding of the failure modes for the particular spillway system is needed. Also, an awareness is needed that the service spillway may see use on a regular basis, where as, the emergency spillway may have never been used. Therefore, the condition of the spillways, based on "wear" may be quite different. Both types of spillways do erode, deform and age. The inspector must be trained in the issues for the particular type of spillway, its use and the aging impact on the materials used in construction.

It is valuable to observe spillways in operation during normal and greater than normal operations to provide a better understanding of the flow and erosion that occurs on a regular basis. The infrequent large flood may not be the worst impact on the longevity of a spillway, but the annual, 5 and 10-year floods may. Observation of the spillway during the 25-year flood may give indication of the potential for the spillway to survive the design flood.

Maintenance

Maintenance of most dams (small to medium sized) may be on an infrequent basis and at the behest of the safety agency, not the Owner's wishes. On the occasions of maintenance, the service spillway generally gets greater recognition, as it should, because it sees more use and has "wear" issues to correct. However, emergency spillways need to be in good repair for performing correctly when called into use. Concrete structures are

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subject to movement and cracking, erosion of foundation materials, deterioration, and collection of deleterious materials. Earth spillways are subject to deterioration of the slope protection materials (riprap, vegetation, etc), erosion from flows and slope movements. Over-the-top spillways, as being used on many embankment dams today, are subject to movement, cracking and aging of materials and require special considerations due to the high consequence of their failure.

Monitoring

Monitoring and evaluation of monitoring data is the best way to predict potential performance in all types of spillway events and to set a plan for maintenance and upgrading of spillways. The measurements to be taken on a particular spillway system are very specific to the dam, its features, and its operation. Each facility is different. Typically measurements of movement, cracking, deterioration and aging issues are typical of service and emergency spillway monitoring plans.

Data from monitoring is of little value unless it is used. Many dam owners have stacks of data that have never been reviewed. Documents such as survey records, photos, checklists and inspector's notes need to be viewed by knowledgeable personnel when first gathered and then compared to subsequent years' documents for evaluating performance and changes from historic to current.

Closing

Despite our toughest desires, aging is occurring and with it several things become obvious. The initial design may not have been to the level of safety now required for the spillway(s) and the changes that are occurring are detrimental to successful operation of the spillway(s)

As we have all been taught, dam failures occur and spillways are the leading cause, and inspection, maintenance and monitoring are tools we use to ensure that the spillway will safely function when needed.

Unlined Spillway Erosion Risk Assessment

Joe Koester[19]

Spillway erosion analyses are affected by the highly variable nature of spillway geometry, geologic material, and unpredictable flood events. Improved tools are urgently needed to determine probability of spillway damage as part of portfolio risk assessments of dam safety, in order to effectively prioritize remediation activities. Essentially, the purpose of risk assessment in these cases address three main questions:

- What can go wrong?
- What is the likelihood it can go wrong?
- What are the consequences?

Nested uncertainties compound the problem; this research investigates the relative effects of uncertainties associated with flood events, material properties, and performance of unlined spillways. Various logistic regression techniques are presented and applied to quantify erosion potential against known site performance data.

[19] Joseph Kester, Supervisory Research Engineer, CEERD-GS-E 3909, Halls Ferry Road, Vicksburg, MS 39180-6199, phone: 601-634-2202, Joseph.P.Koester@erdc.usace.army.mil

Appendix C

Presentations

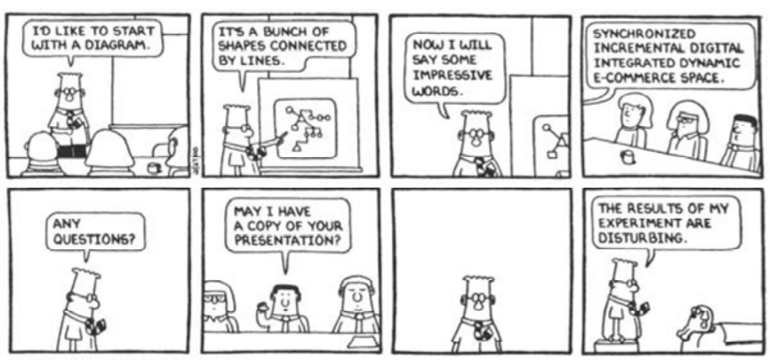
This appendix provides the MS Word PowerPoint presentations of the state-of-practice regarding dam service and/or emergency spillways. All the presentations presented at the workshop are included in this appendix as documentation of the state-of-practice and research needs as seen by the presenting experts.

Presentation 1: Hydraulic Design of Labyrinth Weirs and Fuse Gates

HYDRAULIC DESIGN OF LABYRINTH WEIRS

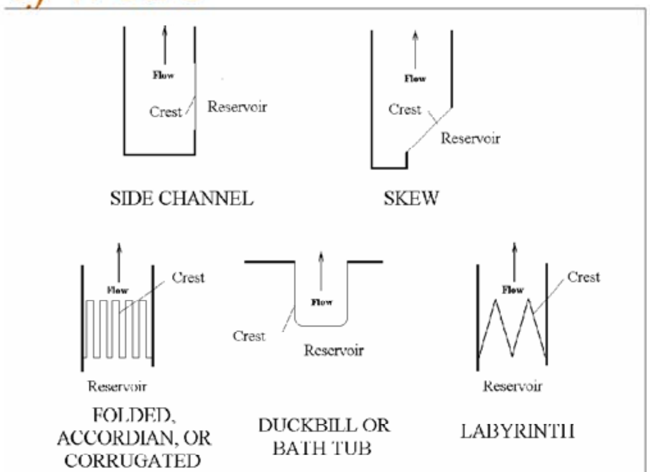
Henry T. Falvey & Associates, Inc.

Outline of Presentation



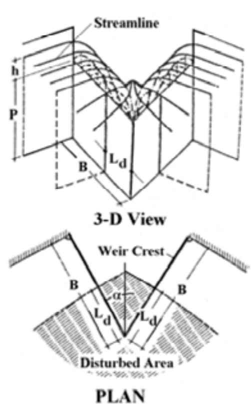
Henry T. Falvey & Associates, Inc.

Types of Weirs



Henry T. Falvey & Associates, Inc.

Nappe Interference



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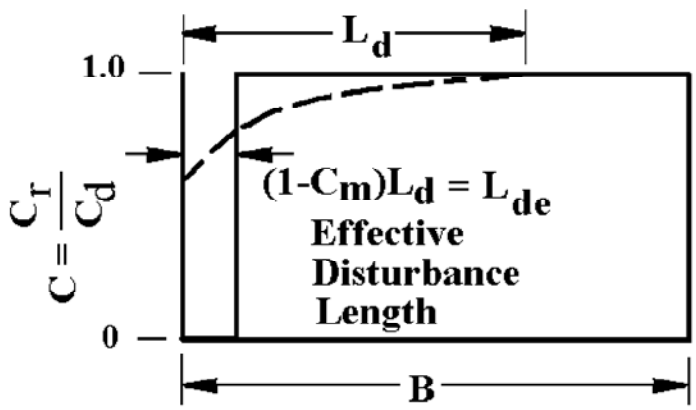
Effective Disturbance Length



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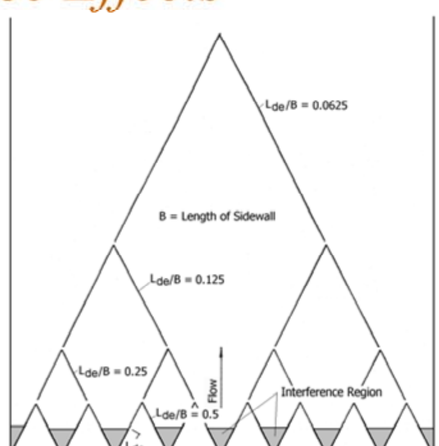
Interference Effects



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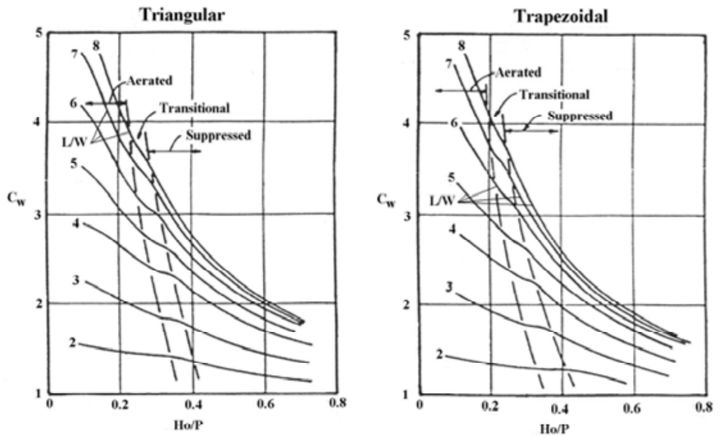
Design Curves – Lux/Hinchliff



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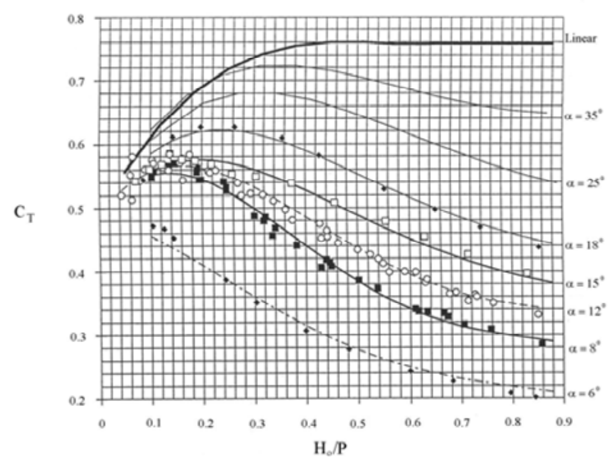
Design Curve - Tullis



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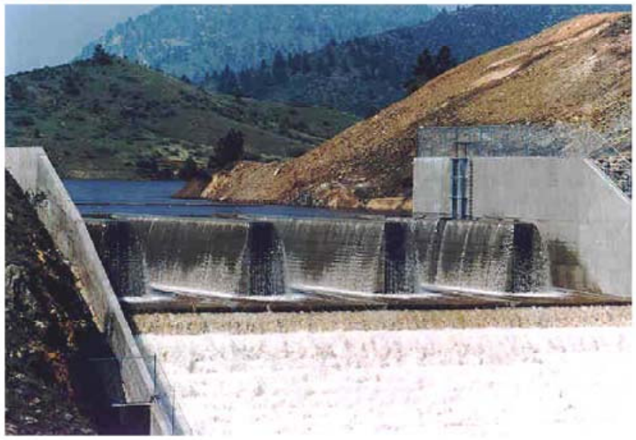
Nappe Oscillation – Milton Reservoir



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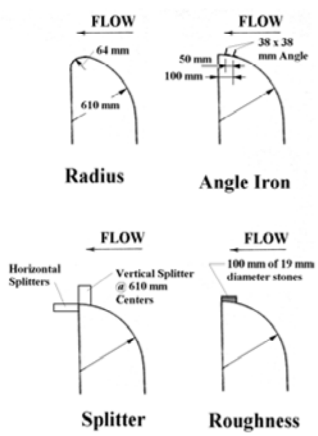
Solutions to Nappe Oscillation



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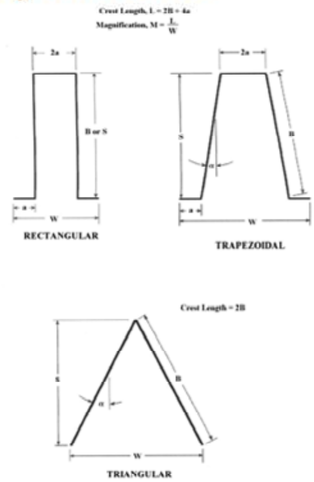
Geometric Definitions



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Design Considerations – New versus Old

- Lux recommends $0.45 < H_o/P < 0.55$ $W/P = 2.5$, and $2 < L/W < 6$.
- New criteria allows Ho/P to be as high as 0.90, W/P is superceded by interference ratio (L_{de}/L) and L/W superceded by efficacy.

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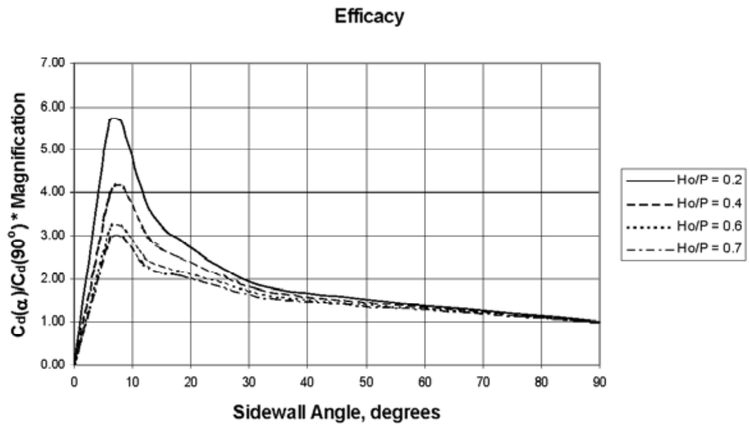
Design Considerations - Efficacy



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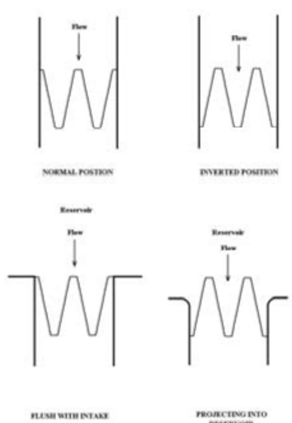
Design Considerations - Position



Henry T. Falvey & Associates, Inc.

Research Needs

- Crest Shape
- Interference Verification
- Need for Splitters on Crest
- Approach Flow Considerations
- Raised Invert Effects

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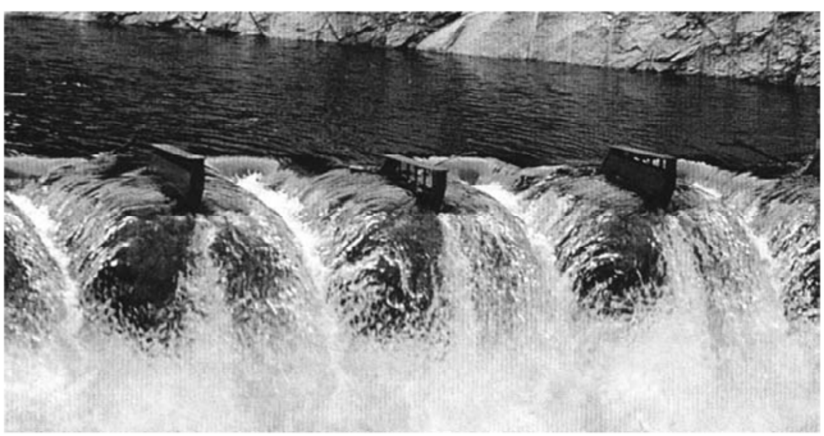
FUSEGATES



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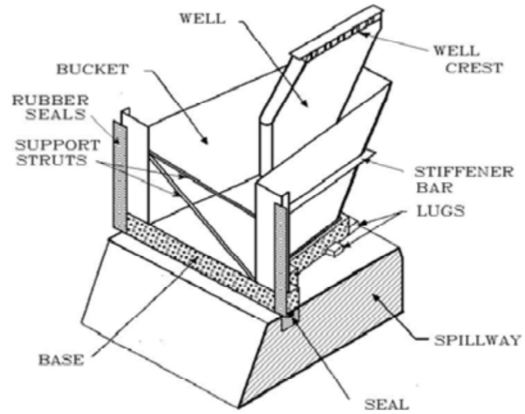
Fusegate Geometry



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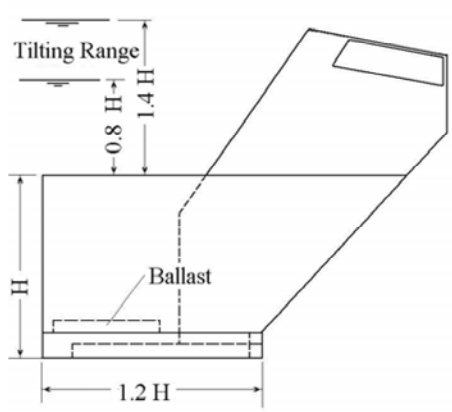
Profile



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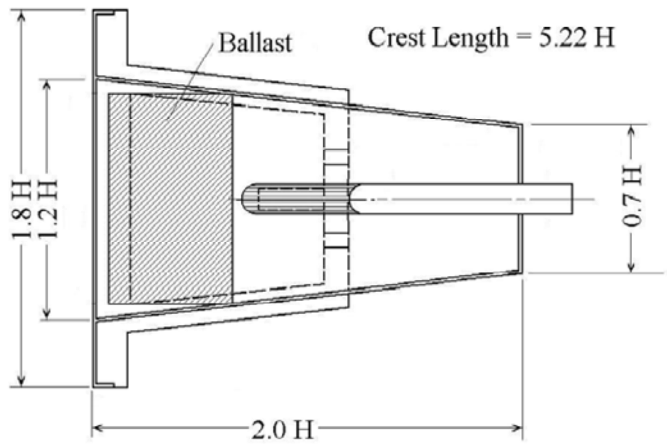
Elevation



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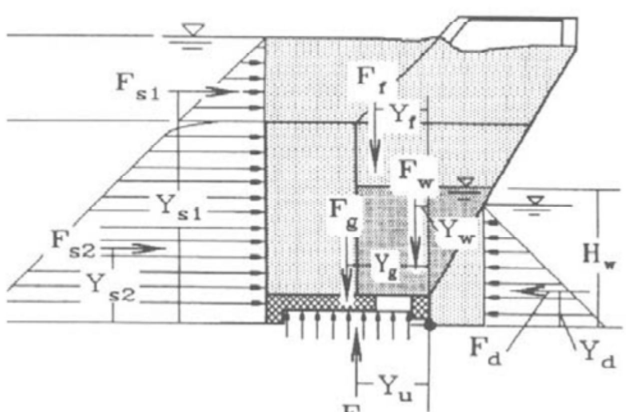
Forces on Fusegate



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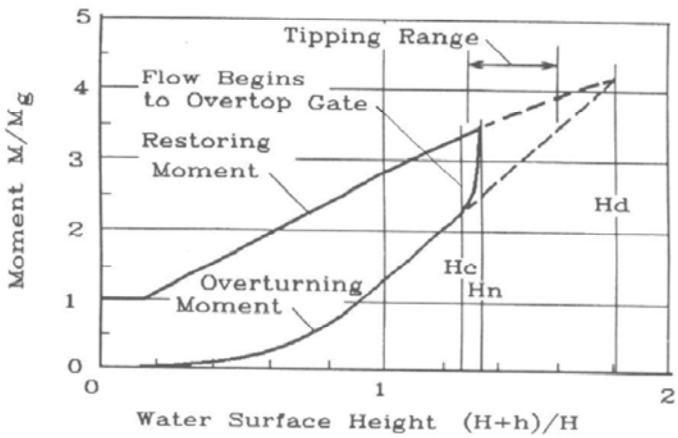
Moments on Fusegates



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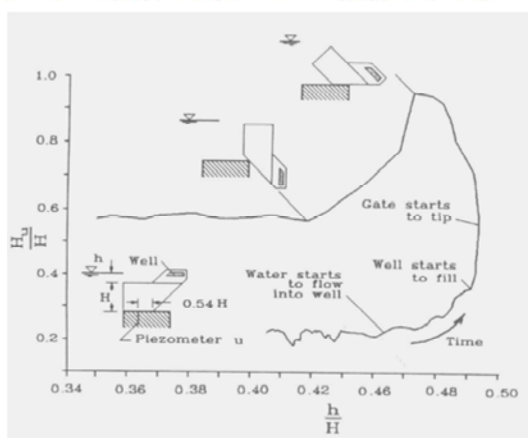
Fusegate Chamber Pressures



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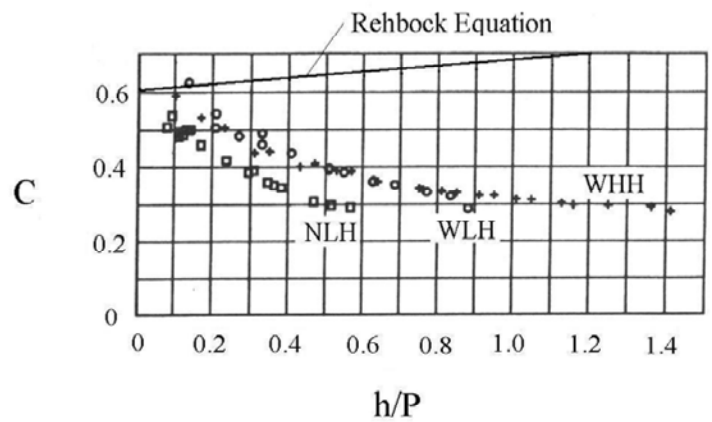
Discharge Characteristics



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Issues with Fusegates

- Wave loading has been studied
- Ice loading has been studied
- Seismic loading has been studied
- Tailwater effect has been studied
- Downstream channel clogging has been studied
- No major research needs

Henry T. Falvey & Associates, Inc.

Presentation 2:
Fuse Plug Embankments —State of the Art and Practice, and Research Needs

Fuse Plug Embankments

State of the Art and Practice, and Research Needs

Tony Wahl

Bureau of Reclamation

Water Resources Research Laboratory

Bureau of Reclamation

Managing Water In The American West

State of the Art

- Design concept by Tinney and Hsu (1961)
  - Proven in their lab tests, Oxbow field test, and 1980's Reclamation lab tests
- Core is inclined downstream
  - Failure is by scouring out non-cohesive supporting zone, causing core to be a cantilevered beam
  - Initiation is **reliable, rapid**
  - Lateral erosion rate is predictable, depends on head and embankment cross section

Design Concept

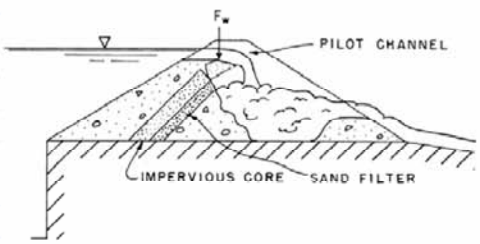


Figure 16 Flow through the pilot channel showing the failure mode of the impervious core.

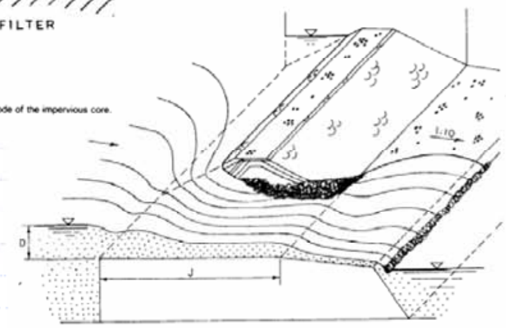


Figure 27. – Schematic of the lateral erosion process. The water flows across the face of the embankment, around the core, and erodes the noncohesive material downstream from the core.

Laboratory Testing

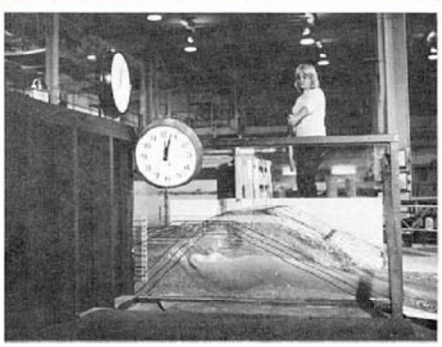
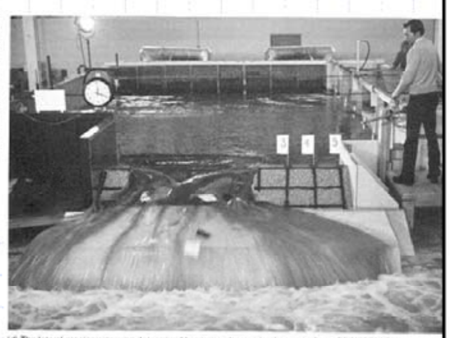


Figure 4. – Initial breach viewed through end wall, test No. 8. P801-D80946.



(d) The lateral erosion rate was determined by timing the erosion between flags. P801-D80952

Figure 26. – Views of the washout process. – Continued

State of the Practice

- How many have been built (or are being built)?
- What design concept are they using?
  - Tinney & Hsu inclined core
  - More traditional embankments
    - Vertical core or homogeneous fill
- Operational history

State of the Practice

- Reclamation fuse plugs
  - Horseshoe and Bartlett Dams
    - 262,000 cfs (~10 yrs)
  - New Waddell Dam
    - 129,000 cfs
  - Jordanelle Dam
    - 5,500 cfs (~10 yrs)
  - Sumner Dam
    - 150,000 cfs (1955)

Fuse Plug at New Waddell

State of the Practice

- Fuse Plugs Built by Others
  - Center Hill Dam (USACE) (USBR consulted)
  - Lake Pontchartrain fuse plug levee (1936)
  - Yahekuo Dam, China (vertical, tapered core)
    - Fuse plugs reported to be widely used in China
  - Arvada Reservoir (10-bay homogeneous embankment)…considering rehab
  - Many, many small dams
    - e.g., 4 dams North Carolina (Nantahala Power)

Operating History

- Very few spillways have operated
  - Oxbow Field Test was a prototype
  - Fuse plug at Silver Lake on Dead River in Upper Peninsula of Michigan *failed(?)* in May 2003.
    - Greater portion than anticipated gave way
    - Apparently eroded too deep…no fixed sill
    - Nobody I talked to was willing to say much right now

Research Needs

- Investigating long-term stability of inclined clay core
  - Cracking due to dessication or differential settlement
    - issues of concern on SRP fuse plugs
  - Contact with floor and side walls
  - Is long-term water storage against a fuse plug desirable, undesirable, or not an issue?

Research Needs

- Designs utilizing other materials that might offer better long-term performance or ease of construction
  - Impermeable membranes
  - Inclined concrete core
- Research to define inventory of fuse plug spillways, their design concepts, and operational histories

Presentation 3:
Crest Parapets and Dam Raising

Crest Parapets/ Dam Raising

Dwayne Fuller
U.S. Army Corps of Engineers
Engineer Research and Development
Coastal and Hydraulics Laboratory

Recent Projects

- **Tygart Dam**, Tygart River, West Virginia, Pittsburgh District
- Original Design Flow, 270,000 cfs
- PMF Flow, 373,000 cfs
- 38% increase

- **Bluestone Lake Dam**, New River, West Virginia, Huntington District
- Original Design Flow, 430,000 cfs
- PMF Flow, 950,000 cfs
- 120% increase

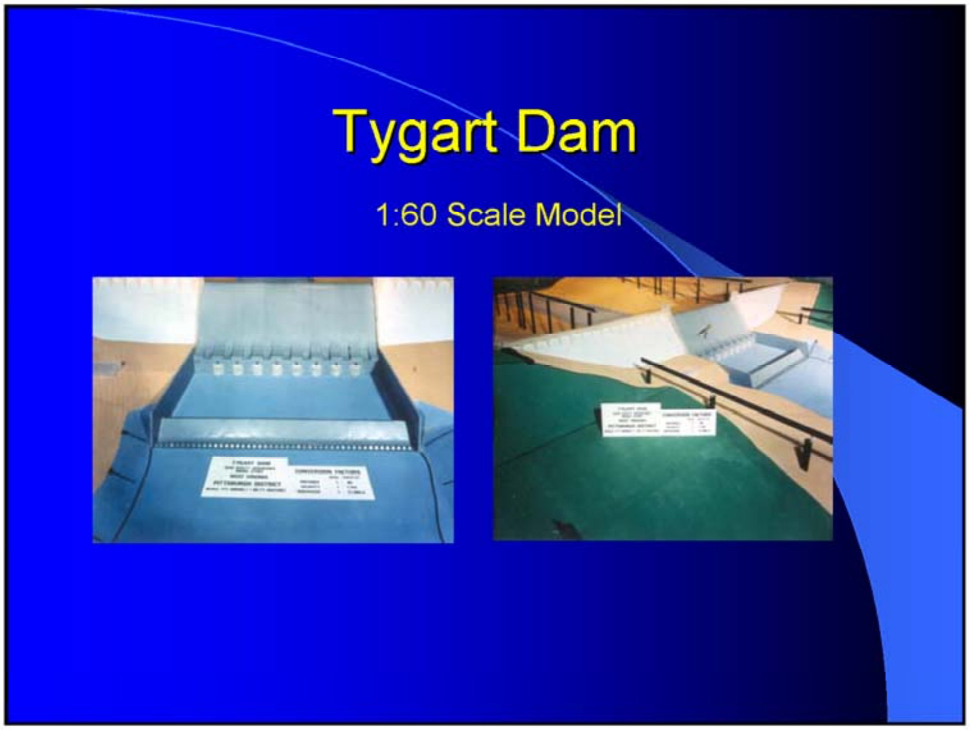
Typical Model Objectives

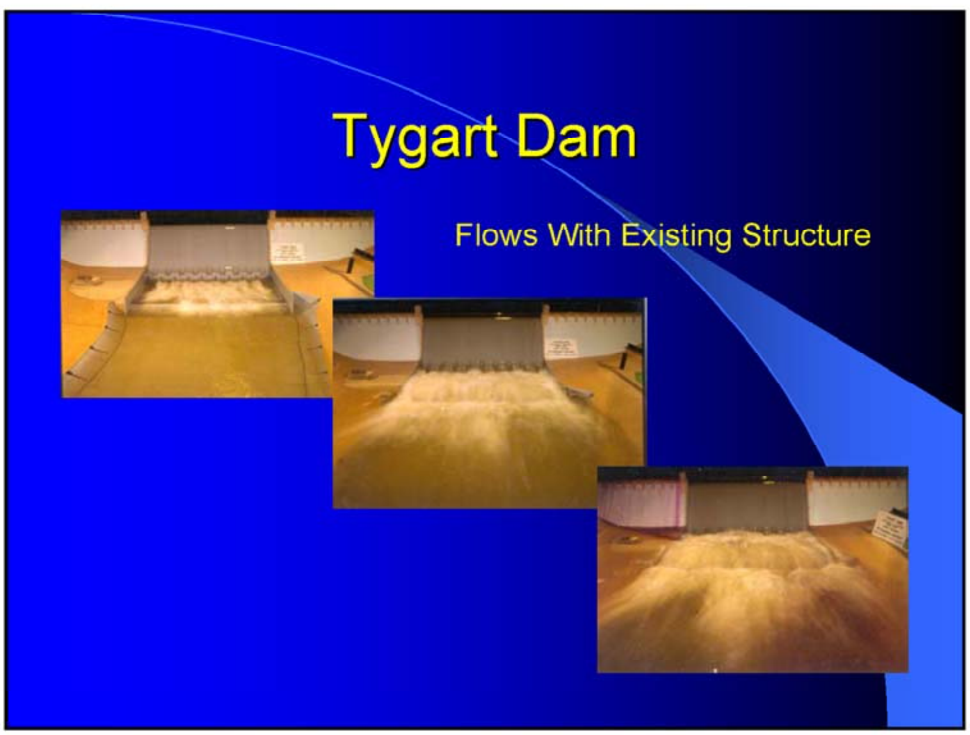
- Extend rating curve
- Crest pressures
- Gate and pier pressures
- Energy dissipation component forces
- Stilling basin forces
- Scour pad forces
- Tailrace scour

Tygart Dam

Alternatives

- No action
- Raising the dam (approximately 6')
- Spillway modification (gated spillway with lower crest)
- Auxiliary spillway
- Overtopping
- Dam replacement


Tygart Dam
1:60 Scale Model


Tygart Dam
Flows With Existing Structure

Tygart Dam

Redirected Spill

Tygart Dam

Bluestone Lake Dam

1:65 Scale Model

Bluestone Lake Dam

<u>Alternatives</u>

- No action
- **Raising the dam** (approximately 14')
- Spillway modification
- Auxiliary spillway
- **Overtopping (partial)**
- Dam replacement

Bluestone Lake Dam

Original Design Flow

High Flow

Concerns

- Spill capacity (PMF passage)
- Stilling basin
- Cavitation (spillway and penstocks)
- Erosion
- Component inadequacy
- Hydraulic loads
  - Forces on side walls
  - Basin forces
  - Forces on temporary structures
- Flow conditions in tailrace
- Debris build-up in basin (side flow)


Possible Research Needs
Effects of side flow into stilling basin
Debris damage in basin
Force measurement techniques
Temporary structure design criteria

Presentation 4:
Gated Spillways: Enlargement, Modification, and Rehabilitation —State of the Practice

GATED SPILLWAYS

ENLARGEMENT, MODIFICATION AND REHABILITATION

STATE OF THE PRACTICE

Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

GATED SPILLWAYS

- Determine Function and Needs
- Risk Neutral
- Types
- Design & Research Needs

Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

DETERMINE FUNCTION AND NEEDS

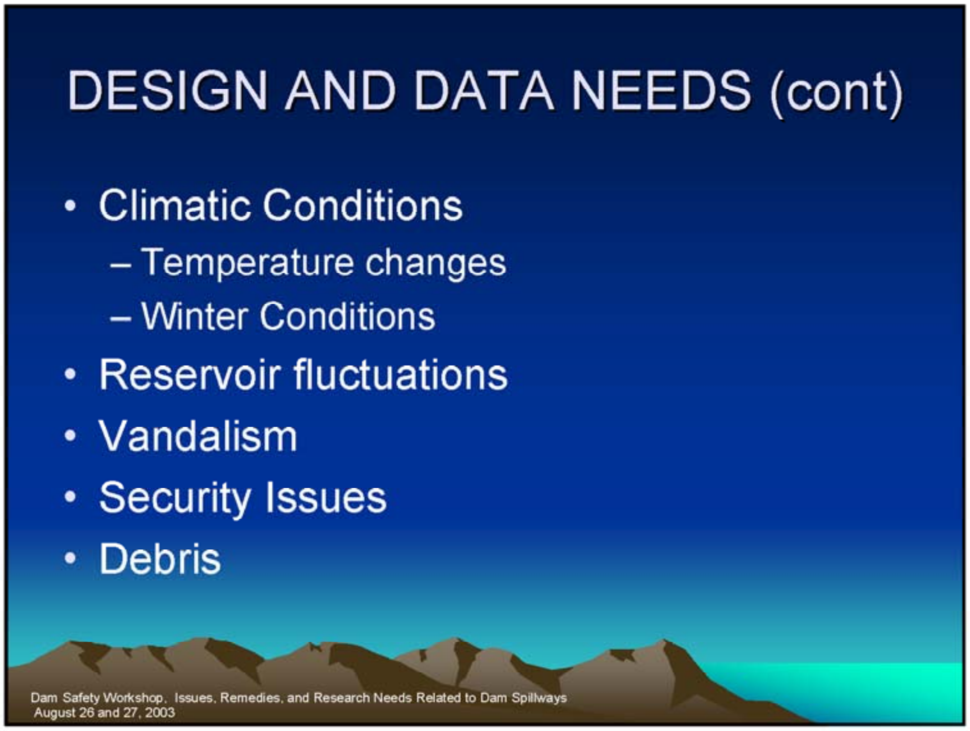
- High Head vs. Low Head
- River Flows
- Storage Issues of Large Floods (>100 Yr)
- Maintenance
- Attendance issues

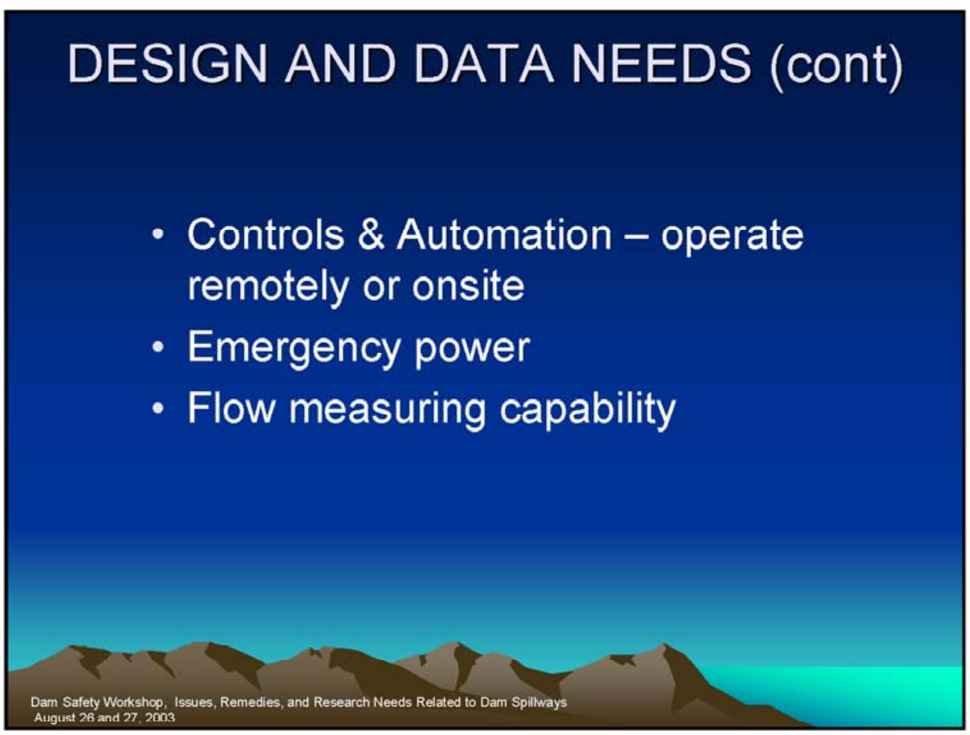
Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

DESIGN AND DATA NEEDS

- River Flows
  - Normal
    - Annual river flows
  - Minimum Flows
    - Is a bypass needed?
  - Maximum Flows
- Storm Storage

Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003


DESIGN AND DATA NEEDS (cont)
• Climatic Conditions
– Temperature changes
– Winter Conditions
• Reservoir fluctuations
• Vandalism
• Security Issues
• Debris
Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

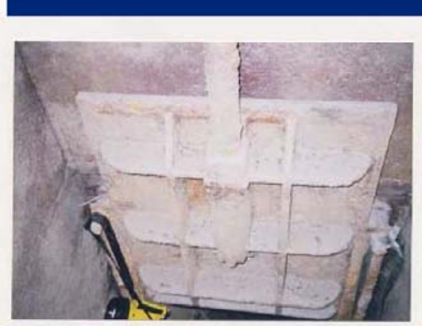

DESIGN AND DATA NEEDS (cont)
• Controls & Automation – operate remotely or onsite
• Emergency power
• Flow measuring capability
Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

TYPES

- Slide Gates
- Wheel Gates
- Radial Gates
- Drum Gates
- Crest Gate
- Rubber Dams
- Fusegates
- Flashboards

Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

Slide Gates (Unbonneted)



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August 26 and 27, 2003


Wheel Gates
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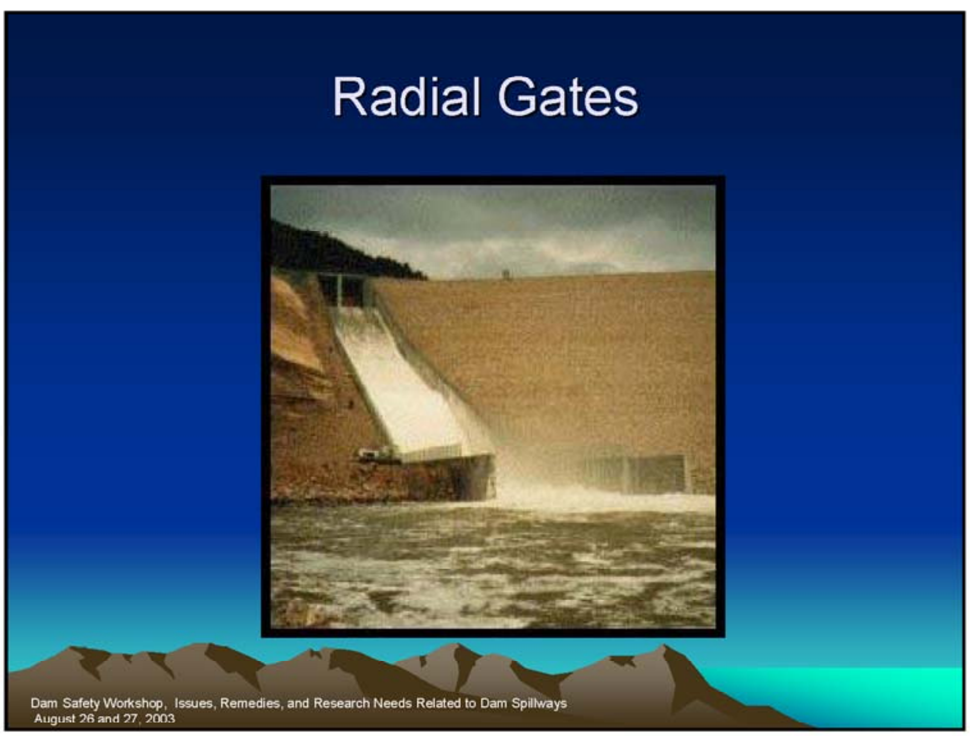
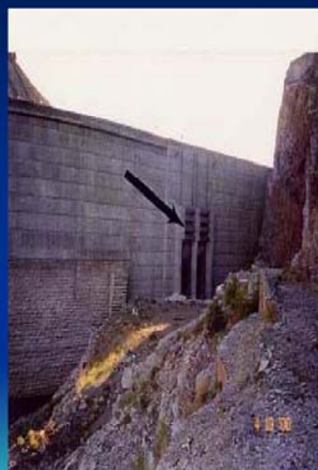
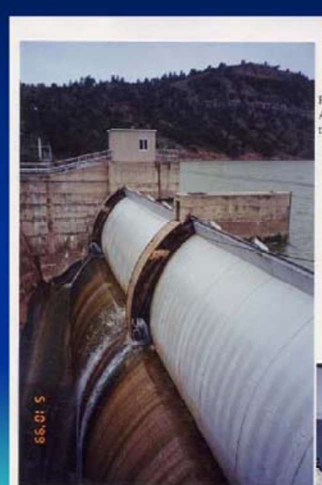

Radial Gates
Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

Top Seal Radial Gates



Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

Drum Gate



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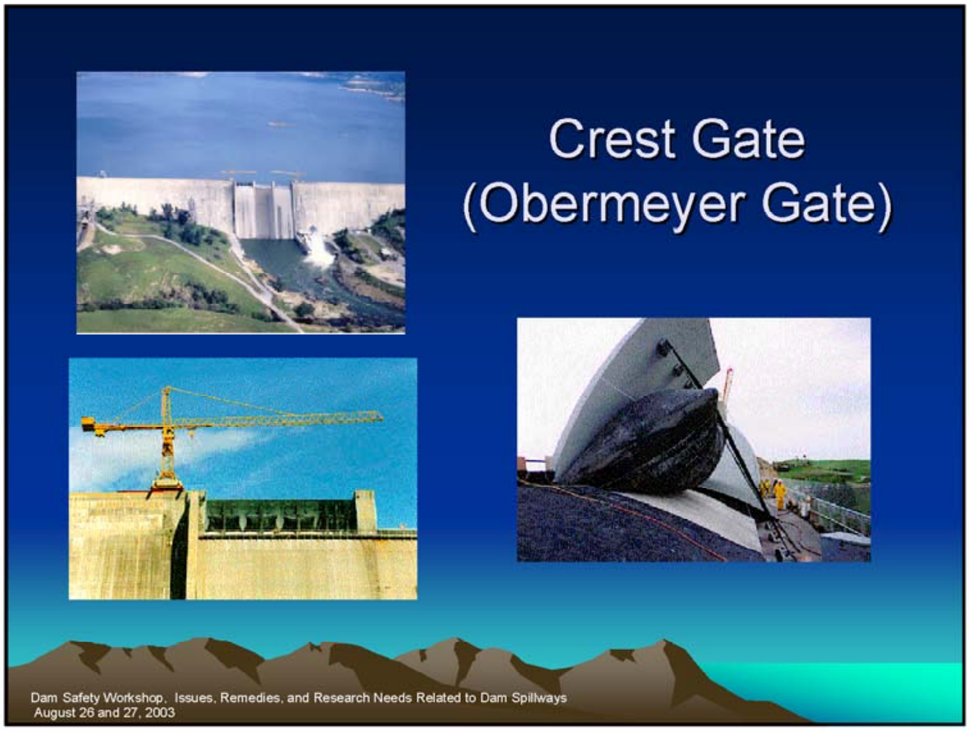
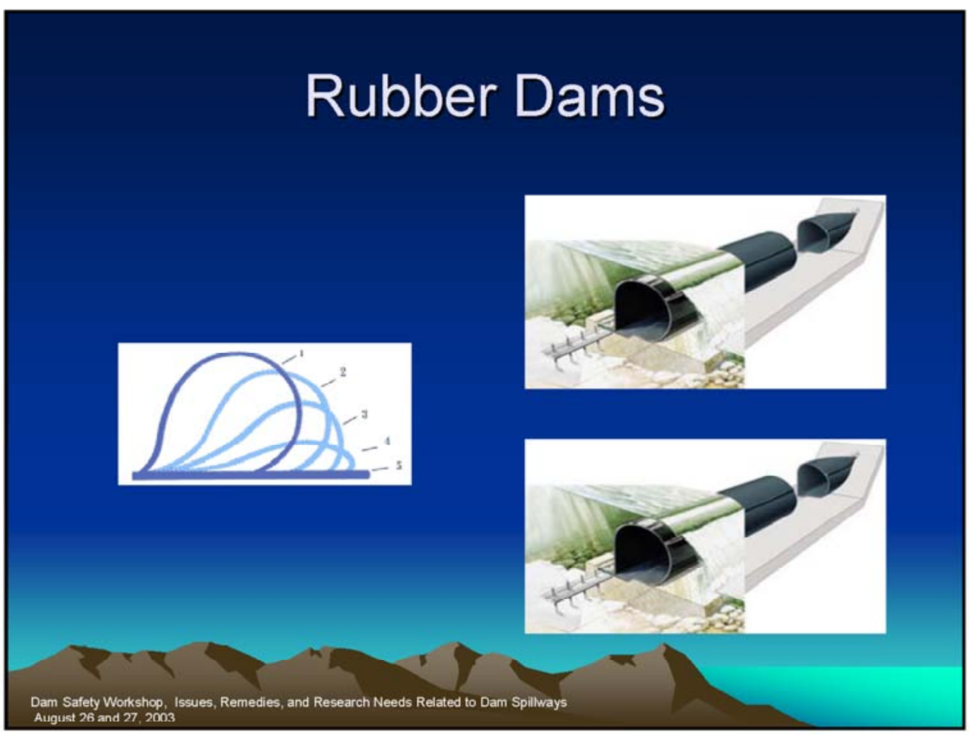
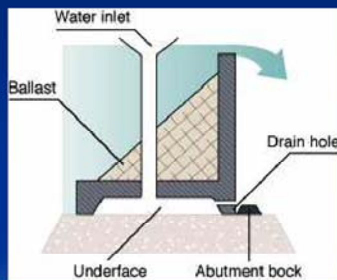
August 26 and 27, 2003


Crest Gate
(Obermeyer Gate)
Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003


Rubber Dams
Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

Fusegates (Hydroplus)



Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

Other Types of Gates

- Flashboards
- Cylinder Gates
- Other

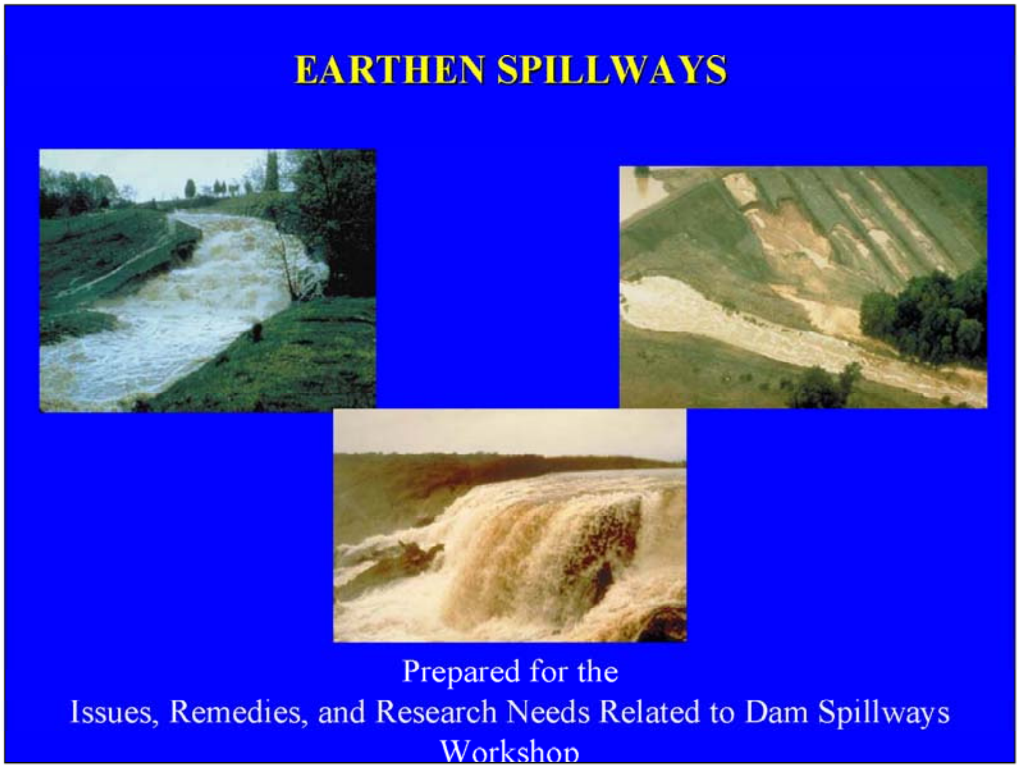
Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003


RESEARCH NEEDS
• Discharge data
• Submergence effects on discharge
• Extrapolation to other situations
• Flows released during failure
• Seismic and security modifications
• Cost
• Maintenance and Durability
Dam Safety Workshop, Issues, Remedies, and Research Needs Related to Dam Spillways
August 26 and 27, 2003

Presentation 5:
Earthen Spillways Design and Analysis
State of the Practice

Thank you. I am with the Agricultural Research Service, and one of the first questions that may come to mind is "What interest does the Agricultural Research Service have in Spillways?"

As the research arm of the USDA, we are responsible for performing the research needed by action agencies; including the Natural Resources Conservation Service. Within USDA, only the Forest Service has its own research branch. Therefore, although we do cooperate with Universities and other Federal agencies, and I'll try to touch on some of their concerns, my discussion today will generally be from the perspective of the USDA.



USDA has significant experience with vegetated earth spillways, and has collected substantial field data from spillway flow events.

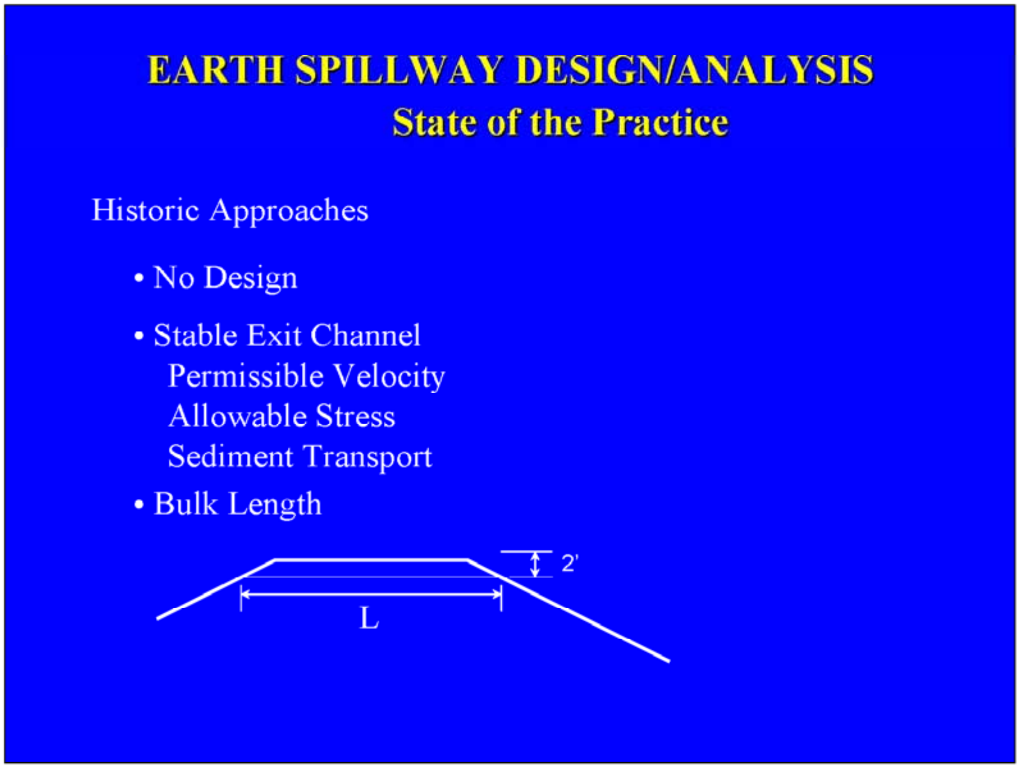
The primary concern that is unique to earth spillways is that they are erodible. Or at least we hope that we don't have that problem with other spillways. In general, the philosophy has been that, because flows are infrequent, some erosion may be acceptable providing the spillway is able to pass the design storm without failure.

Because they often offer economic and aesthetic advantages, there have been a large number of earth emergency or auxiliary spillways used. USDA has assisted with the construction of over 10000 flood control reservoirs, and most of these have earth spillways. They have also been used on other dams either alone or in combination with structural components.

They have been designed using various criteria. And I'll touch on that more in just a moment.

As with other types of spillways, the capacity may be inadequate. This may be due to a number of factors, but for USDA assisted dams, the most common reason is a change in hazard classification changing the design storm.

Inadequate maintenance can also create problems. Vegetation and earth are often thought of as not requiring maintenance, but in some instances, maintenance may be an important factor.

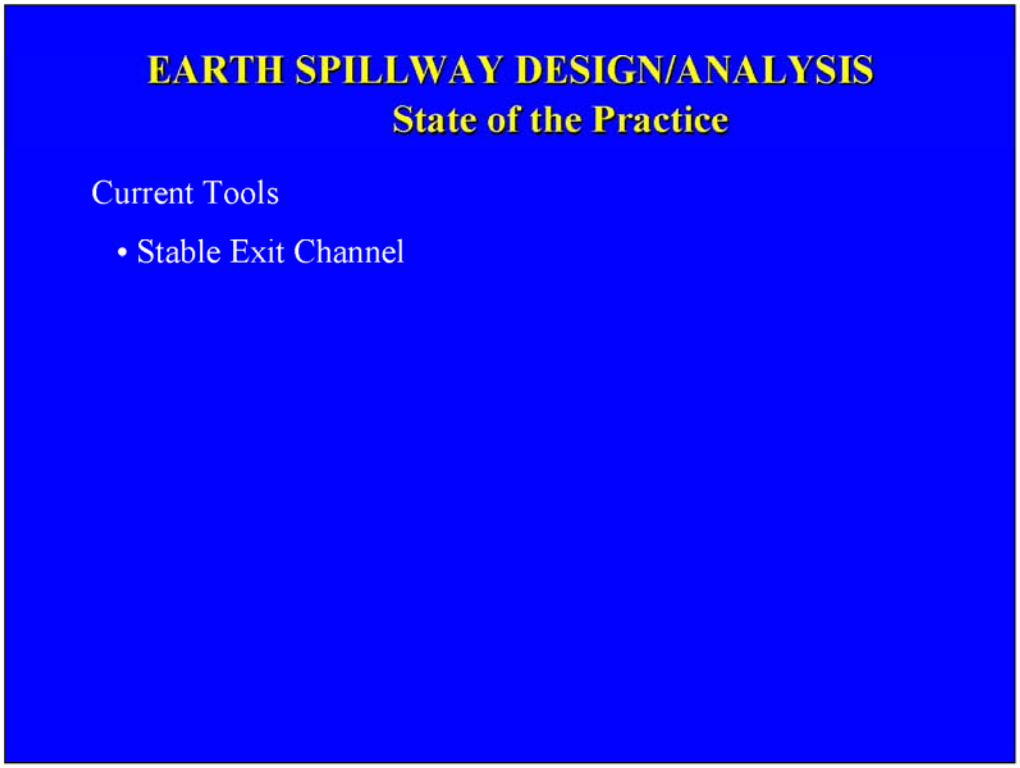


Looking at the approaches used to design earth spillways during the glory years of dam construction, the first approach was to just let it happen. This approach was generally only associated with smaller agricultural dams in the early years when some engineers tended to be of the opinion that the emergency spillway would never flow anyway and the spillway was just a convenient borrow for the dam construction.

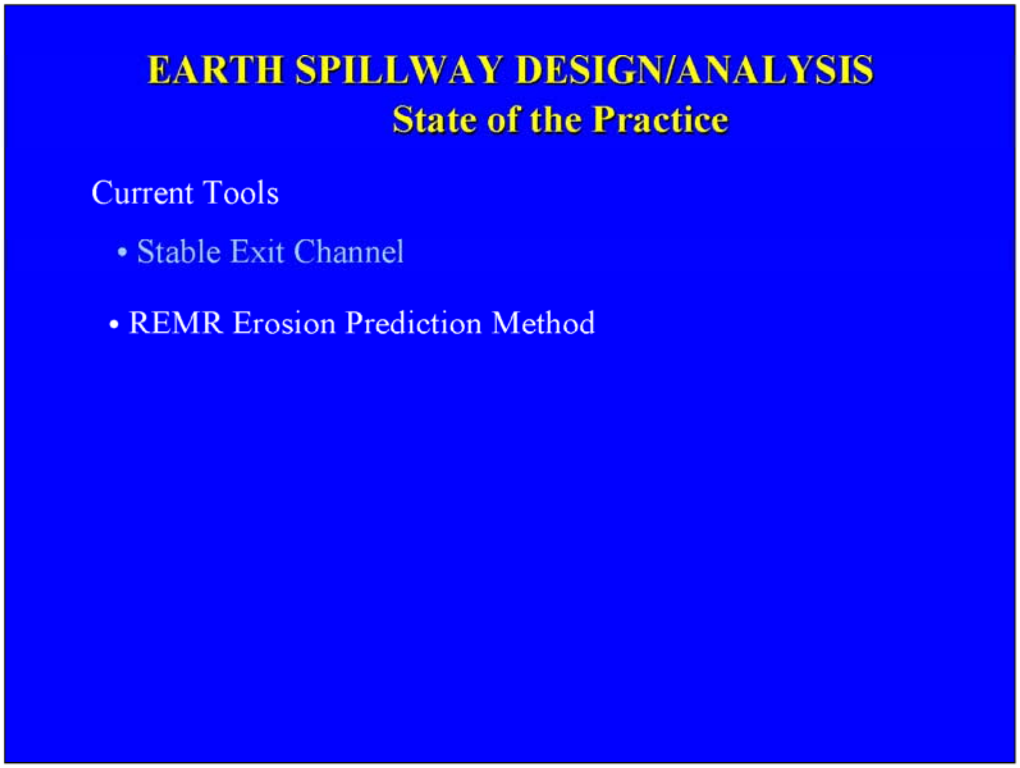
On the other end of the scale was design of the spillway to conduct the design flow as a stable channel. The tools applied were generally the clear water approaches of permissible velocity or allowable stress, but more sophisticated procedures were sometimes used. These procedures were more often applied to larger spillways with longer flow durations. Designing channels using procedures developed for application to canals or stream and river channels tended to be somewhat conservative because of the infrequent and limited duration of spillway flows.

In the 70's the Soil Conservation Service moved to an approach that included both a stable exit channel component and a bulk length, or volume of erosion approach. The exit channel was designed to be stable for an emergency spillway design storm, usually defining the width of the spillway. The concept here was one of the channel not requiring maintenance for less than the emergency spillway storm.

The spillway was also required to have a bulk length determined by the geologic material and the total discharge per unit width of spillway for the freeboard storm. The bulk length was defined as the distance through the crest 2 feet below the hydraulic control.



It may still be appropriate to use channel design and analysis software for spillway design or evaluation. This is particularly true when long exit channels are involved and sediment transport is expected to be a major consideration.



Other tools have also been developed, including the REMR erosion prediction method developed by the Corps.

REMR RISK CLASSES

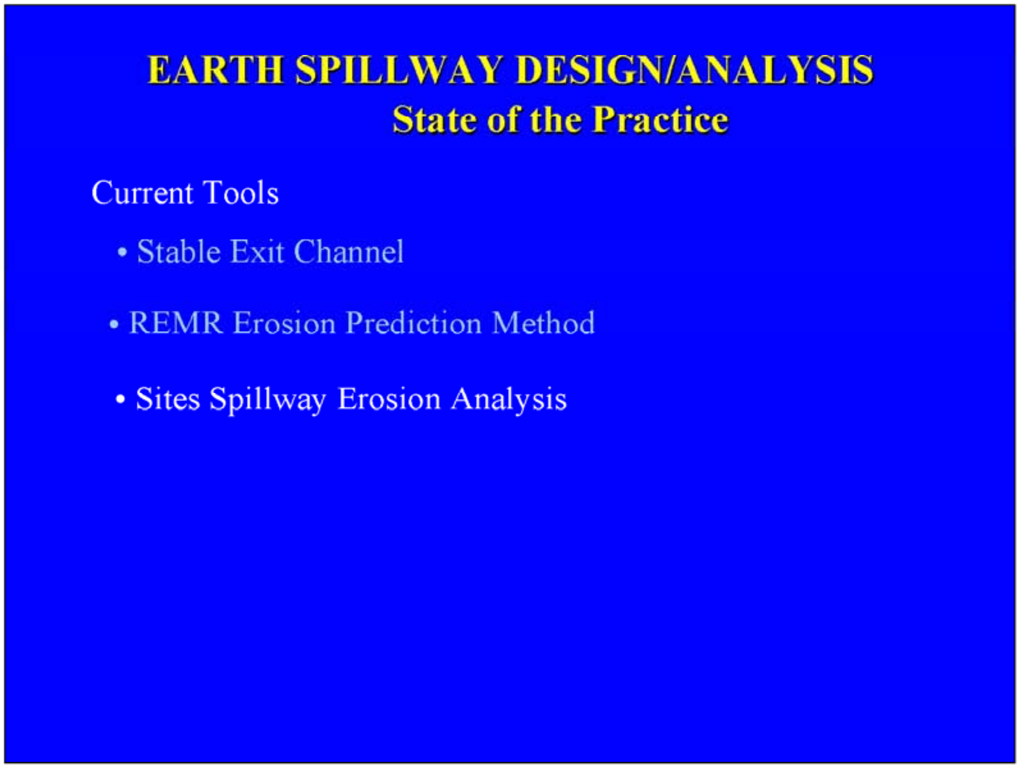
EROSION RISK	EROSION RISK CLASS			
	AAAA	AAA	AA	A
Slope (percent)	30 - 45	15 - 30	4 - 15	< 4
Flow Velocity (m/sec)	3.1 – 4.6	2.1 – 3.1	1.2 – 2.1	< 1.2
Geometric Anomaly	Extreme	Major	Moderate	None
AAAA	High Erosion Risk			
AAA	Significant Erosion Risk			
AA	Moderate Erosion Rate			
A	Slight Erosion Rate			

This empirical method is based on a combination of experience and judgment that compares an erosion risk class that includes hydraulic attack in the form of maximum mean velocity, against

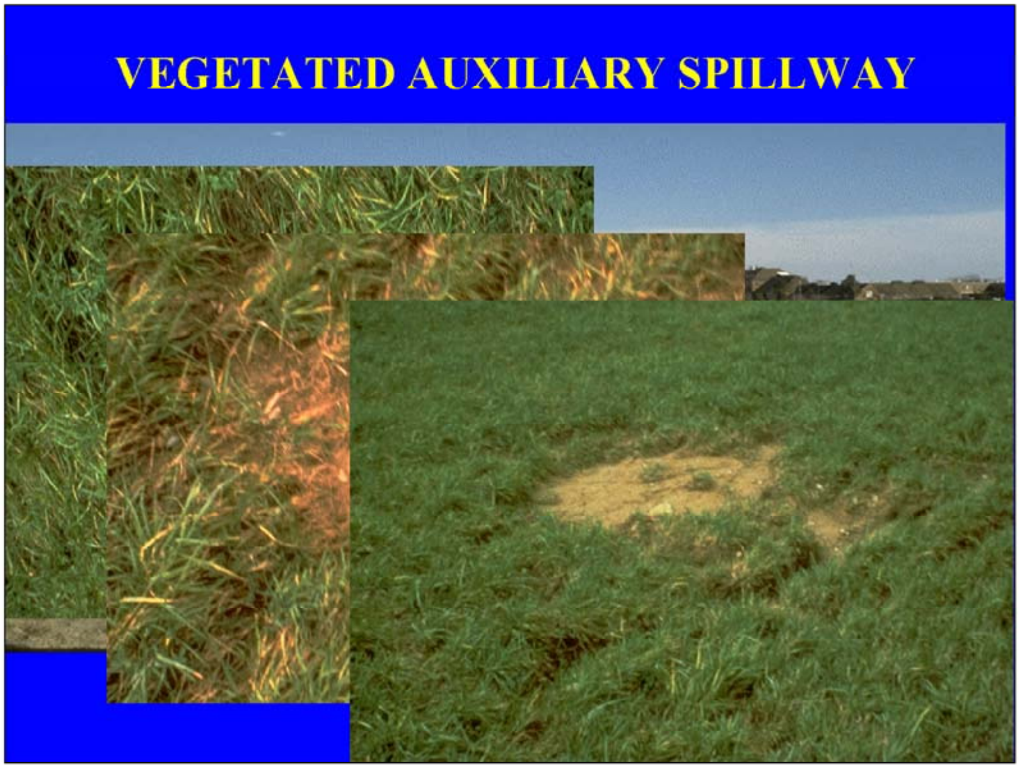
REMR EROSION POTENTIAL CLASSES

EROSION POTENTIAL	EROSION POTENTIAL CLASS			
	AAAA	AAA	AA	A
AAAA	Erosion Resistant Rock			
AAA	Moderately Erosion Resistant Rock			
AA	Moderately Erodible Material			
A	Erodible Soil			
LITHOLOGY				
Sandstone	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx			
Shale & Siltstone	xxx xxxxxxxxxxxxxxxxxxxxxxxxx			
Limestone	xxxxxxxxxxxxx			
Granular Soil (Low PI)				xxxxxx xxxxx
Cohesive Soil (High PI)			xxxxxxxxxxxxxx	
Intrusive Igneous	xxxxxxxxxxxxx			
Extrusive Igneous	xxxxxxxxxxxxxxxxxxxxxxxxxxxx xx			
Massive Metamorphic	xxxxxxxxxxxxxxxxx xx			
Foliated Metamorphic	xxxxxxxxxxxxxxxxxxxxxx			
SUBSTANCE				
Density (kg/m^3)	> 2243	2003 - 2243	1858 - 2003	< 1858
Uniaxial Strength (MPa)	> 41.4	13.8 – 41.4	1.3 – 13.8	< 1.0

Erosion potential classes. Note that here, the table has been truncated, there is more geologic information required than shown; and that the focus tends to be on rock materials. If the erosion risk is greater than the potential, then damage is expected.

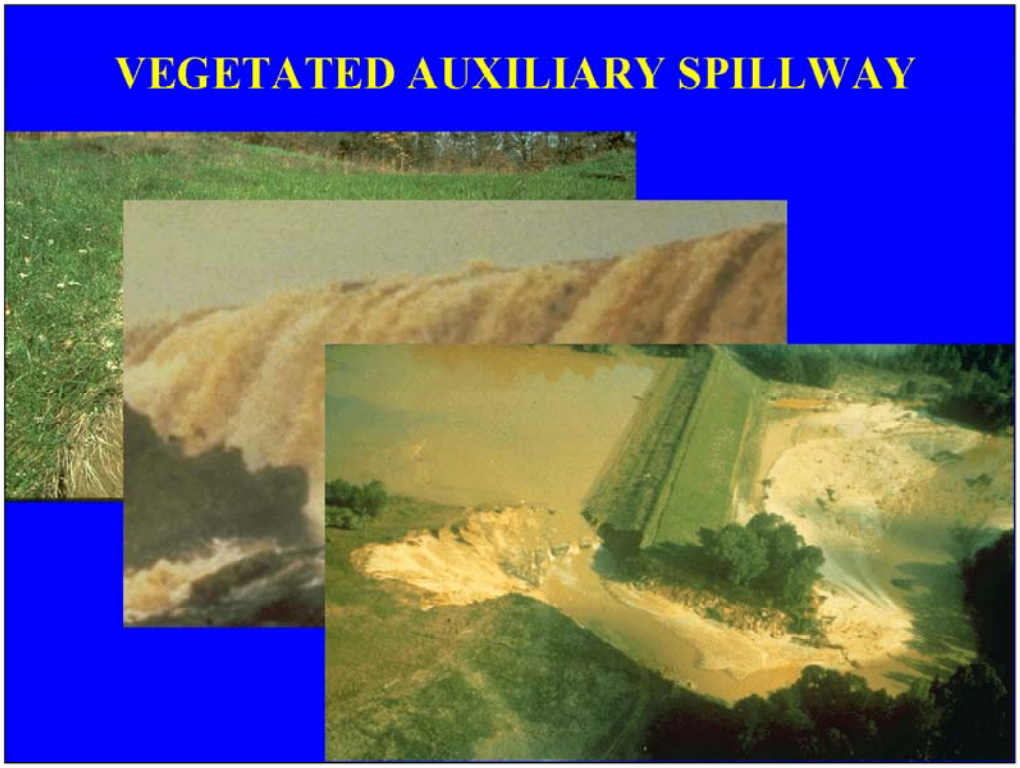


The approach that is presently used by USDA's NRCS for design and analysis of earth spillways is that incorporated into the Sites software. I'll take a few minutes to go into the basis for this procedure, and then address some of its limitations as we move into the research needs.



The Sites software uses a three phase spillway erosion model to evaluate the potential for spillway breach. The beginning point for the conceptual model is a spillway such as we see in the background. For this condition, the erodible boundary is initially protected from erosion by the presence of the grass cover. However, if the flow persists long enough or the stress is high enough, erosion will be initiated in a weak area (Natural materials such as vegetation and soil are never homogenious), and the cover will begin to unravel. The weak area will enlarge until the vegetal cover is no longer effective and the flow tends to concentrate in the local eroding area. That local removal is phase 1 of the failure process.

Phase 2 of the process consists of enlargement and deeping of the eroding area due surface detachment as a result of the flow and stress concentrations. The end of this phase is the point where the flow tends to break up, and a headcut is formed. The depth of erosion corresponding to the end of phase 2 is discharge dependent.



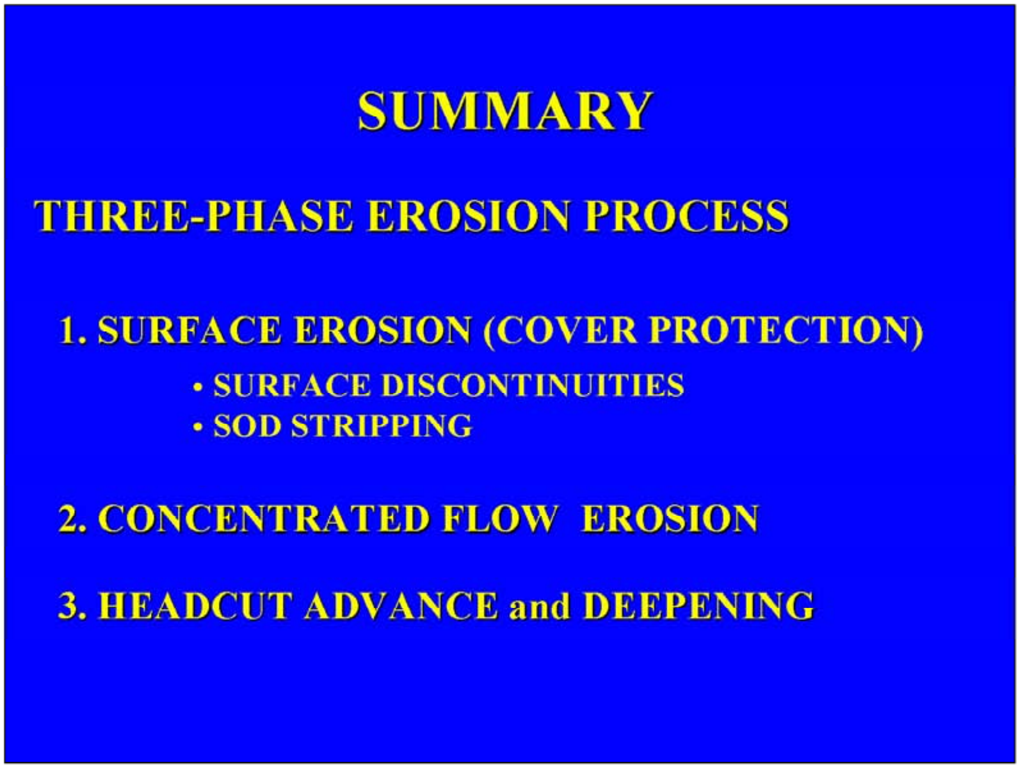
The third phase of the failure process is the deepening and upstream movement of the headcut. Widening occurs simultaneously, but is not tracked by the present Sites computations.

For worst case conditions, the upstream advance of the headcut may result in spillway breach and drainage of the reservoir. However, the Sites model was developed only to evaluate potential for breach, and does not take the computations on through the actual breach process. We're working on that for embankments and consider the development of that phase of the model to be a research need.

Another thing that is introduced in the sites model is the concept of major and minor discontinuities in the vegetal cover. These can be very important for spillways designed for low head conditions in highly erodible materials. Minor discontinuities are those such as cross-roads, or trees;

Major discontinuities such as access roads immediately concentrate the flow and essentially negate phase 1 protection.

Note also, that for large heads and steep exit channel slopes, phase 1 protection may not be significant anyway.

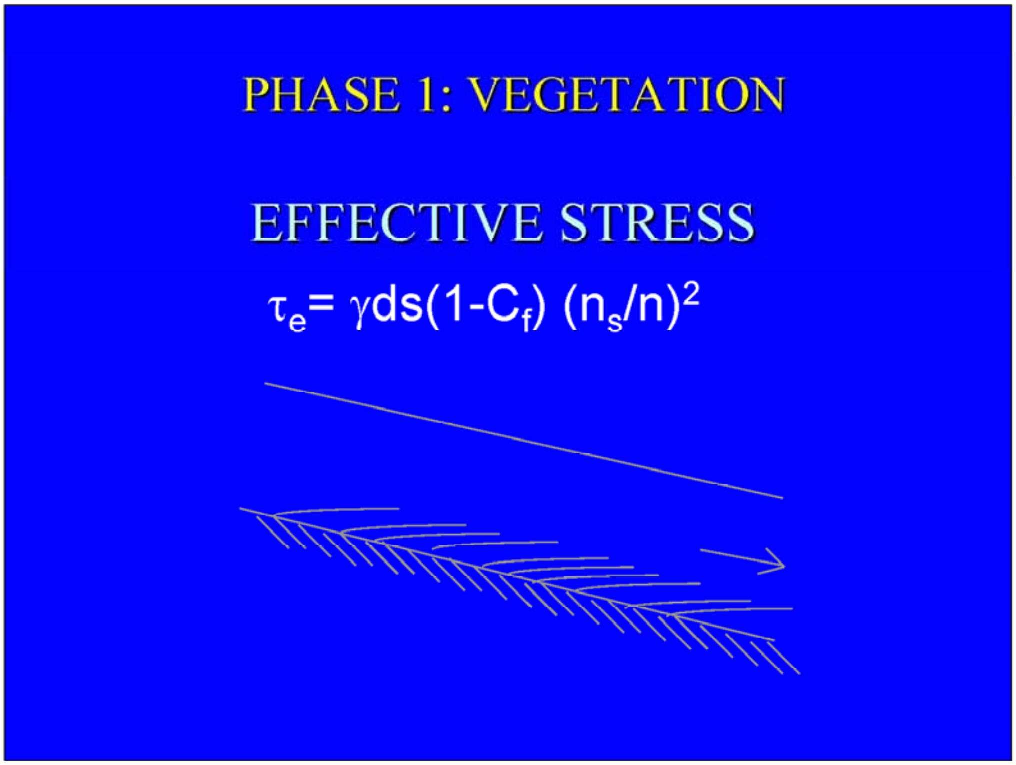


Briefly then, the Sites model describes a three-phase process of surface cover failure, including accounting for discontinuities. We also account for stripping of shallow rooted covers, although I didn't cover that for reasons of time today.

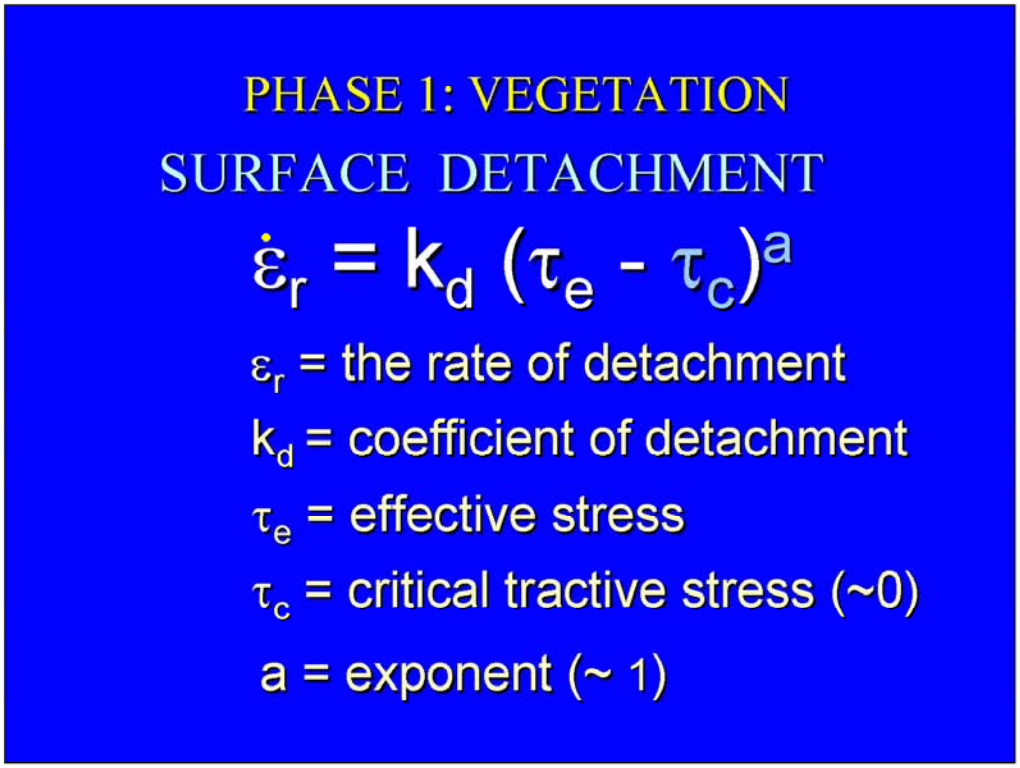
The second phase is a concentrated flow erosion leading to the development of a headcut,

And the third phase is the deepening and upstream advance of that headcut. Each of these phases is described in the model by it's own set of threshold-rate relations.

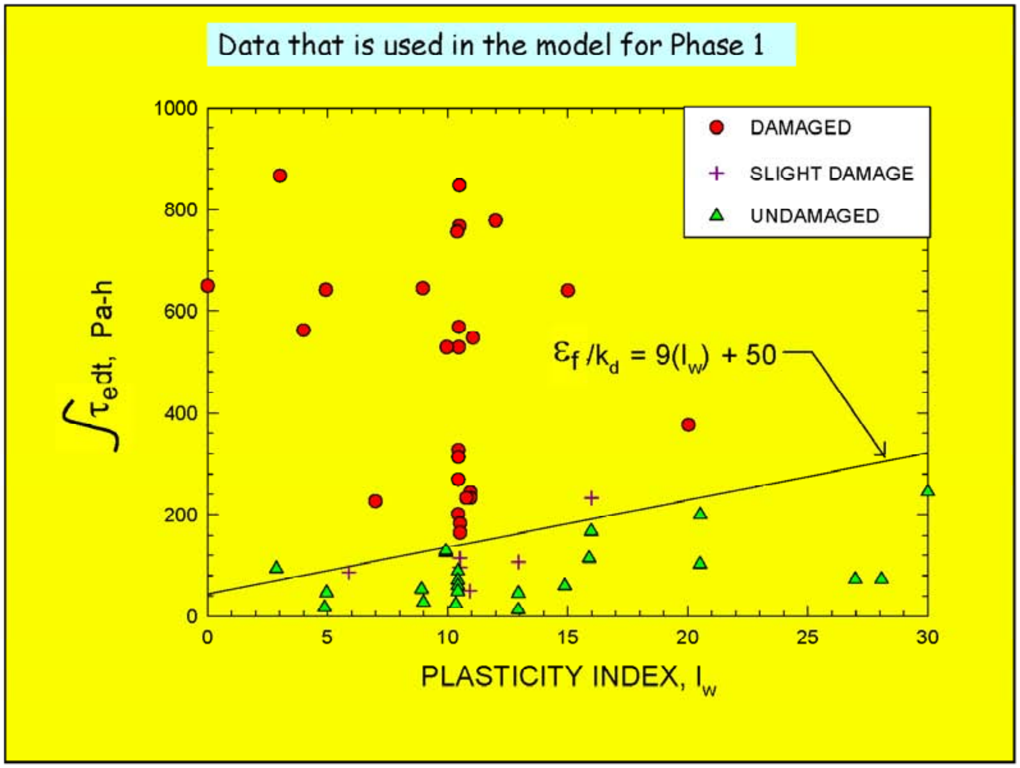
The relations tend to be a somewhat simplified representation of the processes, and I'm going to go through them rather quickly as a lead-in to the weaknesses and research needs.



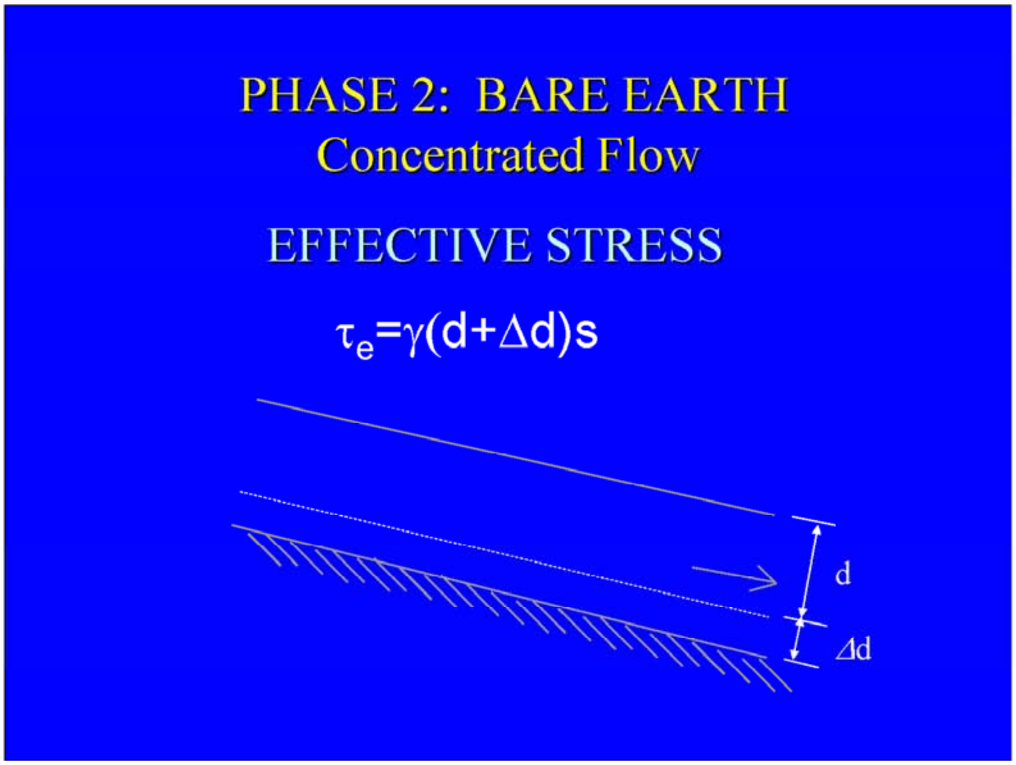
Phase 1 uses an erosionally effective stress approach that computes gross stress from normal depth, gamma d S, and adjusts it for the type of cover 1-Cf, and for the transfer of stress to the boundary by the plant root system ns/n squared.



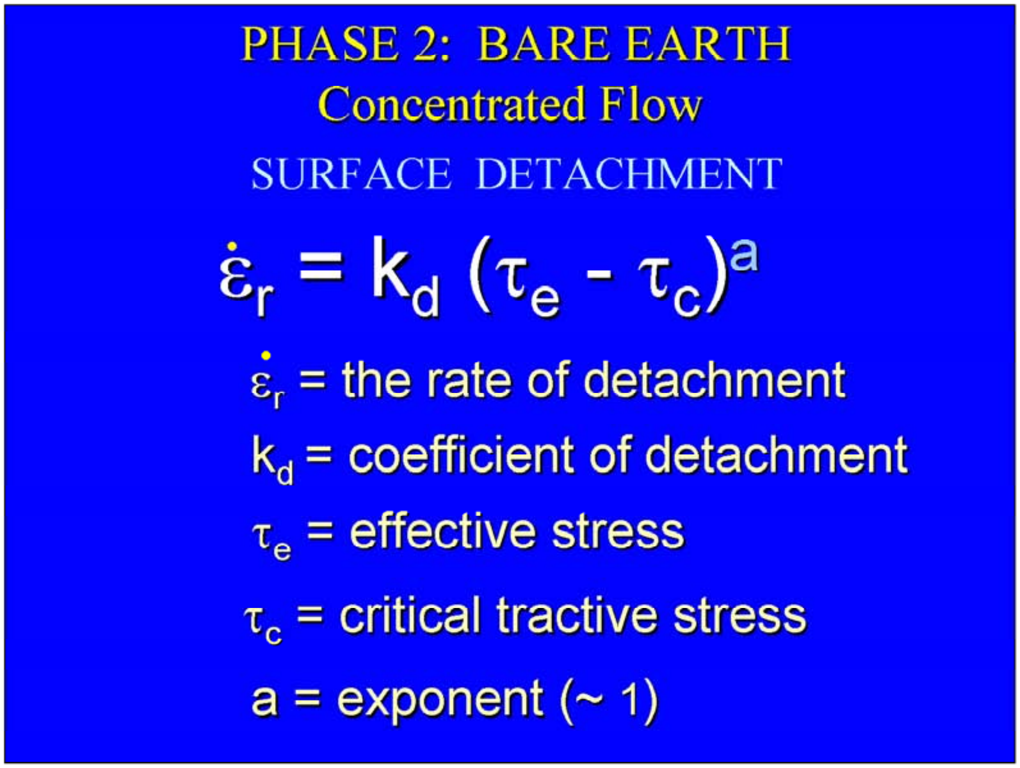
This is combined with an excess shear detachment rate relation with the critical shear stress assumed to be negligible. The assumptions that the process is detachment limited and the material is fine grained tend to be reasonable because we are applying the relations to spillway flow over vegetation. When the material does not support vegetation, phase 1 tends to be negligible, and we immediately move to phase 2.



The failure point is calibrated to field data, and tends to fit the available data fairly well. Note that the material properties are represented by plasticity index for this phase.



Since phase 2 is also surface detachment, we also use the same stress approach, but now, we assume that all of the stress is effective in detaching material, and account for flow concentration by assuming the water surface elevation in the eroding area is controlled by the surrounding flow.



We also use the same detachment rate relation, but now, the critical stress is a function of particle diameter based on Shields diagram, and Kd is determined explicitly.

PHASE 2: BARE EARTH

Concentrated Flow

DETACHMENT RATE

$$k_d = \frac{5.66\gamma_w}{\gamma_d} \exp\left[-0.121(c\%)^{0.41}\left(\frac{\gamma_d}{\gamma_w}\right)^{3.10}\right]$$

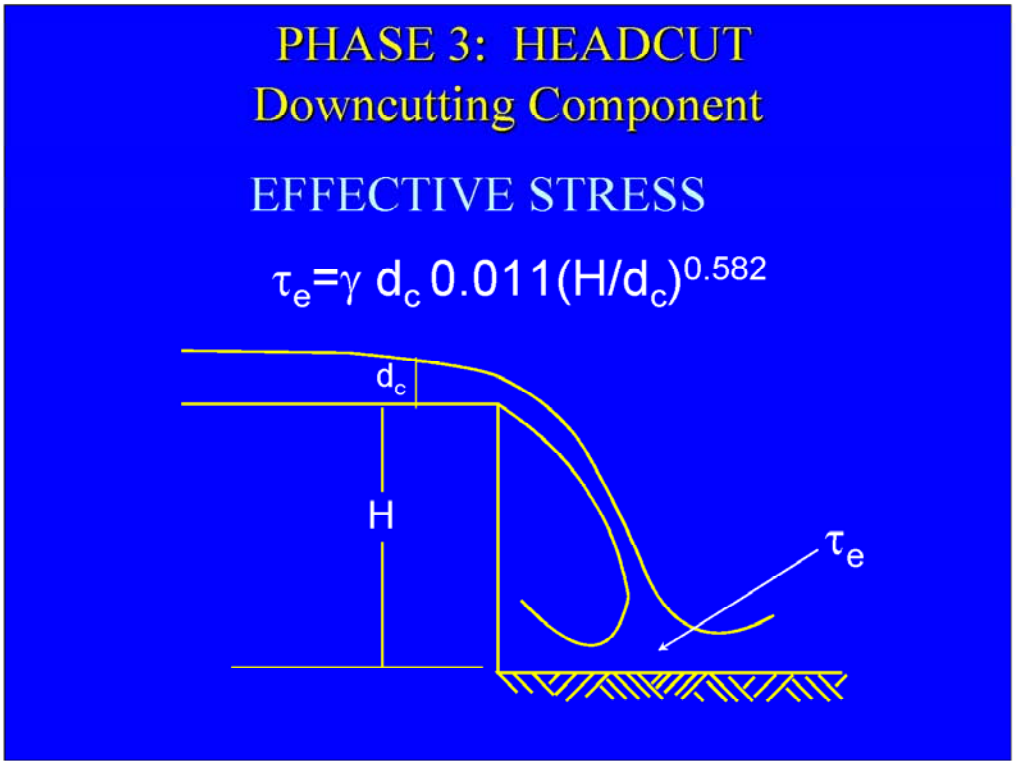
k_d = detachment rate coefficient

$c\%$ = percent clay

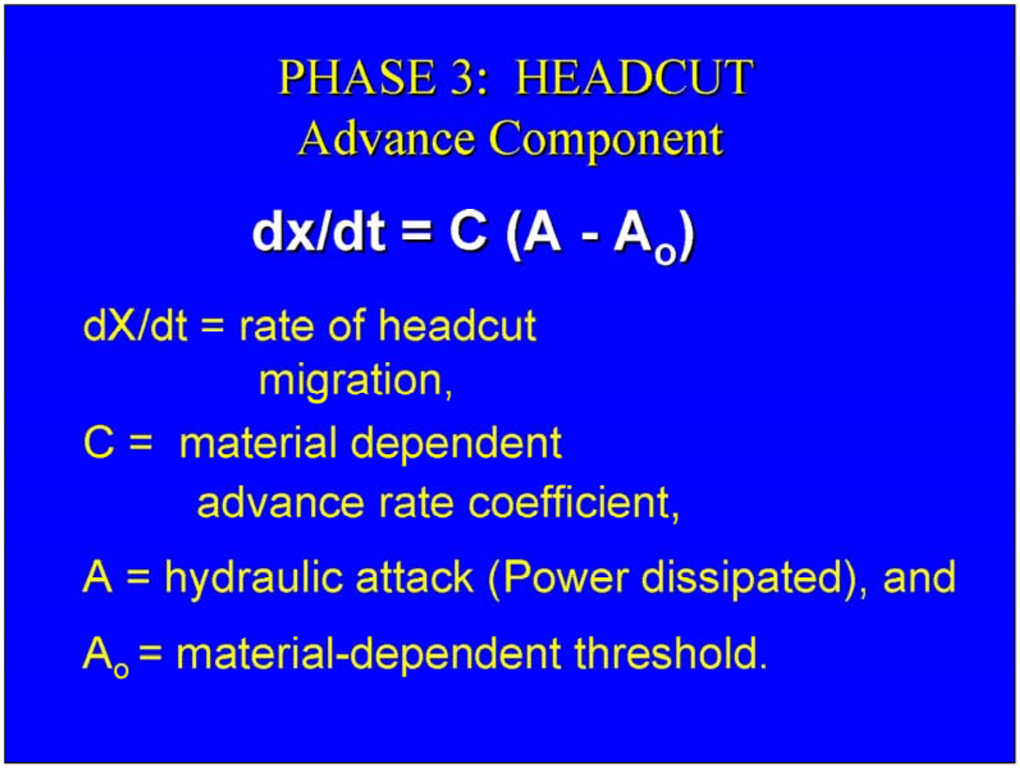
γ_d = dry unit weight

γ_w = unit weight of water

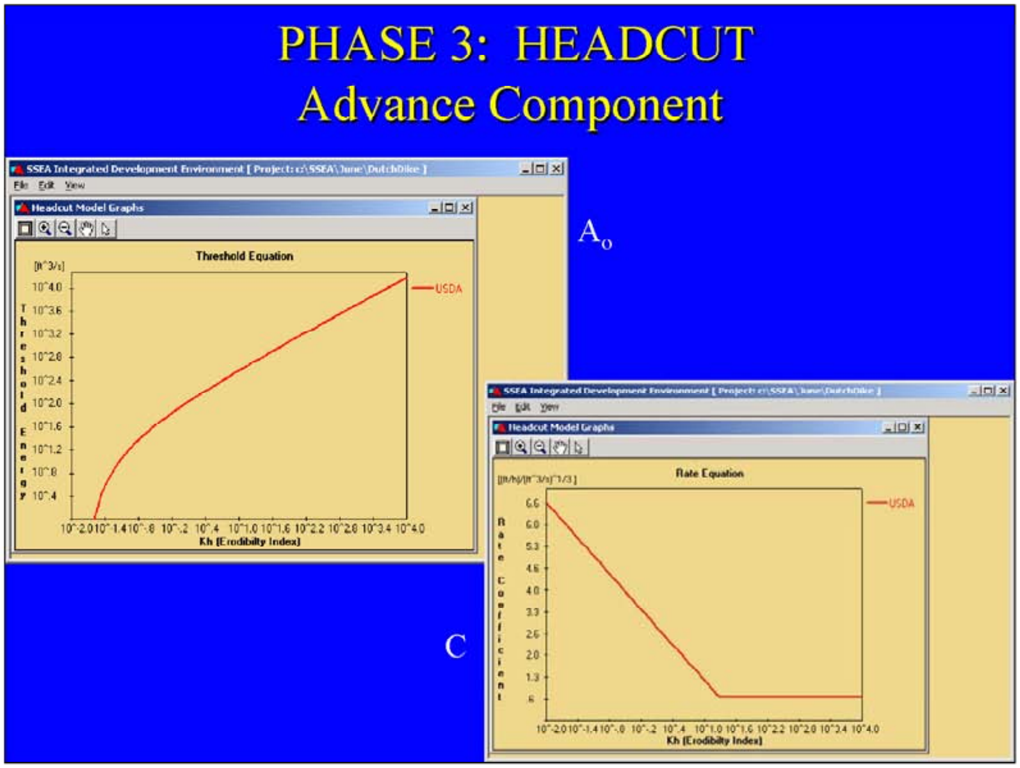
Kd may be measured for soil materials using the jet test for erodibility or estimated from percent clay and density. This means that for soil materials, phase 2 tends to be dominated by the clay and density properties, whereas for rock, particle diameter dominates. We are still assuming detachment limited conditions and concerning ourselves with a point in the spillway.



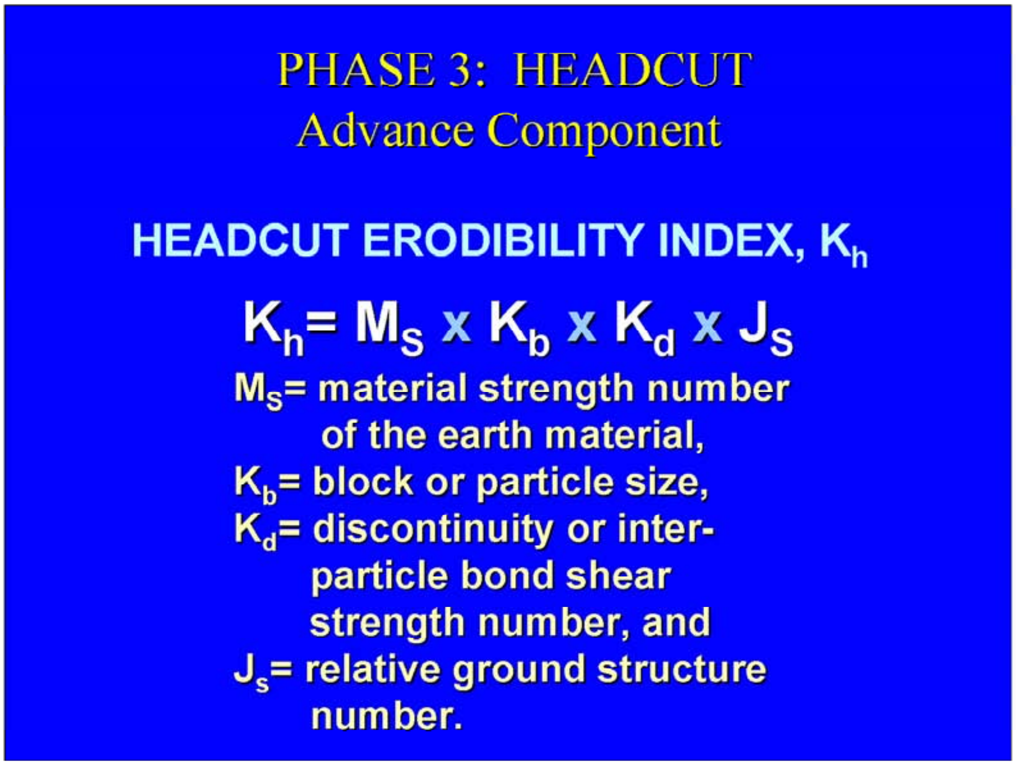
Phase 3 is divided into two parts for computation. The downward movement and the headward movement. For the downward component, surface detachment is taking place, and we continue to use an excess stress approach with the stress computed assuming low tailwater conditions. The detachment rate relation is the same as applied previously.



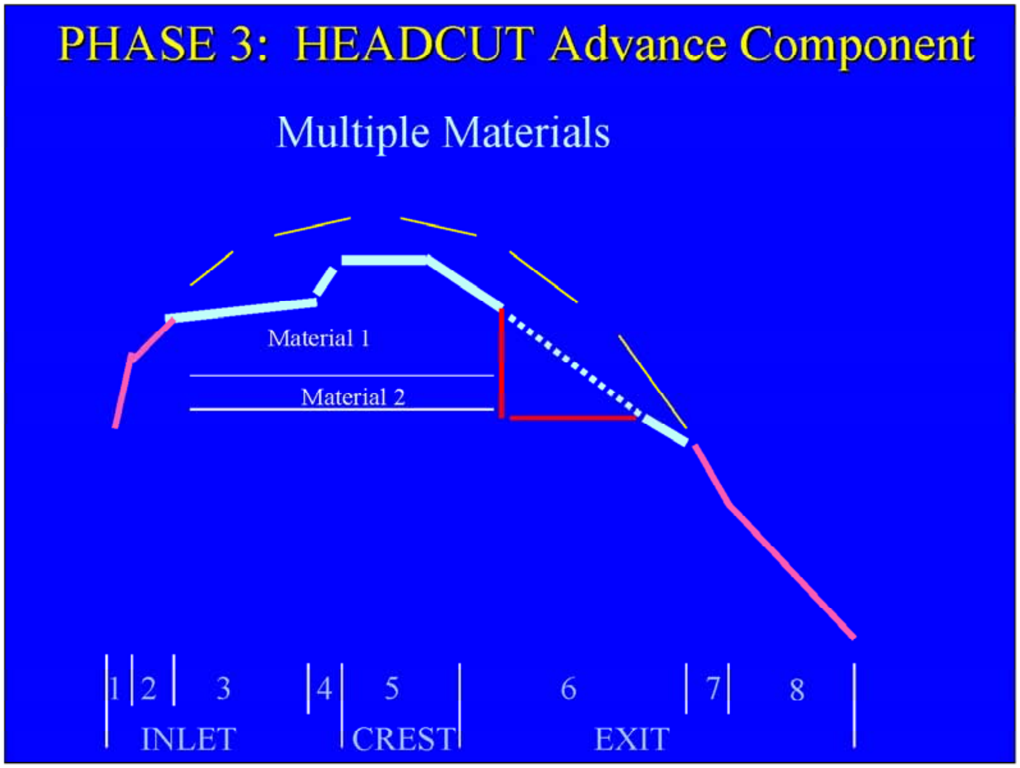
The headcut advance relation is of the same general threshold rate form as the other relations, but is energy rather than stress based. Although several modes of headcut advance have been observed from undercutting to surface detachment on a steep-sloped face, all have in common the focused dissipation of flow energy.



As applied, both the threshold and the rate coefficient are expressed as functions of the headcut erodibility index. This index was adopted from work done in South Africa on material excavability, and that work in turn was built on work in Scandinavia on tunneling. The curves shown here are those developed from data collected over a 10 year period from field spillways on flood control reservoirs. The Corps also used the approach to analyse data from some of their spillways and came up with slightly different curves. We are presently working with Corps researchers in Vicksburg to reanalyse all of our data to see if we can refine these relations.



The index itself is a measure of the overall strength of the material mass. In the interest of time, I'm not going to go over the details, but references are provided in the materials we made available for the workshop.



Of course, spillways never exist in a single material, so use of the relations requires determination of a representative value of headcut erodibility index for multiple materials. Since the index lives in log space, the form of averaging used is

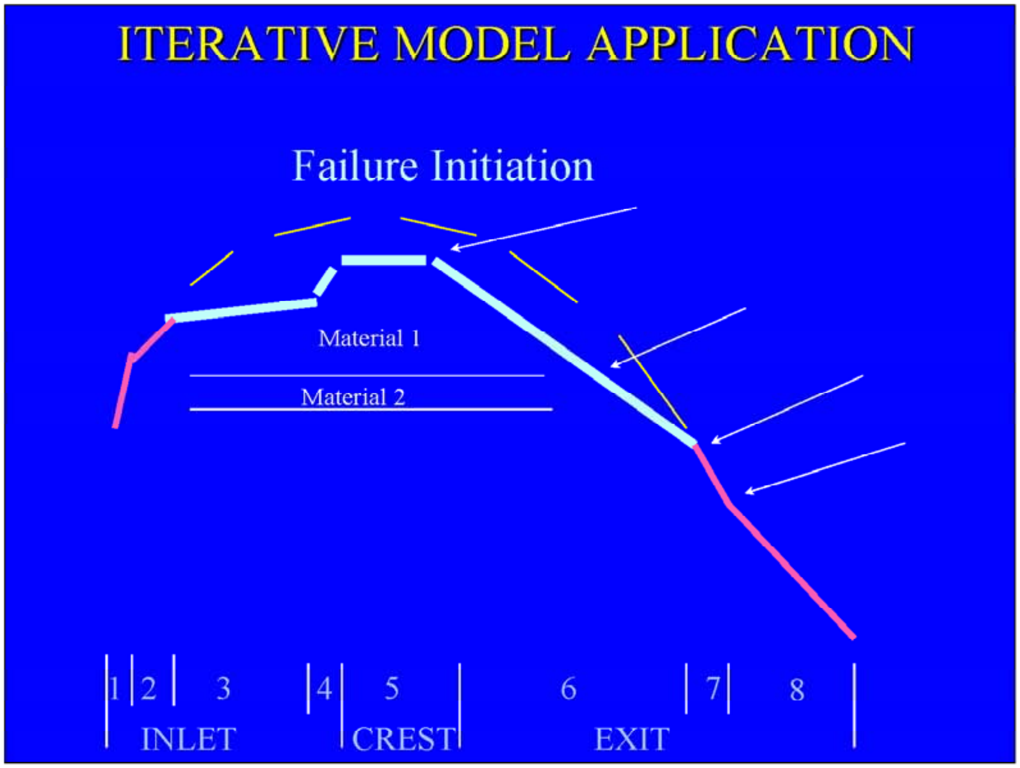
PHASE 3: HEADCUT Advance Component

Multiple Materials

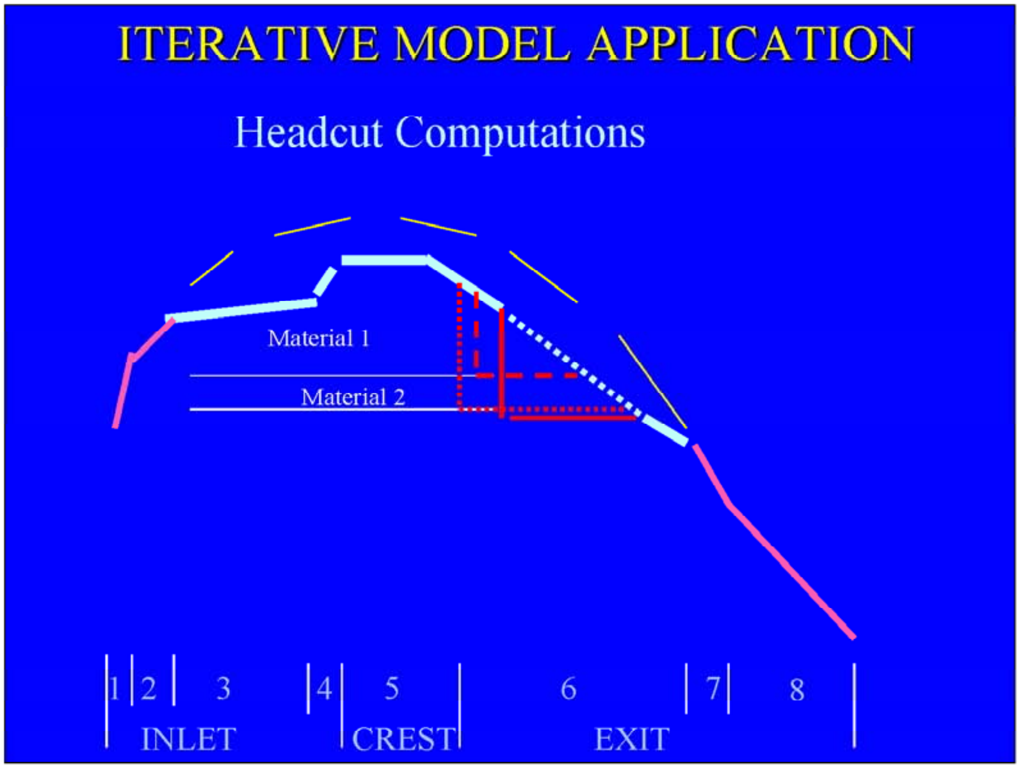
$$K_h = e^{\frac{\sum h_i \ln(K_{h_i})}{\sum h_i}}$$

h_i = the thickness of material i, and
Summation is carried out over all materials exposed on the face

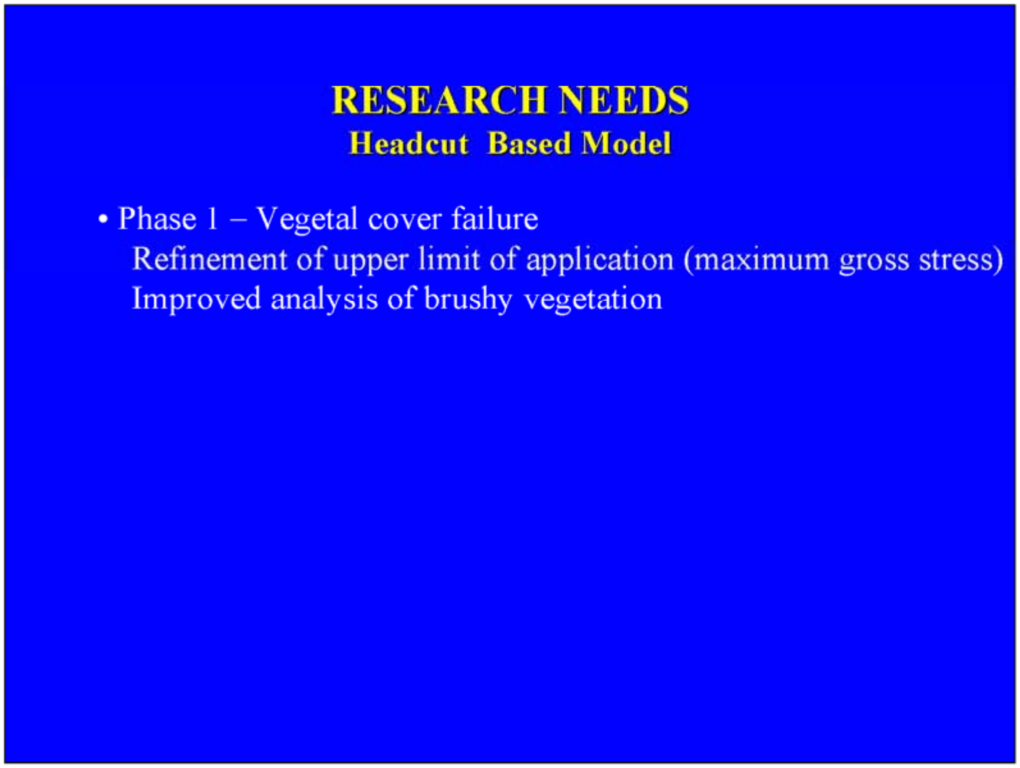
A depth weighted log averaging scheme. This has been found to work surprisingly well.



It is also necessary to apply the method iteratively to determine the worst case condition for location of headcut formation. It is not immediately obvious whether a headcut formed early in the flow at the end of the exit channel will pose a greater or lessor risk of breach than one formed later near the crest. If material 2 happens to be a sand lense, it may also be that the headcut that exposes that material the most rapidly will be the one posing the greatest risk.



On the other hand, if material 2 is a rock, it may be that a headcut following the upper surface of the material will move more rapidly than one penetrating into or through that material. All of these scenarios must, therefore, be evaluated. In the present model, they are evaluated one at a time as if that headcut were the only one present.



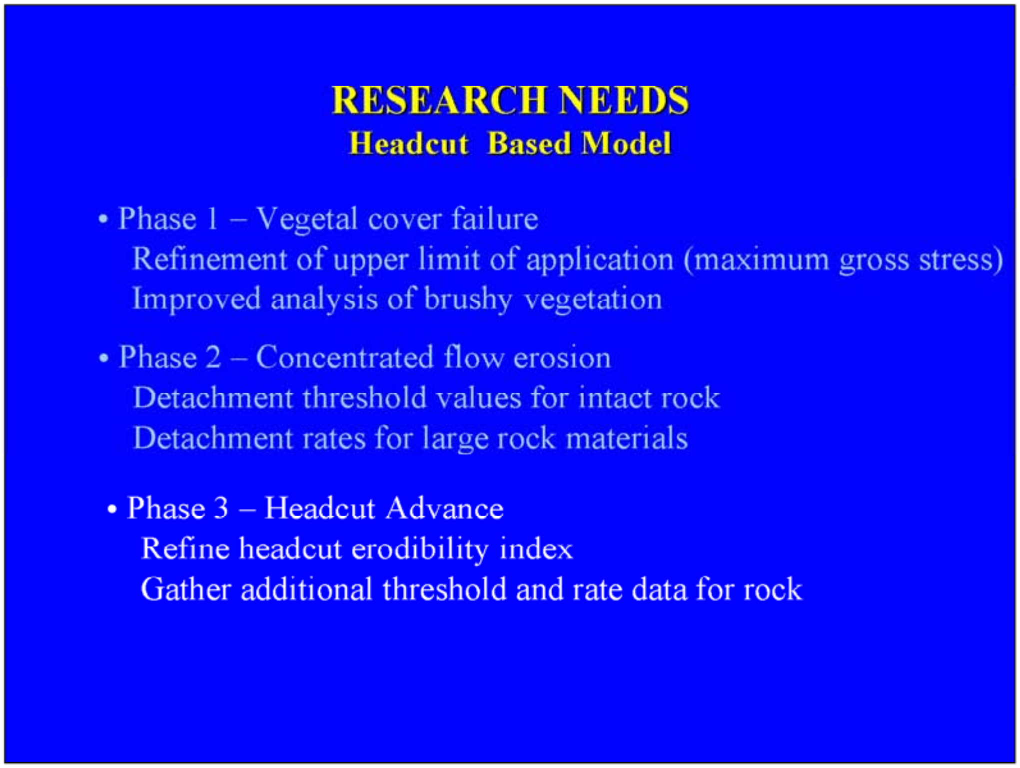
Let me begin the discussion of research needs in the context of the Sites erosion model. And I'll begin by noting that Sites represents a first attempt at quantifying the overall process for field application, and there is no part that couldn't be refined; And we recognize that it does not apply to every spillway problem.

In terms of the phase 1 processes, there are a number of areas that could be improved, but the model is probably consistent with the extent that we normally have information to describe the condition of the surface. Areas where advances could be made include improved determination of the upper limit of applicability of the erosionally effective stress relation; that is At what gross stress does the vegetation begin to experience damage directly?; and improved analysis of the effects of brushy vegetation. The fact is though, that phase 1 plays an important role only for relatively low heads and relatively erodible materials, so the mileage were going to get from refinement here is somewhat limited.

RESEARCH NEEDS
Headcut Based Model

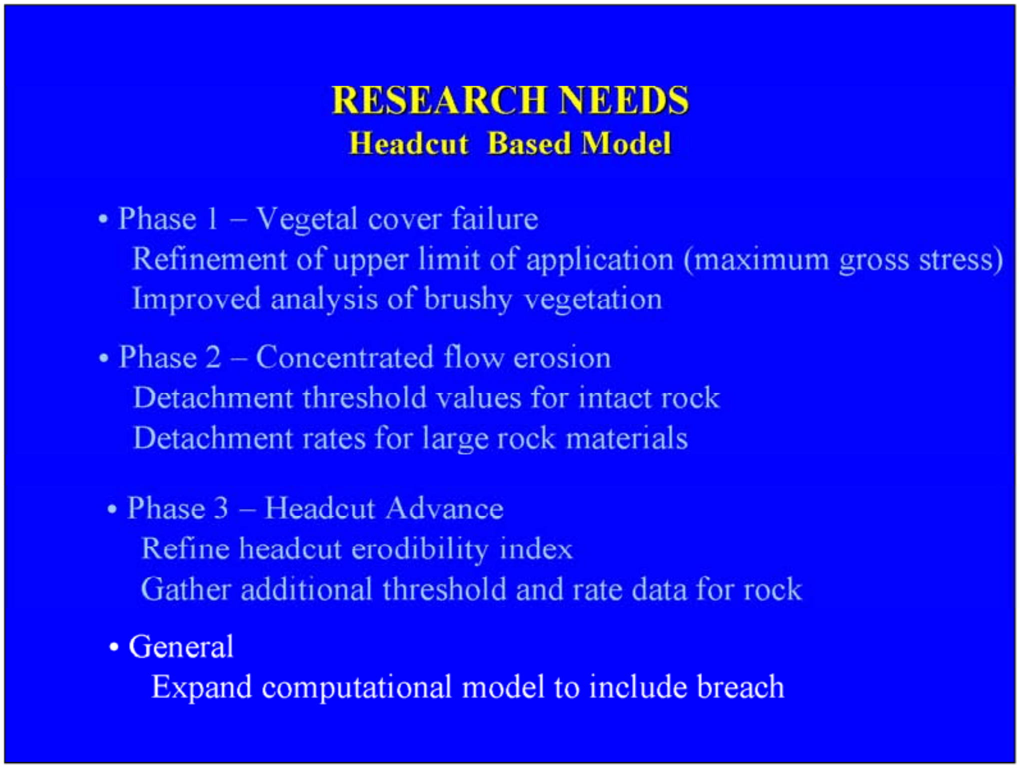
- Phase 1 – Vegetal cover failure
  Refinement of upper limit of application (maximum gross stress)
  Improved analysis of brushy vegetation
- Phase 2 – Concentrated flow erosion
  Detachment threshold values for intact rock
  Detachment rates for large rock materials

Phase 2 is usually the most important for spillways with rock materials near the surface of the spillway. The present model implicitly assumes loose material (based on diameter only) and will often be over-conservative. The model needs to be refined. This could be done using either stress or energy approaches, but will require data that is rather scarce.



In terms of the downcutting portion of phase three, all of the considerations of phase 2 apply, plus the need to better tie the downcutting and advance parameters together to avoid inconsistent data.

The headcut erodibility index itself needs refinement. USDA is presently working on refining our means of estimating it in the never-never land between soil and rock. However, more fundamental work on the index itself is needed. As it presently exists, it was simply adopted from excavability applications. The processes are similar, but not identical. The index was named as it is so that future modification would be possible without confusion with other application related indices.



A more general need that has been identified is to expand the model to include breach computations in such a way that we could account for the ability of changing geologic materials to stop complete breach. If you think about what is involved, that is no small task. We could also expand to talk about three dimensional geology, tailwater effects, air entrainment effects, etc., but those would require substantial advances in material mapping and description before inclusion in a general application model could be justified. Some of these issues are addressed in the publications included in the list provided to the workshop.

RESEARCH NEEDS
Earth Spillway

- Identify Failure Modes

- Develop consistent means of evaluating uncertainty

The three phase model with with headcut advance to breach represents a major portion of the earth spillways observed to have experienced damage. However, it does not represent all conditions. For example, this spillway in volcanic rock eroded due to abrasion in areas of reverse flows where potholes were developed. This type of erosion is not addressed at all in the Sites Model. Likewise, long flat sloped spillways in material where sediment transport is an issue are not properly analysed by the Sites model, because Sites assumes detachment limited conditions and movement of the detached material out of the immediate area.

We could go on much longer with this, but I'll stop with this one last comment. All of the available models are simplified and we seldom know exactly what materials will be exposed during the erosion process. This uncertainty needs to be evaluated along with the uncertainty related to the flow conditions. Some work is going on now at Vicksburg in this area, but spillway erosion analysis is still in its infancy. We still have much to learn.

Presentation 6:
Spillway Foundation Erosion

Dam Safety Workshop
Spillway Foundation Erosion

James F. Ruff, Ph.D., P.E.
Department of Civil Engineering
Colorado State University

Spillway Components

- Entrance channel
- Crest/control structure -- ungated, gated
- Conveyance -- chute, conduit, tunnel, or combination
- Terminal structure -- stilling basin, flip bucket, plunge pool

- Incidence of spillway foundation scour is relatively low
  - Cause generally result of discharge greater than design.
- Foundation undermined by scour from downstream
  - Major damage
  - Time constraints
  - High repair costs
  - Reservoir operations affected by foundation scour

Gibson Dam

June 8, 1964
20 hour duration
1 m overtopping

1979 Modification
$1,240,000

Colorado State University Experimental overtopping and foundation erosion facility

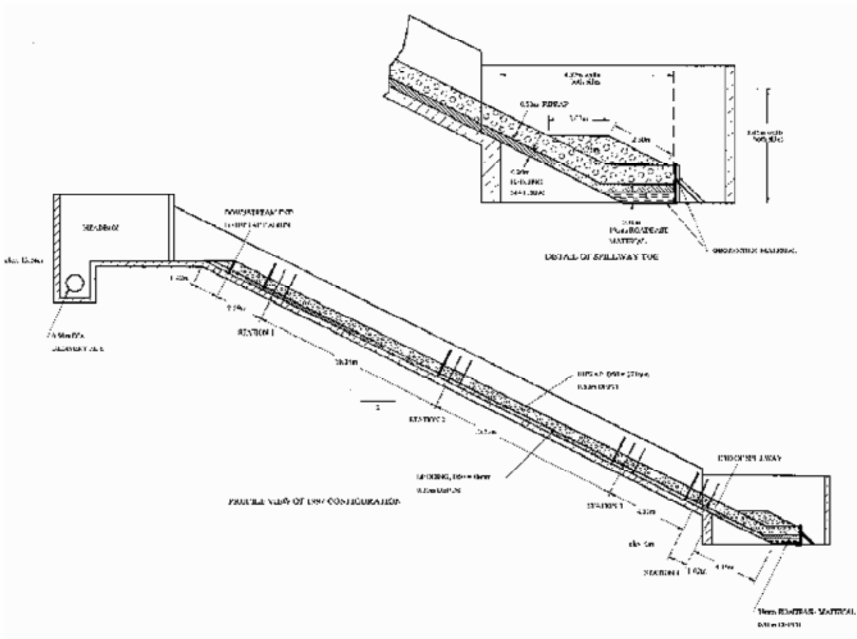


Figure 3.9: 1997 layout of the riprap slope with the piezometer towers before testing

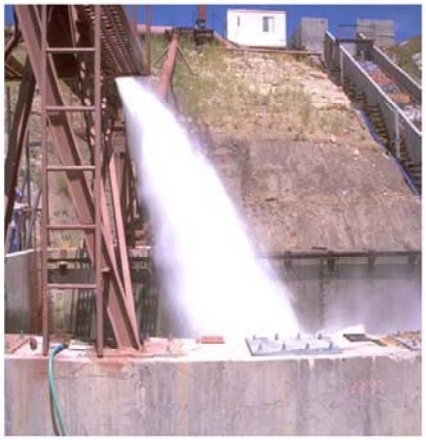
Scour Prevention & Research
Focus on Depth, Rate

Spillway models - component testing
- Small scale
  - estimate scour depth and location
  - pressures on chute and in stilling basin

Foundation erosion by plunging jets
- Near-prototype scale
  - gravel bed
  - simulated rock

Foundation protection
- concrete blocks
- riprap chute and toe

Scour of simulated fractured rock

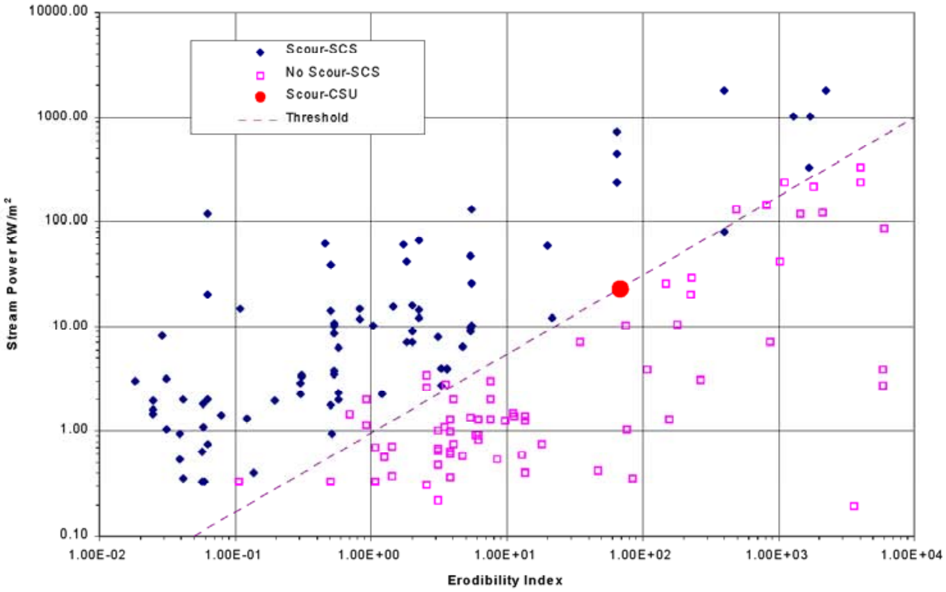


Spillway riprap protection

Figure 3.10: Numbering of rocks in 1995

Figure 4.9: Large plumes of water (1995) (Q=2.12 m^3/s)

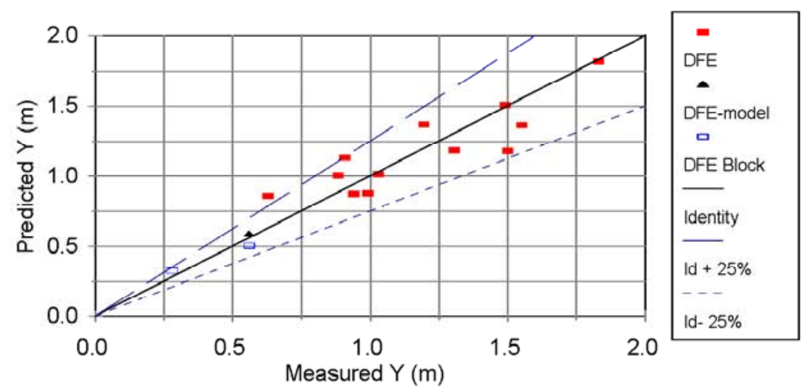
Prototype foundation scour data



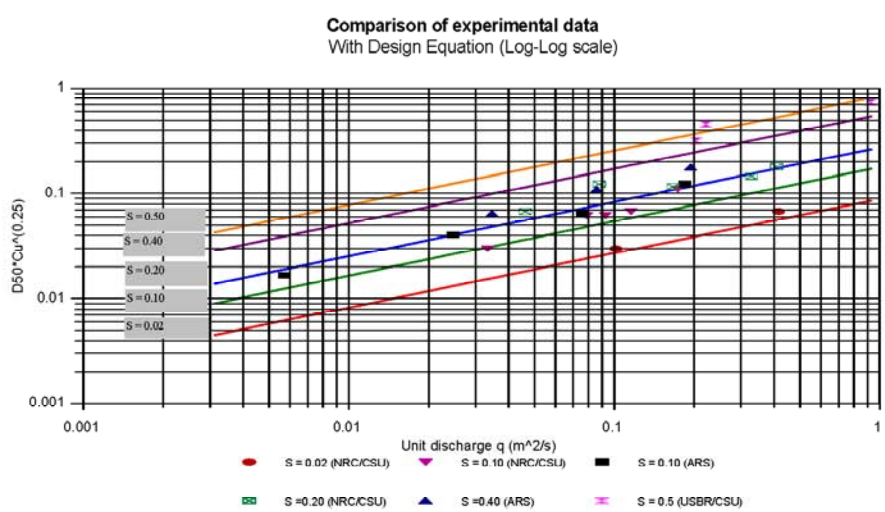
CSU Foundation scour depth equation for non-cohesive material and simulated fractured rock

$$\frac{Y}{y_c} \approx 3.111 \frac{\left(\frac{V_i}{\sqrt{g b_i}}\right)^{0.07}}{\left[\frac{(TW/\cos\delta)}{b_i}\right]^{0.39}\left(\frac{w}{\sqrt{g\ b_i}}\right)^{1.13}} \qquad (6.5)$$

CSU Foundation scour depth equation for non-cohesive material and simulated fractured rock

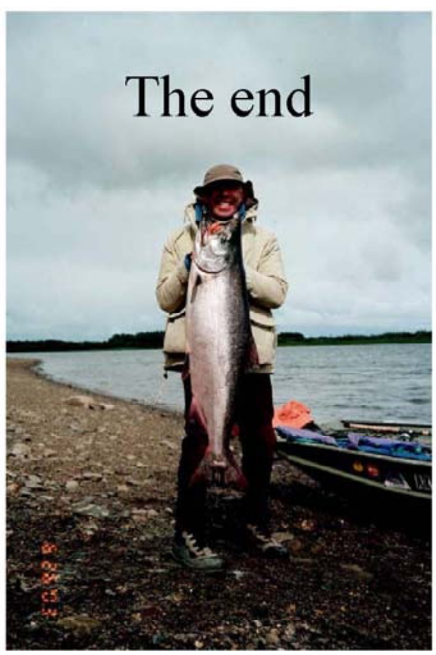


Universal design equation for overtopped riprap



Research needs on dam spillway foundation erosion

- Evolution of velocity and air concentration profiles along the jet, namely at the impact with plunge pool free surface.
- Lined plunge pools – slabs and foundation drainage design criteria.
- Mechanism of rock erosion due to the spillway operation and development/improvement of physically based analysis models.
- Prototype data collection for the improvement of scour prediction formula.
- Scour depth and shape evolution versus time of operation and hydraulic / geologic parameters.
- Evaluate effects of jet entry angle on plunge pool performance and scour.
- Investigate near-prototyope riprap protection at additional slopes.



Presentation 7:
Dam Overtopping Protection Technologies
State of Practice and Research Needs

DAM OVERTOPPING PROTECTION TECHNOLOGIES

STATE OF PRACTICE AND RESEARCH NEEDS

Kathy Frizell
US Bureau of Reclamation
Water Resources Research Laboratory
Denver, CO

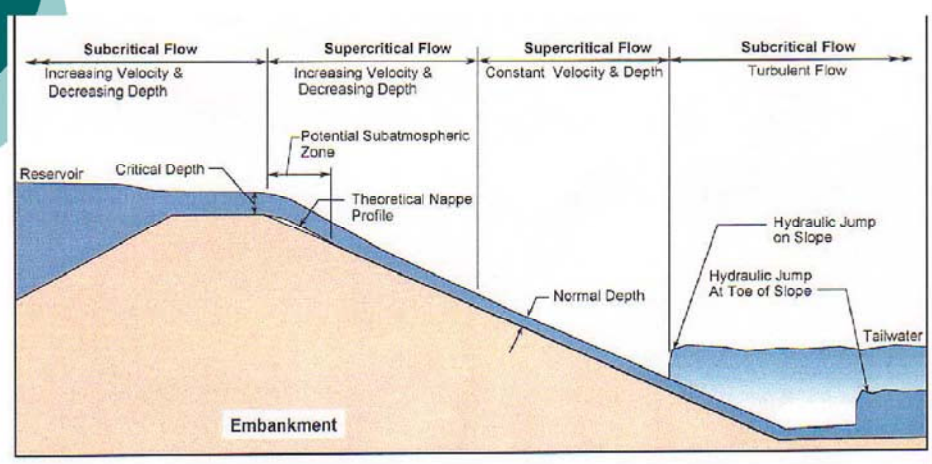
Overtopping Technologies

- Earthen embankments
- Grass covered earthen embankments
- Geotextiles & Membranes
- Gabion/Reno mattresses
- Riprap
- Concrete blocks
  - Cable-tied, interlocking, overlapping
- Soil cement
- Reinforced concrete slab
- RCC
  - Smooth
  - Rough lifts
  - Formed steps
- Stepped spillways over embankment or concrete dams
  - Formed RCC or reinforced concrete

Introduction

- Many options
- Overtopping protection methods all have hydraulic criteria that must be met
- VERY brief discussion of each method
- Design guidance or limitations
  - Based upon testing or field performance
- Maintenance requirements
- Research needs

Hydraulics of Overtopping



Earthen or grass lined embankments

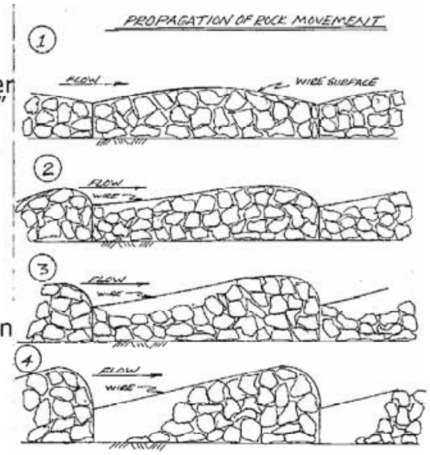
- Cannot add anything to Darrel's discussion!
- Grass covered limitations:
  - Overtopping up to 1.5' of head, short duration, velocities less than 12 ft/s.

Geotextiles & Membranes

- Protective fabric is placed over compacted earth w or w/o a filter
- FHWA tests: Enkamat w/asphalt, 2:1 slope, 6' high dam, V=13 ft/s; Geoweb, V=9.5 ft/s
- USBR field test: 36 mil Hypalon geomembrane, 6:1 slope, 19' high dam, V=10-25 ft/s
- Design & Construction
  - Must be placed over smooth surface
  - Must be anchored at crest, toe, sides
  - Must be covered for durability
  - Seams must overlap

Rock or Reno Mattresses

- Performance – FHWA & CSU testing
- Mattresses placed flat over slopes up to 2:1 with 3-6" size rock
- Design based upon shear stress of flow and critical shear stress of mattress
- Thickness 1.5*max rock size
- Max Velocity 24 ft/s
- Filter required
- Case 3 is max deformation allowed
- Grouting helps stability
- Anchoring essential!



Gabions

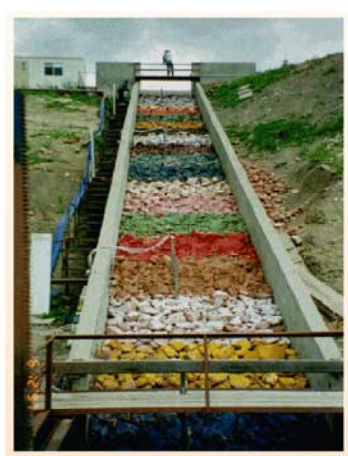
- Gabion baskets are filled with 4-8" rock and stacked leaving a stepped surface on slopes of 2:1 or greater
- Used where mattress criteria is exceeded; steeper slopes & higher velocities
- Performance – Peyras model testing
  - Dam ht. up to 3.3', slopes of 1:1, 2:1 & 3:1, gabions stacked from 2 to 7 steps high, q=30 cfs/ft, V= 20 ft/s
  - Design equation based upon slope, ht., q, allow determination of depth at the gabion slope toe for stilling basin design
- Manufacturer's: Maccaferri (w/design software) & Terra Aqua

Riprap

- Protection is achieved by placement of a designed rock size over an embankment slope or designed spillway channel
  - Application to fuse plug erosion rates and unintentionally overtopped riprap embankment slopes
- Design criteria for riprap size & layer thickness for steep slopes using existing experimental data (including ARS) and data from CSU test program

Test Facility

- 10′ wide, facility q=16 cfs/ft
- Dumped over angle iron & 8″ bedding
- Open frame or down full slope with toe berm
- Rock sizes tested: D_{50}=15.1″, D_{50}=25.8″ over previous, D_{50}=10.7″ full slope & toe (photo)

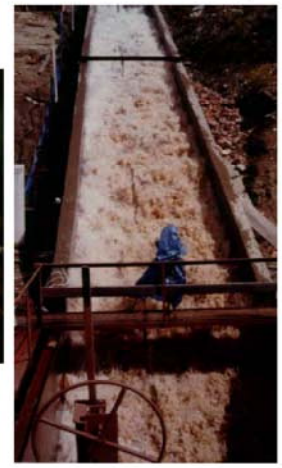


Flow Conditions, Measurements, Failure

- Measured Q, V_i, d
- Velocities in each layer constant
  - Flow beneath the rock surface for 2:1 slope
- Failures (bedding exposed):
  - D_{50}=10.7″,q=2.2 cfs/ft
  - D_{50}=15.1″, q=2.4 cfs/ft
  - D_{50}=25.8″, q=10 cfs/ft

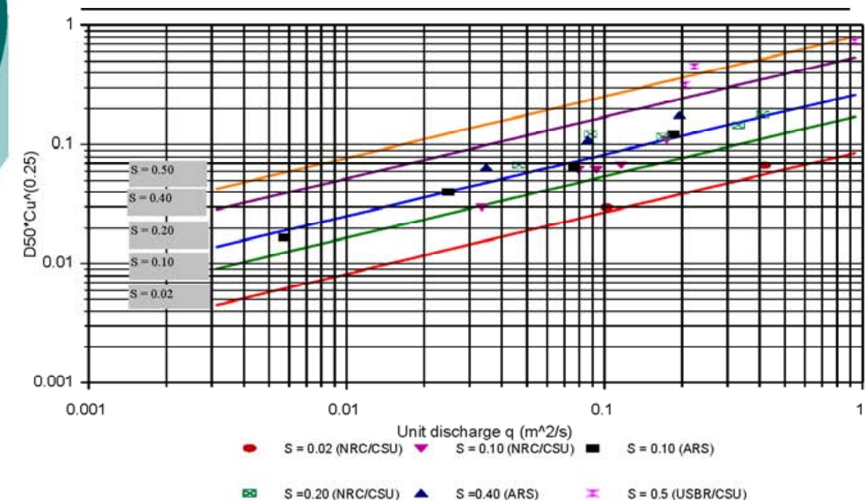
15″ rock

10.7″ rock
1.5 cfs/ft



Total failure
10.7″ rock

Riprap sizing chart based upon q, slope and rock properties – no SF



Riprap Performance

- Design chart and equation provides stable stone size as a function of discharge, stone gradation, and slope.

$$D_{50}C_u^{0.25} = 0.55(q_f)^{0.52}S^{-0.75}\left(\frac{\sin\alpha}{(2.65\cos\alpha - 1)(\cos\alpha\tan\phi - \sin\alpha)}\right)^{1.11}$$

- Layer thickness is a function of discharge, interstitial velocity, stone size and slope.

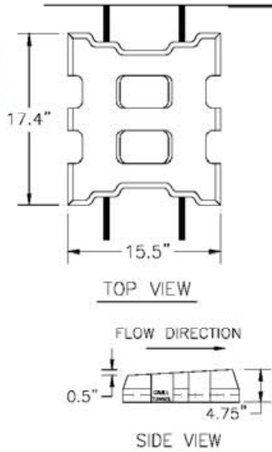
$$\frac{V_i}{\sqrt{(gD_{50})}} = 2.48C_u^{-2.22}S^{0.58}$$

- Interstitial flow for 2:1 slope, flow depth may exceed riprap layer thickness for slopes < 4:1
- Historically, min of $2D_{50}$ or D_{100}.
- Toe more stable than slope.

ACB's

- Concrete block systems widely varied geometries, test programs, applications
- Cable-tied
  - Weight, shape, filter, cabling for stability
- Interlocking
  - Weight, shape, interlocking, filter, careful placement for stability
- Overlapping
  - Shape, filter, maintaining overlap for stability

Cable-tied Concrete Block
Tested ArmorFlex Tapered Unit



Wt. = 66 lbs

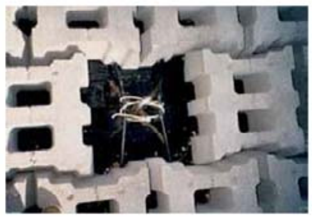
Thickness = 4.75"

Forces on block evaluated under high velocity installation over compacted earth in CSU flume facility

ArmorFlex Mat Delivery

Strahl Lake Dam, Indiana, DNR

- Cable-tied mat sections
- Close up of cable tie section



Strahl Lake Dam

- Crest construction
- Completed system
- Grass covered system

Armortec Tapered Cable-tied Block Design Factors & Performance Data

- Must anchor the crest and provide flow barrier.
- Drainage system enhances performance and is recommended.
- Successfully withstood test with 16- ft-high, 2:1 sloping embankment
  - q=20 cfs/ft, 4' of head, V=26 ft/s, shear stress= 25 lbs/ft^2
- Use maximum velocity and flow depth to determine product needed.
- The hydraulic jump should occur on an armored or non-erodible surface to prevent headcutting and undermining of the ACB layer.
- Needs uni-directional flow over the embankment surface.
- Make sure the specified product has been evaluated under high-velocity testing conditions with steep slopes.
- Maintenance:
  - Keep the protected slope and toe clear of woody vegetation.
  - Prevent vandalism or removal of block units.

Interlocking Concrete Blocks

- Conlok, Tri-lock, Armortec, others
- Testing
  - FHWA/Armortec/SAF
- Design guidance – Generally not as good a product for overtopping protection as other block systems.
- Construction – Critical feature of interlocking block systems exposed to high velocity flows. ANY portion of the block edge exposed to flow impact can fail the system. Install where base surface has NO discontinuities.
- Maintenance
  - Keep the protected slope and toe clear of woody vegetation.
  - Prevent vandalism or removal of block units.

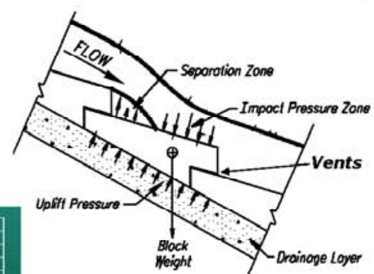
Overlapping Tapered Concrete Wedge Blocks Performance Testing (Armorwedge)

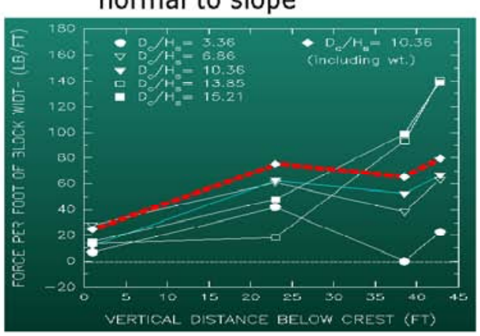
50-ft-high, 5-ft-wide, q=32.2 cfs/ft, blocks placed over angle with gravel filter, anchored at 3rd points on slope, held at toe.

Top slope, 4<hs/l<6, 2.8% vent area on face, min thickness 2"

Forces Acting on the Overlapping Tapered Wedge Block

- Inherently stable
  - Impact on tread & relief of uplift at low pressure zone by aspiration through vents
- Analyzed forces as sum normal to slope





Overlapping Tapered Concrete Block Performance Data

- Successfully withstood maximum flow from test facility:
  - q = 32 cfs/ft, overtopping depth ≈6.5 ft, velocities > 40 ft/s
  - Friction factor, f=0.08
  - Mean air concentration, C=0.39
  - Failed only after block was pried out of the matrix using 600 lb_f

Soil Cement

- Many designs protecting embankments with soil cement either rolled flat over the slope or in stepped lifts. (Freese & Nichols experienced designers)
- Similar to RCC except not the same mix strength
- Hydraulic characteristics the same as RCC and defer the discussion to then.

Reinforced Concrete Slab

- Concrete slab designed over an embankment or rock-fill dam
  - A.R. Bowman Dam (U.S.) feasibility design (full coverage)
  - Crotty Dam – Australia- spillway section
- Critical design features:
  - Drainage system
  - Preventing slab cracking and offsets
  - Designing for influence of tailwater and jump over slab

RCC

- Revolutionized dam rehabilitation & new dam construction
  - Rejuvenated the issue of stepped spillway design
- Ken Hansen will discuss

Stepped Spillways – Formed RCC or Reinforced Concrete

- Located over entire or a portion of the dam or on a separate abutment
  - Discuss embankment dam slopes as that is typically what is thought of when referring to "overtopping".
- Step ht typically driven by construction techniques
- Useful for energy dissipation
- Test programs – incredible number
- Design guidance – controversial
- Maintenance:
  - Ensure concrete is in good shape and cracking minimized

Large-scale Flume Facility – 2-ft-high Steps

Nappe flow – q=5 cfs/ft

Large-scale Flume Facility – 1-ft-high Steps

Skimming flow – q=15 cfs/ft

Embankment Slope Step Designs

- Optimum step ht. $h/d_c \approx 0.3$
- Use air concentration & velocity data to determine energy remaining in the flow.

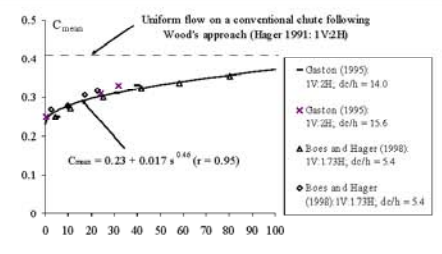
$$d = (1 - C_{mean})\,Y_{90}$$

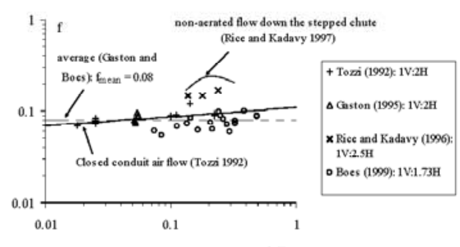
- Assumes uniform flow is attained.

$$U_w = \frac{q_w}{d}$$

- Shows that friction factor is nearly constant over a range of step ht. to hydraulic diameter.

$$f = \frac{2\,g \sin\alpha\, D_h}{U_w^2}$$





Hydraulic Design Considerations

- Calculate distance down the slope and depth at the aeration inception point. $C_{mean}=0.23$
- Determine mean air concentration down the slope
- Training wall height equal to the $Y_{90} = f(C_{mean},$ depth, friction factor)
- Energy at toe= *f(*dam ht, slope, head, friction)
- Design stilling basin using water depth and velocity.
- Cavitation damage has not occurred with designs to date, but might need to be considered for large q.

Design Criteria

- Debate: test facilities and data acquisition methods have dramatically varied. Which is correct?
  - Jorge Matos, IST, Portugal
  - Robert Boes, VAW, Zurich, Switzerland
  - Stephanie Andre, EPFL, Lausanne, Switzerland
  - USBR/CSU
  - Hubert Chanson, University of Queensland, Australia
  - Many other site specific studies added to the mix
- Debate: What presentation method of design criteria is the best? Those based upon:
  - Friction factor
  - Manning's equation
  - Residual energy computations based upon;
    - Continuity
    - Uniform flow equations
    - Both from various measurements of aerated & non-aerated flow from model and prototype tests

Stepped Spillway Research Needs

Development of peer reviewed manual for stepped spillway design that considers all techniques and meets requirements of practicing engineers

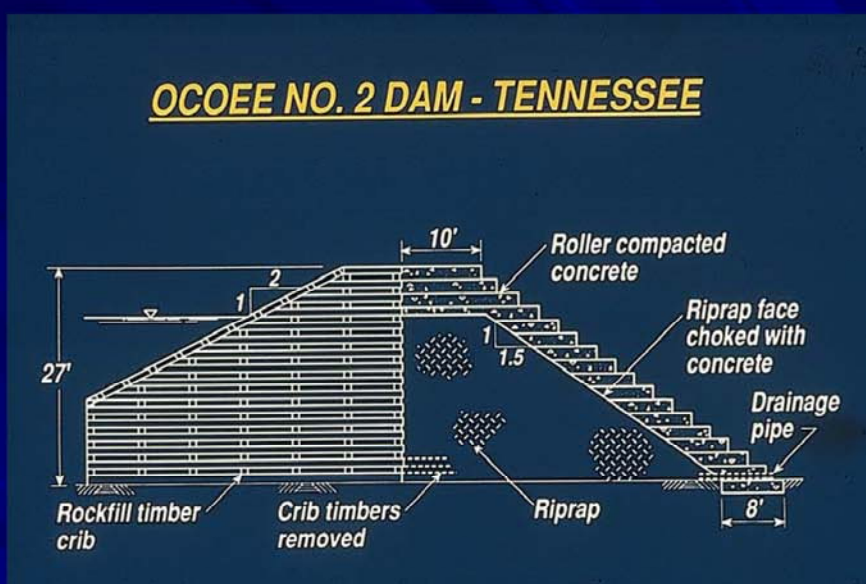
- Needed for low and high dams with high q, uniform & non-uniform flow regions, flatter and steeper slopes.
    - Possibly develop a chart of a ratio V_a/V_t versus total head for various sloping stepped spillways.

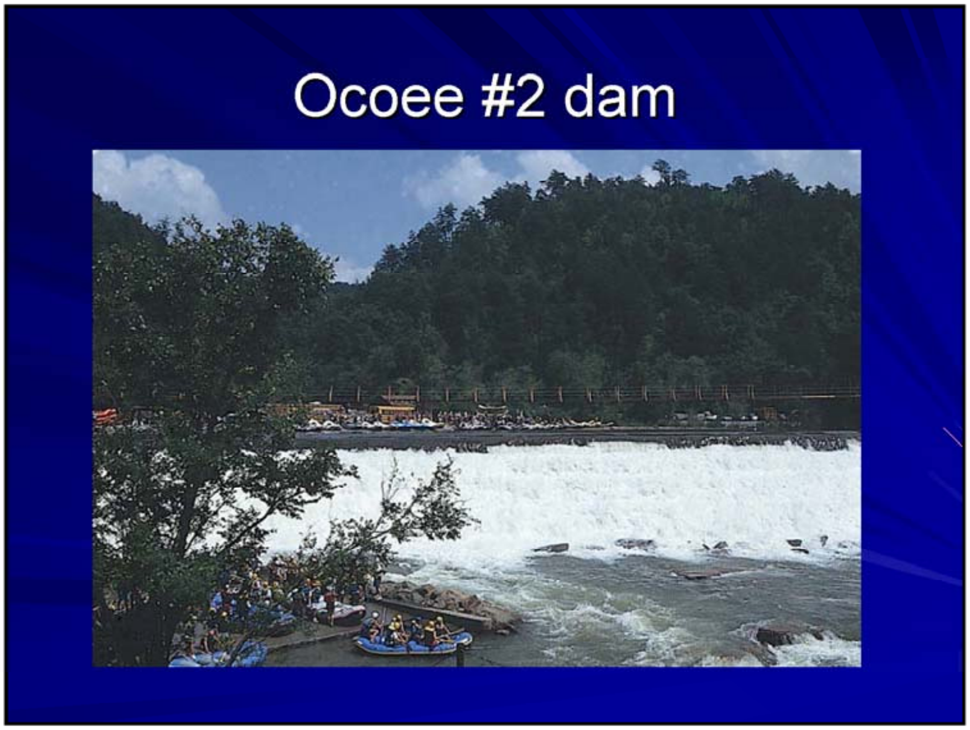
Presentation 8:
Roller Compacted Concrete Overtopping Protection for Increasing Spillway Capacity

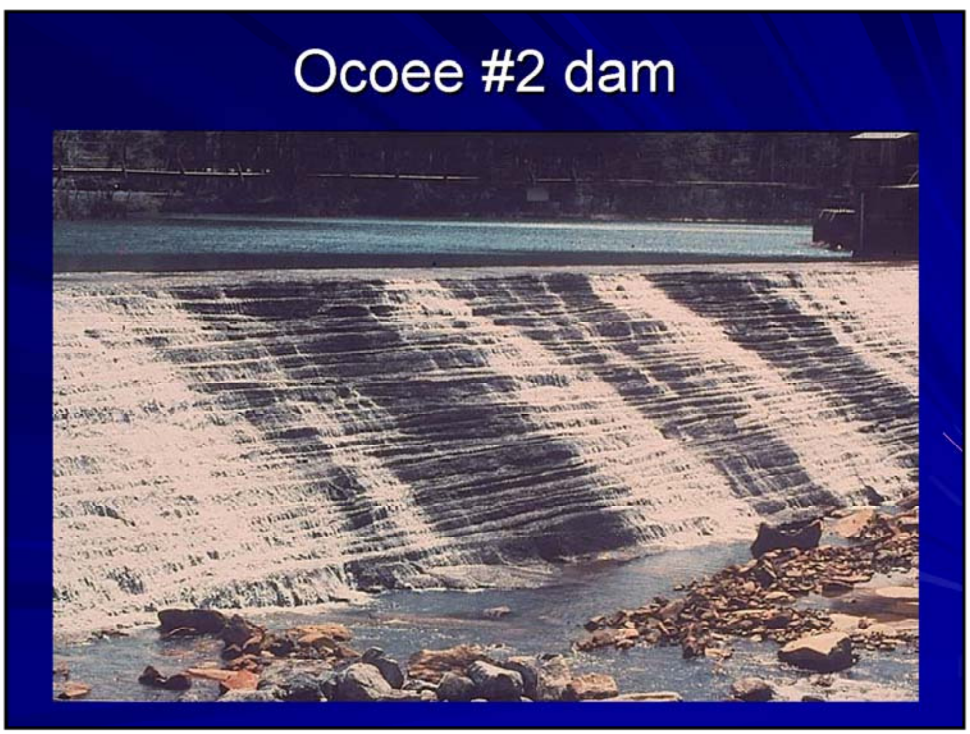
Roller Compacted Concrete Technology

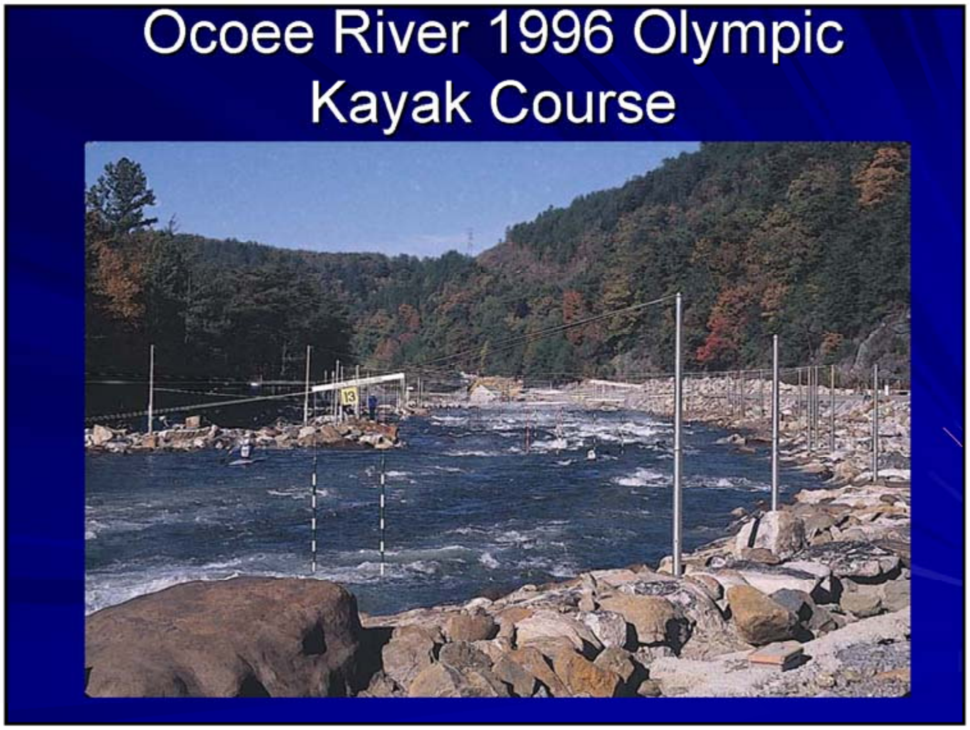
Ken Hansen

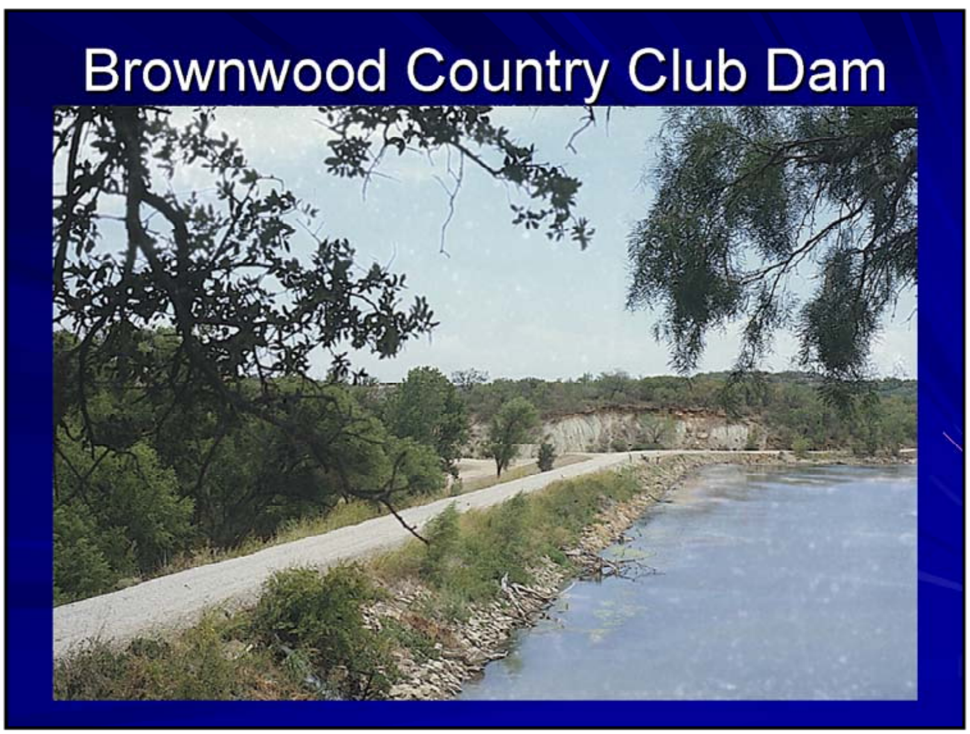
Schnabel Engineering Associates, Inc.




Ocoee #2 dam


Ocoee #2 dam

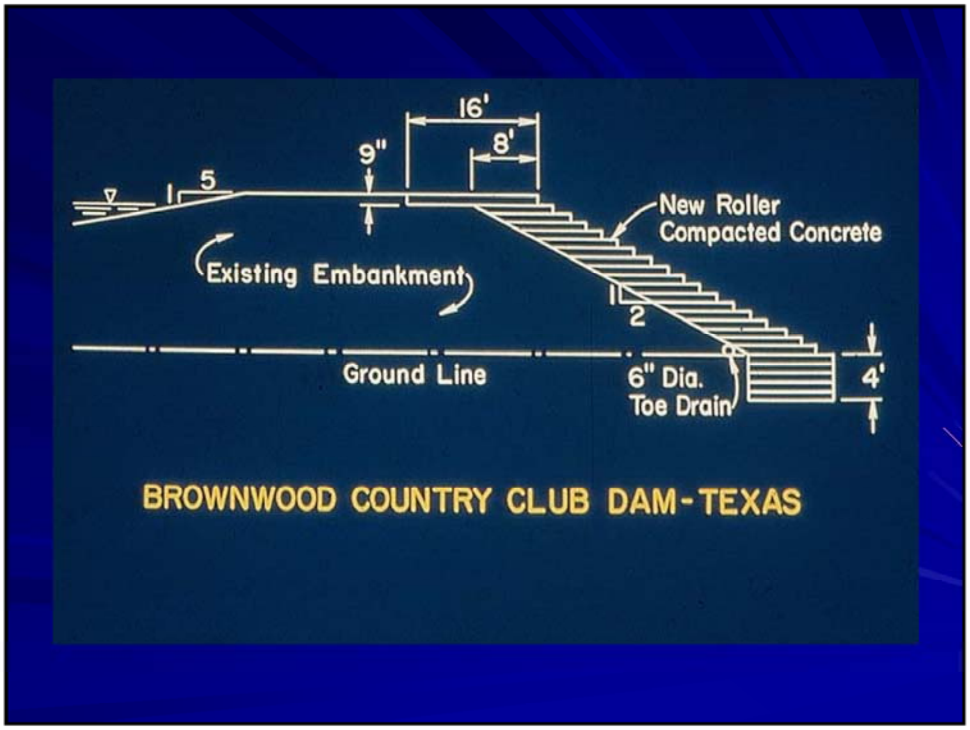

Ocoee River 1996 Olympic
Kayak Course


Brownwood Country Club Dam

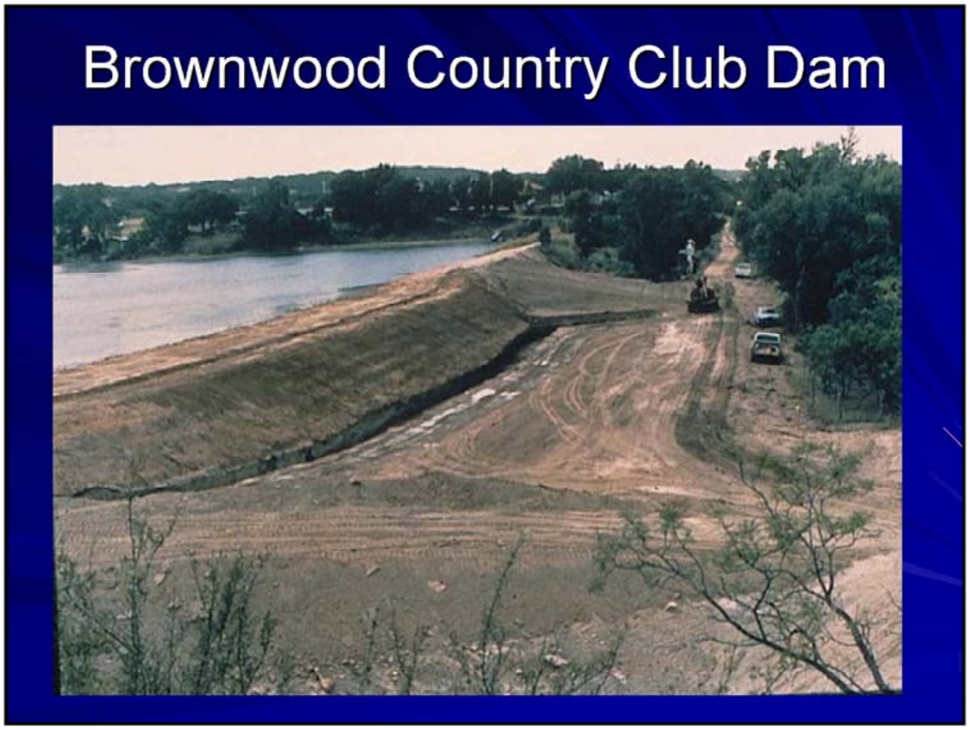
Brownwood Country Club Dam

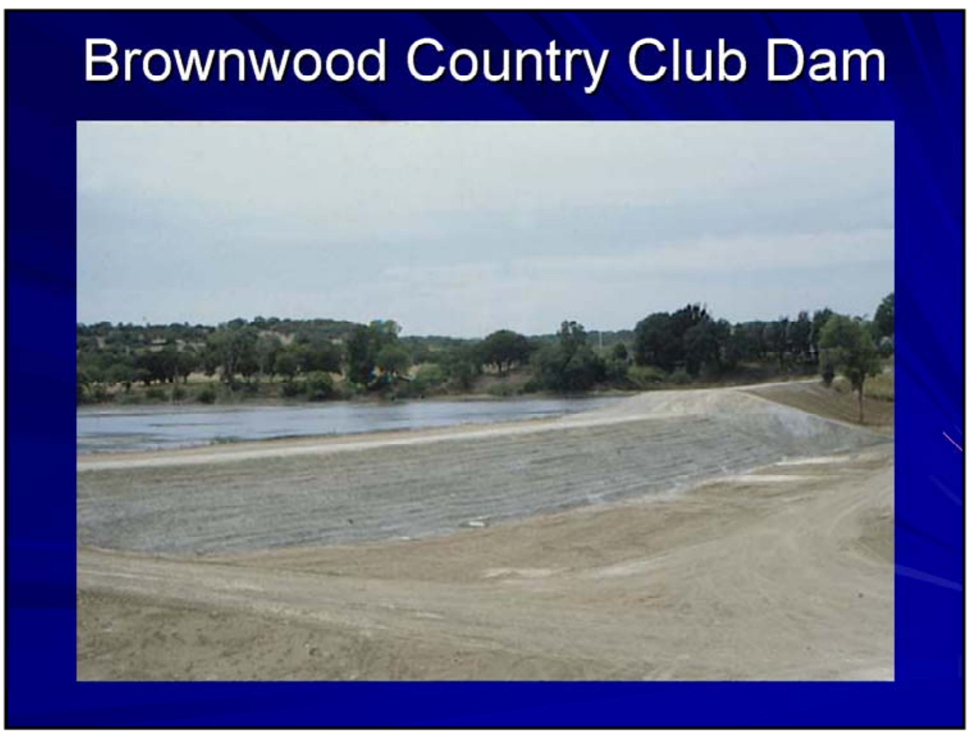
TO REMEDY A HYDRAULIC DEFICIENCY

- Breach The Dam
- Increase Storage
- Increase Spillway Capacity
- Overtopping Protection
- Combination


16'
8'
9"
1
5
New Roller
Compacted Concrete
Existing Embankment
1
2
Ground Line
6" Dia.
Toe Drain
4'
BROWNWOOD COUNTRY CLUB DAM-TEXAS


RCC


Brownwood Country Club Dam


Brownwood Country Club Dam

Brownwood Country Club Dam

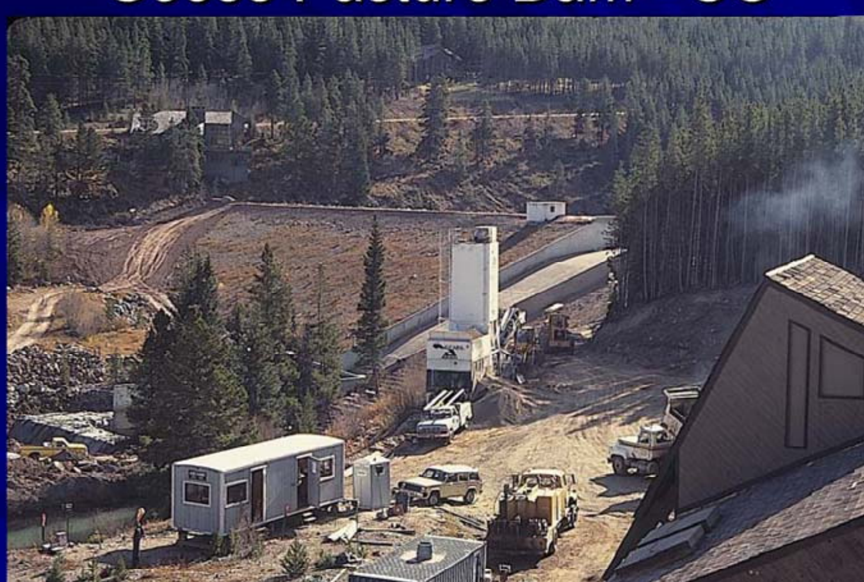
Spring Creek Dam - CO

Spring Creek Dam - CO

DESIGN OBJECTIVES

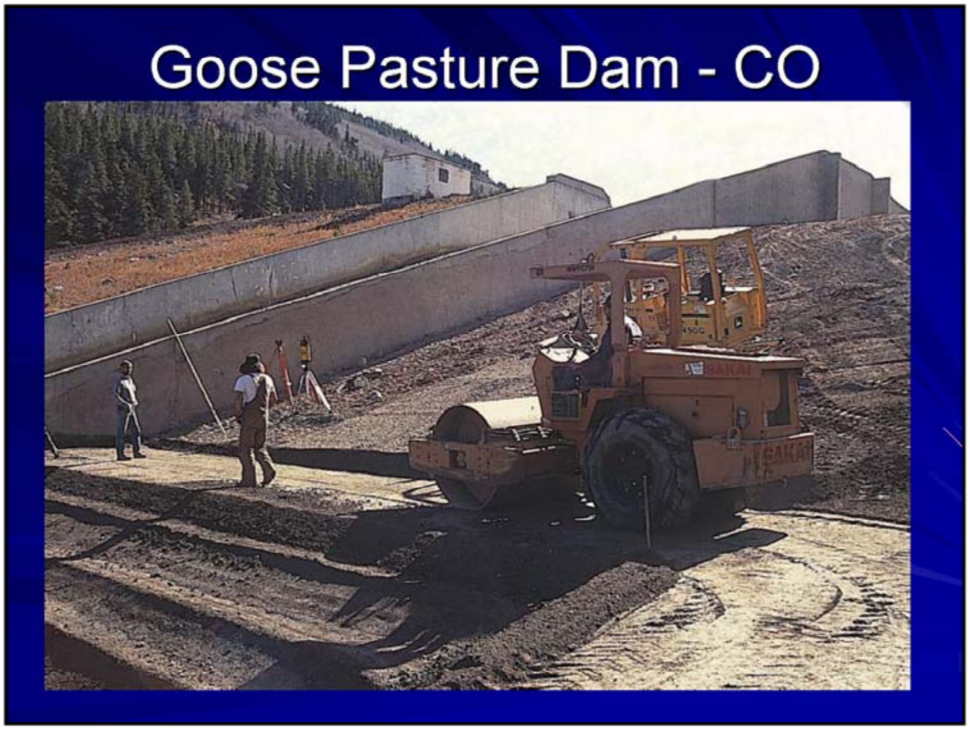
- Life: 50 – 100– 1000 yrs
- PMF Interval?
- Event Duration
- Peak Shifting
- Delay Failure
- Factor of Safety

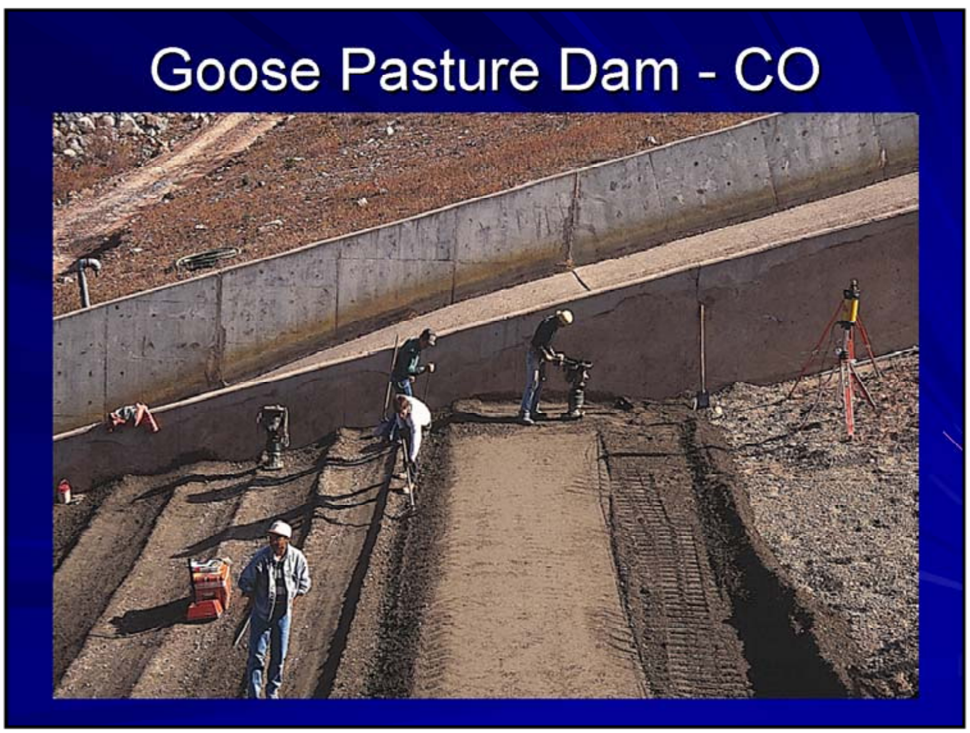
Goose Pasture Dam - CO

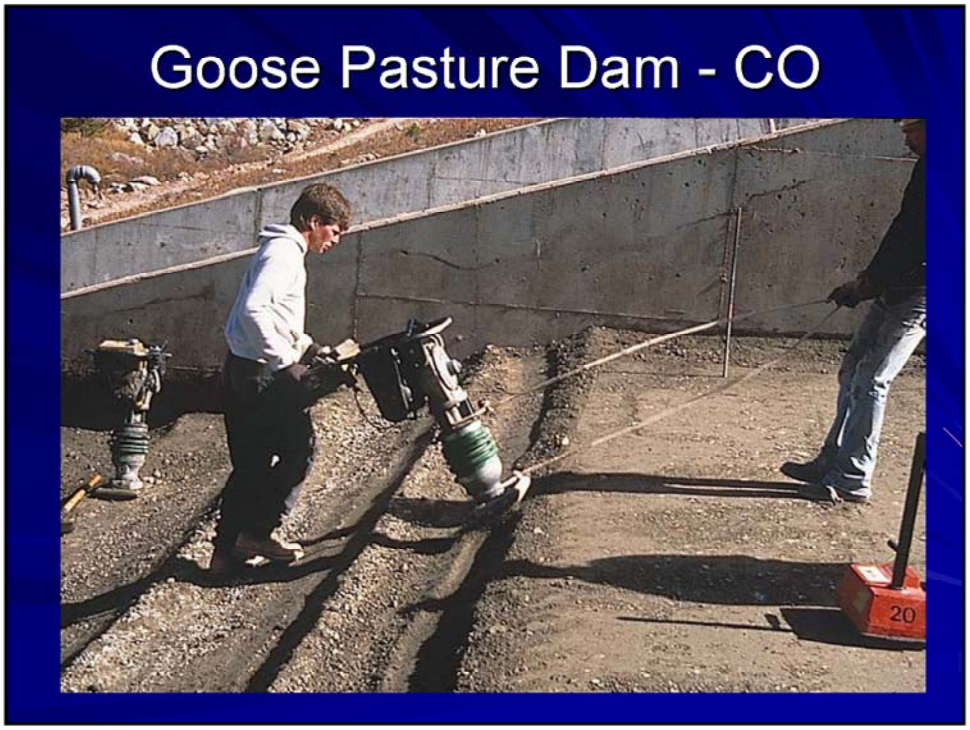


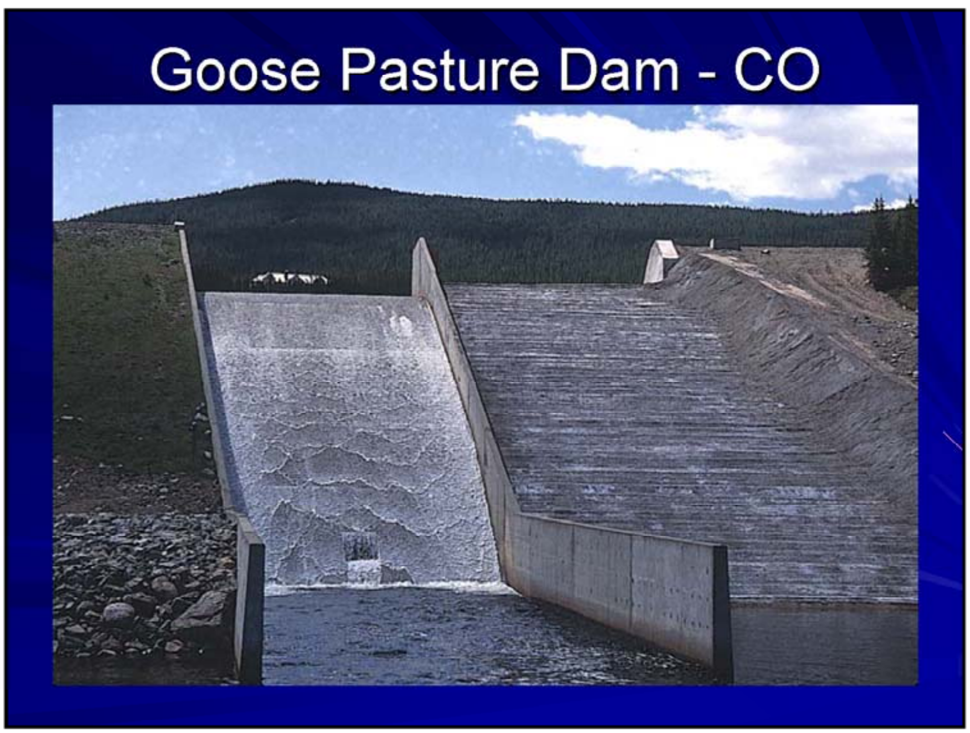
Goose Pasture Dam - CO

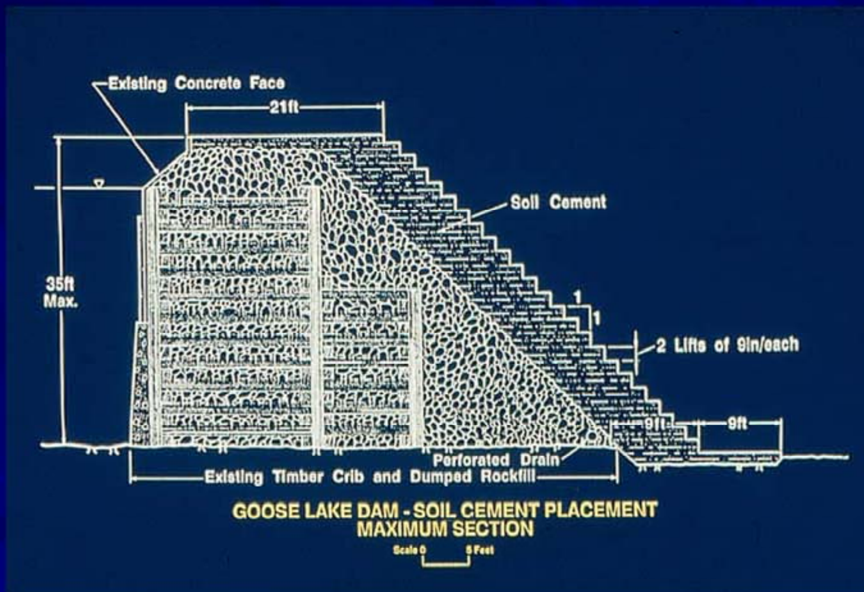
Goose Pasture Dam - CO


Goose Pasture Dam - CO


Goose Pasture Dam - CO


Goose Pasture Dam - CO
20


Goose Pasture Dam - CO



Goose Lake Dam - CO

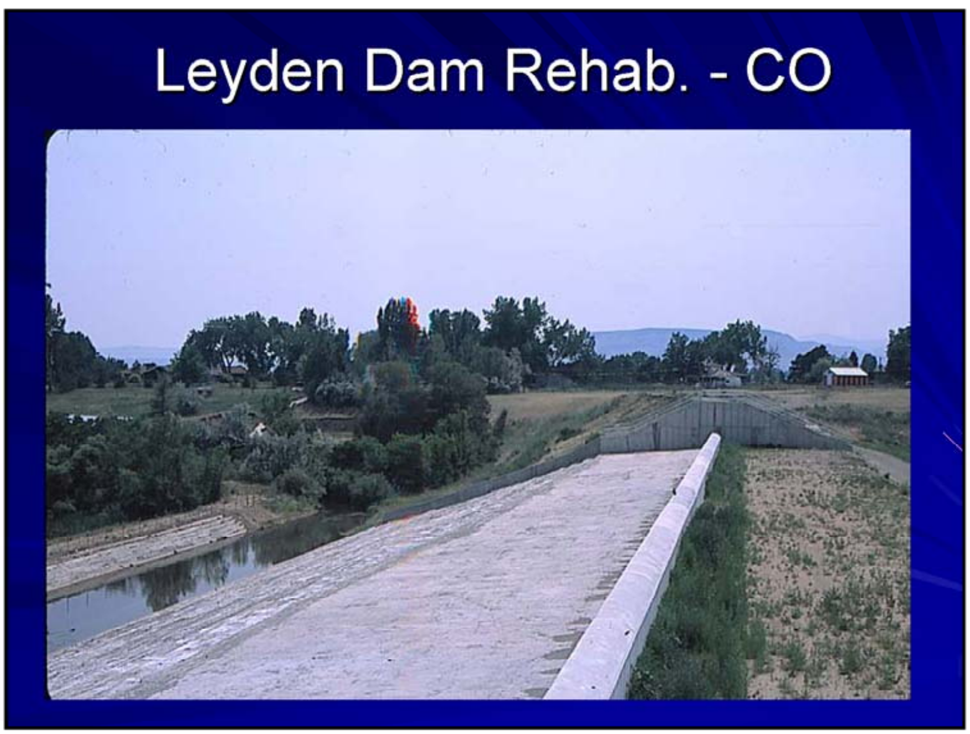
Goose Lake Dam - CO

Goose Lake Dam - CO

Goose Lake Dam - CO

Standley Lake Mod. - CO

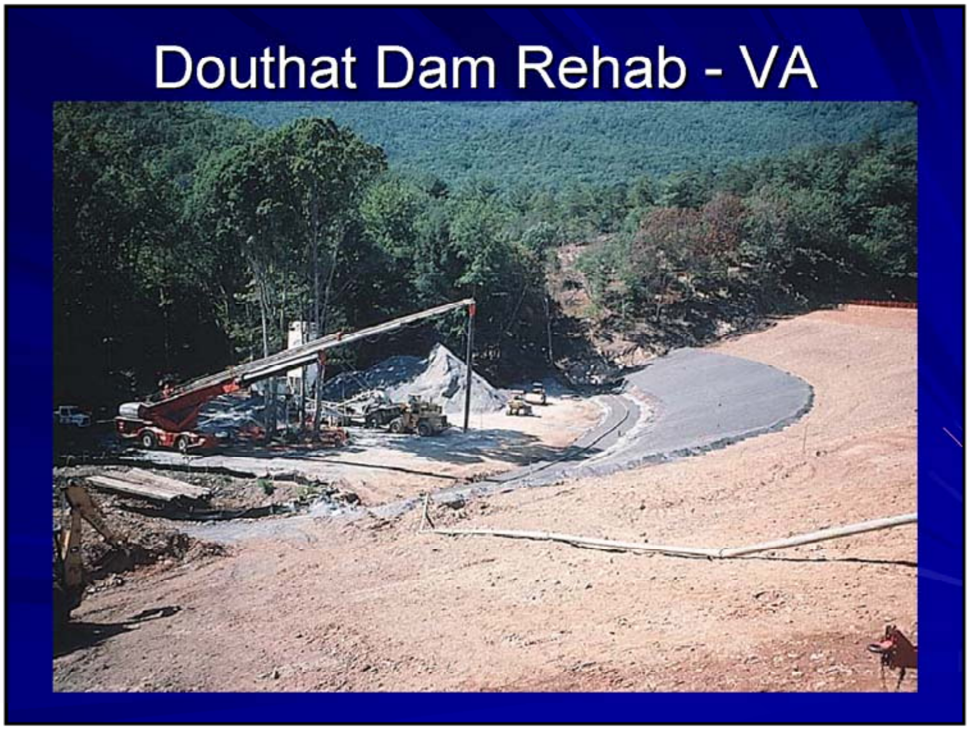

RECOMMENDED
RCC DESIGN
Small Volume Projects
Strength:
Little F/T: 2100 psi @ 28 days
min. (i.e., approx. 250 lb/cu yd)
F/T Zone: 3000 psi @ 28 days m
(i.e., approx 325 lb/cu yd)

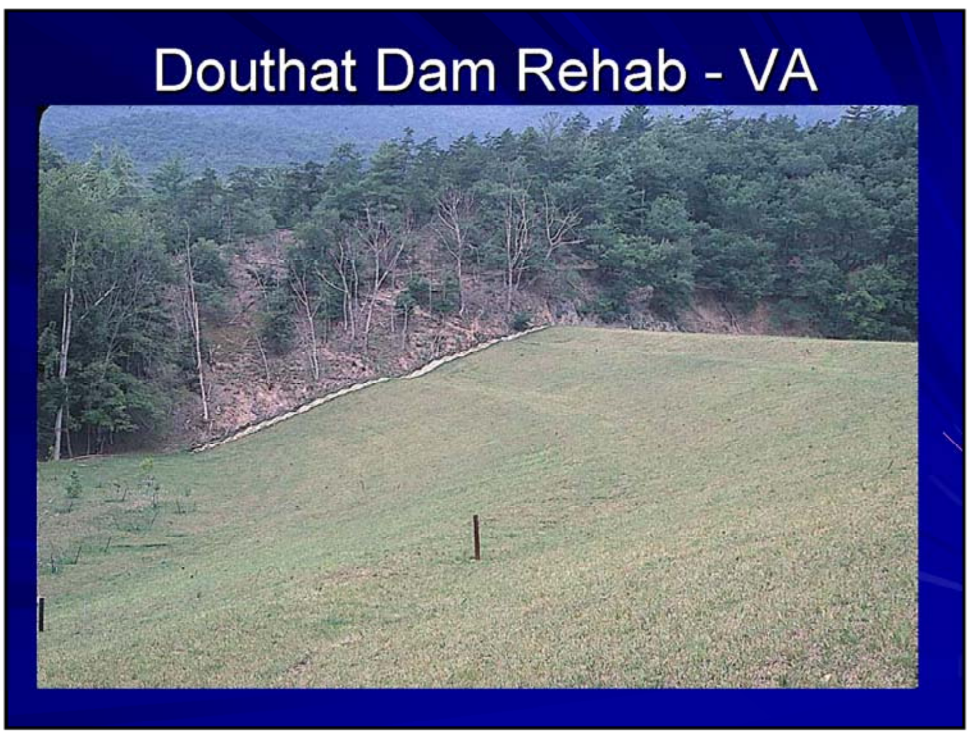

Leyden Dam Rehab. - CO

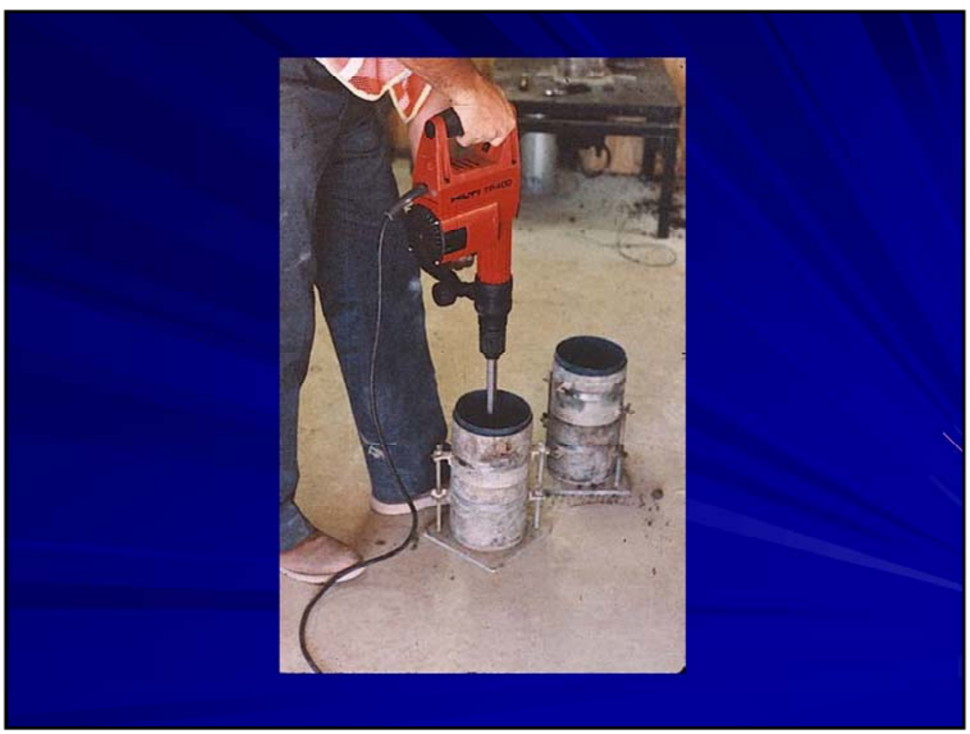
Leyden Dam Rehab. - CO

AGGREGATE

- Good Quality
- Local Availability
- Minimum Processing
- MSA about 1.5" (38mm)
- 40 % passing #4
- 4–8% passing #200
- Cement vs Aggregate Cost


Douthat Dam Rehab - VA


Douthat Dam Rehab - VA




PEE PEE
CREEK

Presentation 9: General Discussion — NRCS Designs and Research Needs

Dam Safety Workshop
Denver, Colorado
August 26-27, 2003

NWMC Functions

- Direct Technical Assistance
- Consultation and Training
- Watershed Plan Development and Review
- Linkage to Other Specialists

USDA NRCS

NRCS Hydrologic Criteria

Maximum Frequency of Use for Vegetated Auxiliary Spillway
(Storage above the Principal Spillway)

Low Hazard – Class (a):	25 year Precipitation to 50 year Precipitation
Significant Hazard – Class (b):	50 year Precipitation
High Hazard – Class (c):	100 year Precipitation

USDA NRCS

NRCS Hydrologic Criteria

Auxiliary Spillway Design Hydrograph

Low Hazard – Class (a):	100 year Precipitation to $(P_{100} + 0.12\ (PMP - P_{100}))$
Significant Hazard – Class (b):	$(P_{100} + 0.12\ (PMP - P_{100}))$
High Hazard – Class (c):	$(P_{100} + 0.26\ (PMP - P_{100}))$

USDA NRCS

NRCS Hydrologic Criteria

Freeboard Design Hydrograph

Low Hazard – Class (a):	$(P_{100} + 0.12\ (PMP - P_{100}))$ to $(P_{100} + 0.40\ (PMP - P_{100}))$
Significant Hazard – Class (b):	$(P_{100} + 0.40\ (PMP - P_{100}))$
High Hazard – Class (c):	PMP

USDA NRCS

NRCS Principal Spillway

NRCS Principal Spillway

NRCS Principal Spillway

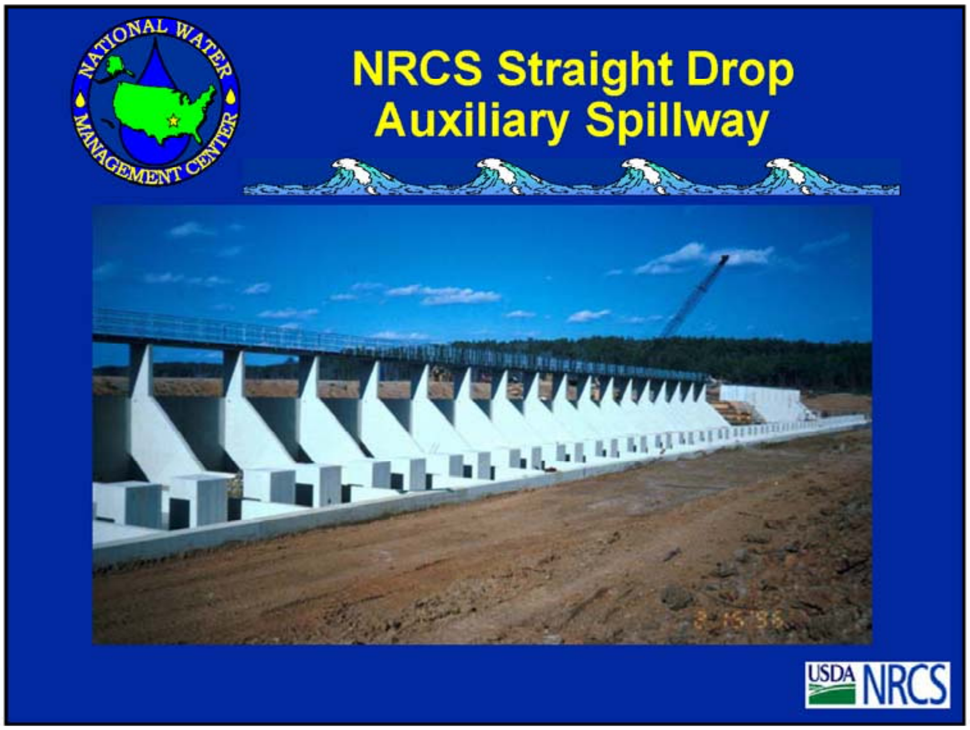
NRCS Vegetative Auxiliary Spillway

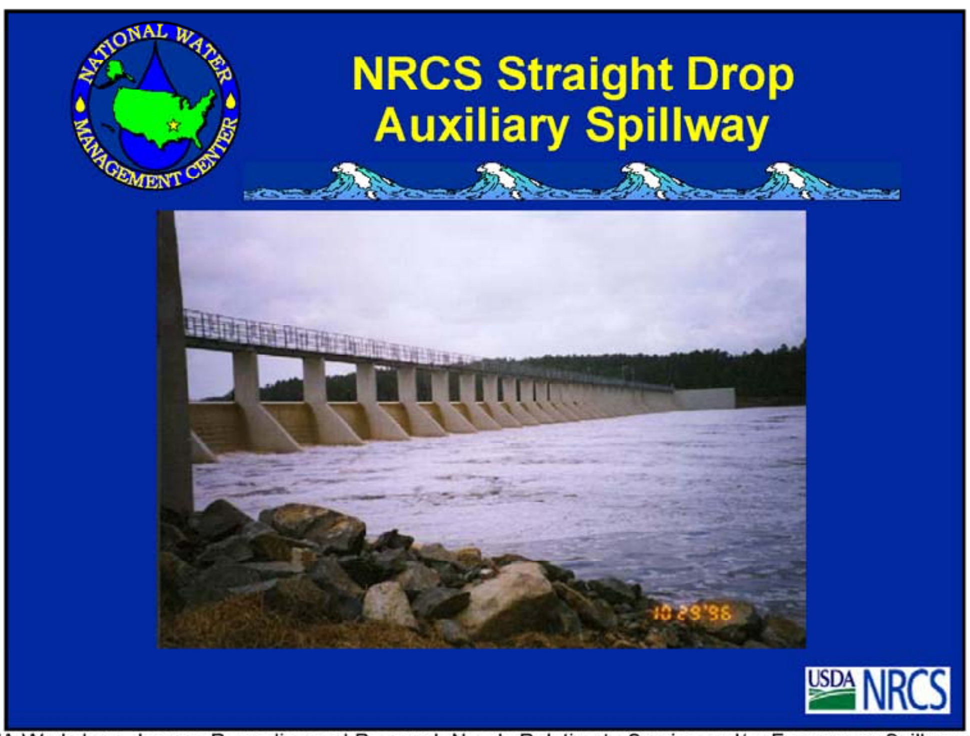
NRCS Vegetative Auxiliary Spillway

USDA NRCS

NRCS Vegetative Auxiliary Spillway

USDA NRCS


NRCS Straight Drop
Auxiliary Spillway
USDA NRCS


NRCS Straight Drop
Auxiliary Spillway
10 29 '96
USDA NRCS

NRCS Roller Compacted Concrete Auxiliary Spillway

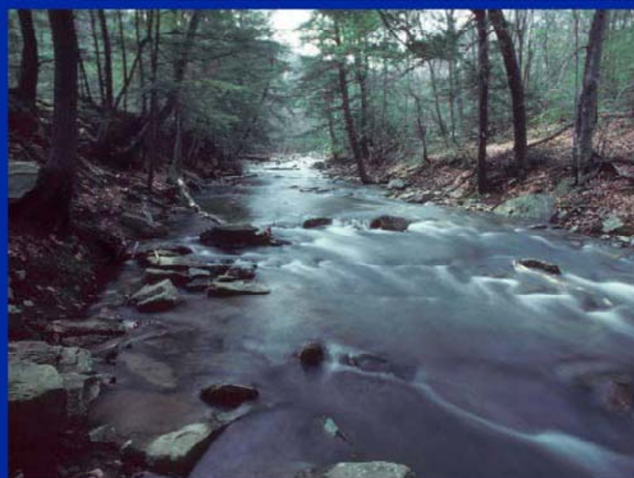
USDA NRCS

Research Needs

- Erosion Model for Breach Determinations from Dam Overtopping
- Peak Discharges from Erosion Breaches
- Stilling Basin Design for RCC Stepped Spillways
- Revised Rainfall/Frequency Maps

USDA NRCS

NWMC
http://wmc.ar.nrcs.usda.gov



USDA NRCS

Presentation 10:
Spillways — An Owner's Perspective

Spillways

Owners Perspective

Spillways

- PMP/PMF
  - Old Story…
- But it is time to take another look!

Spillways – Recent History

- It appears that the upward ratcheting of spillway capacity has slowed…at least a little
- Phase I (1978) identified over 60,000 + dams, most were non federal, earth dams with "inadequate" spillways

The Problem

- Because most of the 60,000 dams are privately owned dams, many can not afford to meet the spillway criteria currently required
- A few owners that can comply (BUREC, FERC Regulated Dams, and Large Utilities) have the funds…most others do not

Spillways

- Most of the problems with private dams have been addressed except in the area of spillways
- Billions have been spent, storage has been lost … and still there are many dams that do not have “adequate” spillways
- The primary driver is the precipitation derived from HMR’s– the PMP

PMP/PMF – WHY?

- The National Weather Service (NWS) introduced the PMP/PMF primarily for COE and other federal dams
- This technology was transferred to private dams (first large then small dams) with little thought about the increased costs to the private sector

Problems with Using HMRs

- Infrastructure costs are simply too high and so states and local governments have invented creative ways to work around the numbers:
  - Incremental Damage Studies
  - "Site Specific" Hydrologic Studies
  - "Grandfathering"
  - Changing Precip. requirements for classes of dams
  - Changing definitions of dam classifications
  - Risk based analysis

More Problems with HMRs

- Data that supports the HMR findings is often lost or can not be supported by the record
- The CORE or the BUREC have not found the "need" or the money to further the science of extreme precipitation events
- The procedures used in the HMR are not well understood and are considered by most to be too conservative

Questions

- Was and is the NWS the right agency to plant the PMP seed that resulted in so many spillways to be inadequate?
- After 25 years, do we need to take another look at why we need “zero” risk when it comes to spillways?

More Questions

- With new techniques and computer models that have been developed in the past 25 years, should new methods and criteria be developed and instituted (site specific)
- With the variety of “state by state” criteria, why should people in one state be more or less protected than other people in another state?... Isn’t there a need to apply the criteria uniformly?
- Is a 5,000 or 10,000 year storm large enough?

Proposal

Have National Academy of Science (Engineering) or similar group:

- Re-review the idea that the PMP level of storm event vs need to protect the public at all costs and risks

Proposal (cont.)

- Develop a new techniques for the PMP/PMF to be used nationally… by all states
- Develop new computer models that are simple to use and understand, easy to update with new precipitation data
- Keep it simple and keep it cost effective for owners

Presentation 11:
General Discussion — Consultant's Spillway Design and Research Needs

Hydraulic Structures Technical Committee

To promote and/or advance research, analysis, design, construction, operation and maintenance of state-of-the-art methodology associated with hydraulic structures.

To accomplish this purpose, the committee proposes and organizes task committees and/or subcommittees to complete projects which advance the science. In addition, the committee promotes the technical exchange of ideas through sponsored sessions at conferences, publications of reports, papers, and monographs, and interaction with other professional and technical societies.

http://www.wadepmoore.com/HSTC/

Hydraulic Structures Technical Committee

Current Membership

• John Hite	Waterways Experiment Station
• Bruce Muller	USBR Technical Center
• John Finnie	University of West Virginia
• Bruce Brand	FERC
• Kevin Nielsen	Carroll College
• Kerry Robinson	USDA - Agricultural Research Service
• Rick Voigt	Polaris Group
• Walt Heyder	USBR Technical Center
• Mike Buechter	Parsons Brinckerhoff Quade and Douglas
• John Laboon	USBR Technical Center
• Wade Moore	Montgomery Watson Harza
• Yifan Zheng	Bechtel
• Richard Stockstill	Waterways Experiment Station

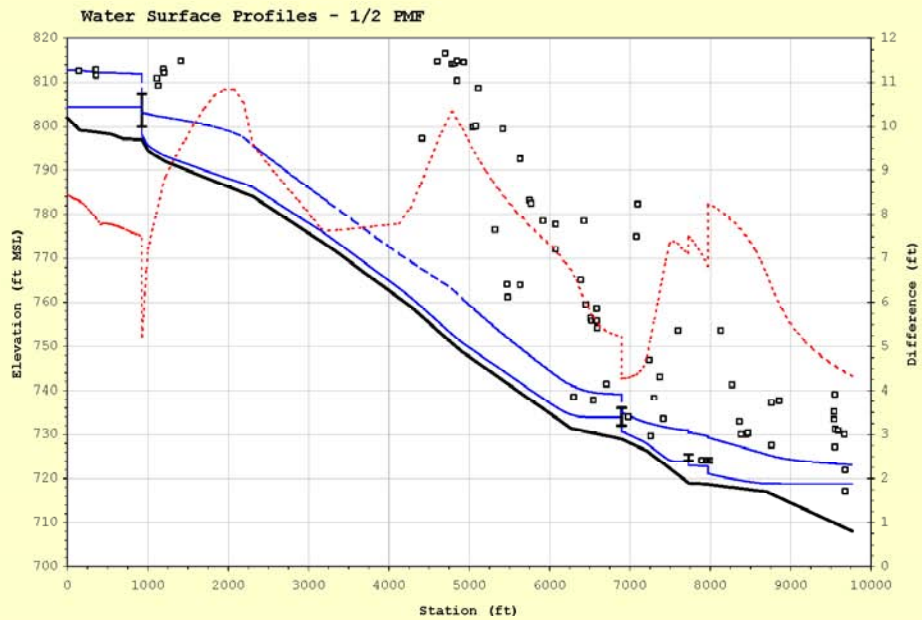
Spillway Expansions by Harza

Cushman I	1990	Conventional Spillway
Brule	1991	Fuse Plug
Ponca	1992	Overtopping - RCC
He Dog	1993	Overtopping - RCC
Blue Ridge Dam	1994	Conventional Spillway
Boney Falls	1994	RCC Fuse Plug
Bald Hill	1997	Overtopping - Conventional Concrete
Devil's Gate	1999	Conventional Spillway
Big Dalton	2000	Modify Outlet Works
Granite and Crystal Dams	2000	Fuse Plug
Middle Branch	U/C	Overtopping - RCC

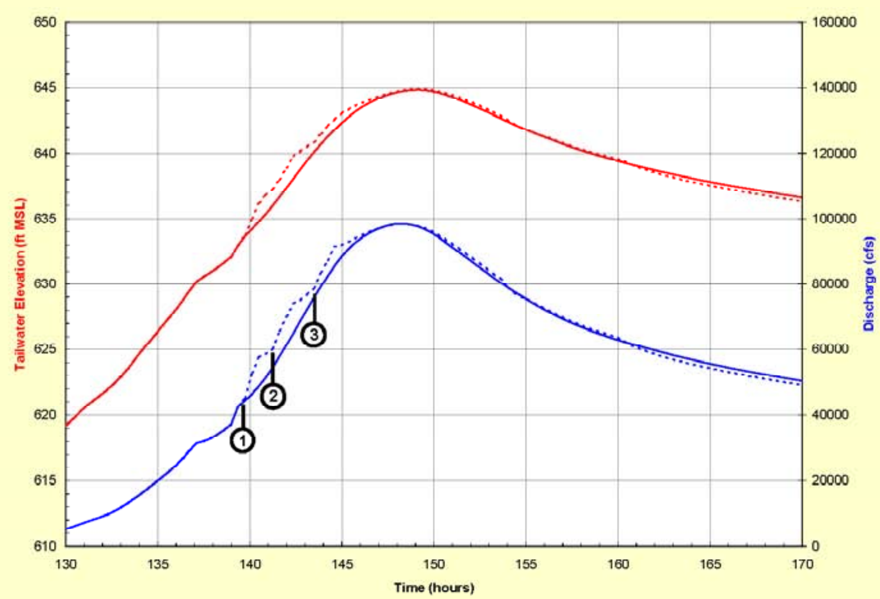
Dam Failure Analysis

- Develop 1-D Unsteady Flow Model of System
- Use FERC criteria to "control" outflow from reservoir
  - 1:1 Side Slopes
  - 2h-4h Breach Width
  - 0.1-1.0 hour Failure Time
  - Failure at Peak Water Elevation
- Perform Sensitivity Analysis
- Perform IDF Analysis
  - Largest Inflow that does <u>not</u> raise water levels d/s more than 2 feet

Dam Failure Analysis



Dam Failure Analysis



Research Needs

- Overtopping Protection - economics of slab vs RCC
- Rip-rap stability – dumped vs hand placed
- Fuse Plugs – speed of erosion, trigger mechanisms, smaller sizes
- Fuse Gates – ice, debris, seals
- “Single” Use Spillways - allowable damage and repair
- Small Spillways - rock chutes, etc.
- Exceeding Design Head - damage prediction
- Conventional Chutes - converging walls, supercritical transitions
- Stepped Spillways - step size and shape vs head loss

Research Needs

- Overtopping Protection - economics of slab vs RCC
- Rip-rap stability – dumped vs hand placed
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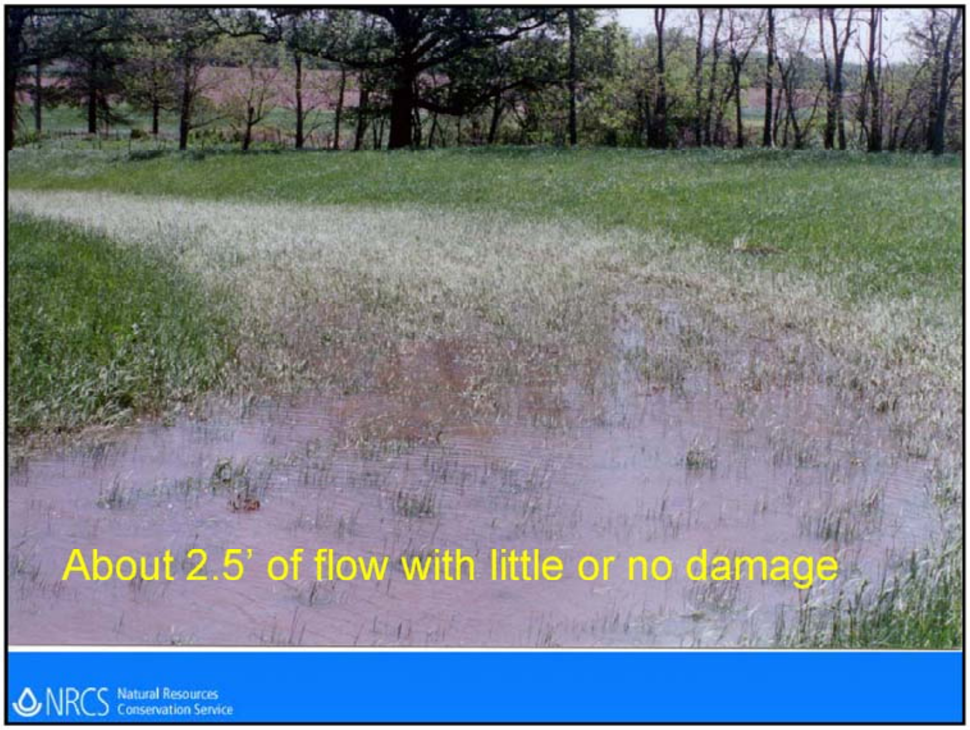
Presentation 12:
Vegetated Earth Spillways — Inspection, Maintenance, and Monitoring

Vegetated Earth Spillways Inspection – Maintenance & Monitoring

Denver, CO

August 26-27, 2003


About 2.5' of flow with little or no damage
NRCS Natural Resources Conservation Service


Well maintained dam.
NRCS Natural Resources Conservation Service

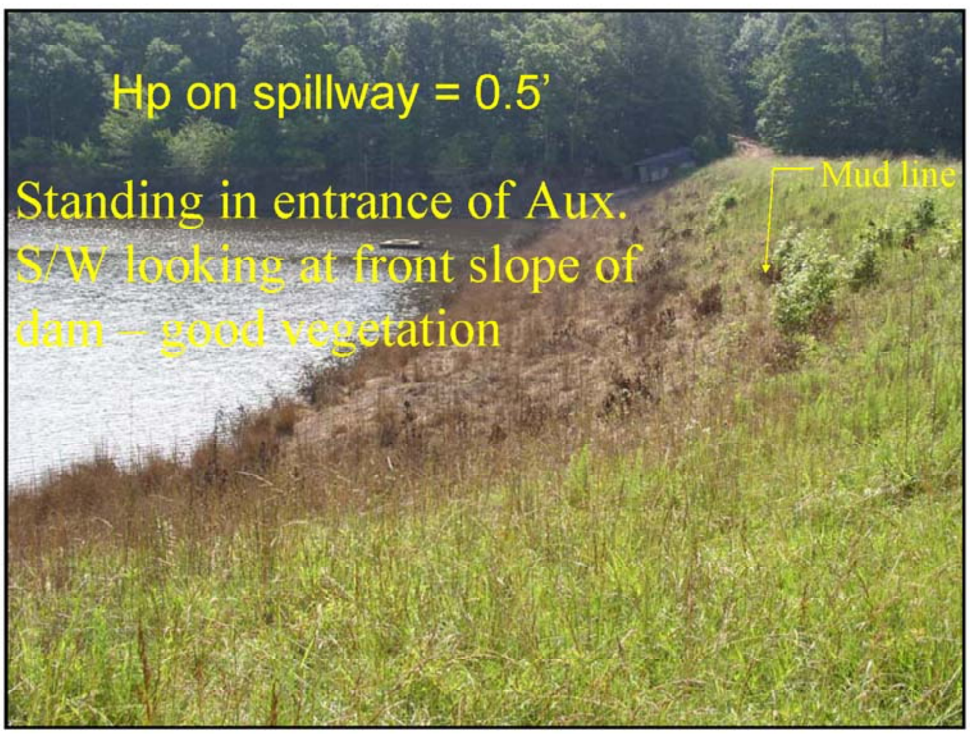

Spillway Looks like it has been well maintained
NRCS Natural Resources Conservation Service


Tire Tracks
Equipment used for maintenance destroyed vegetation
NRCS Natural Resources Conservation Service


Trail develops into a major erosion problem.
Erosion in Spillway
NRCS Natural Resources Conservation Service


Can you see the dam?
Road Up the Spillway
NRCS Natural Resources Conservation Service


Other uses - Trailer in spillway used for a home site
FEB 27 2003

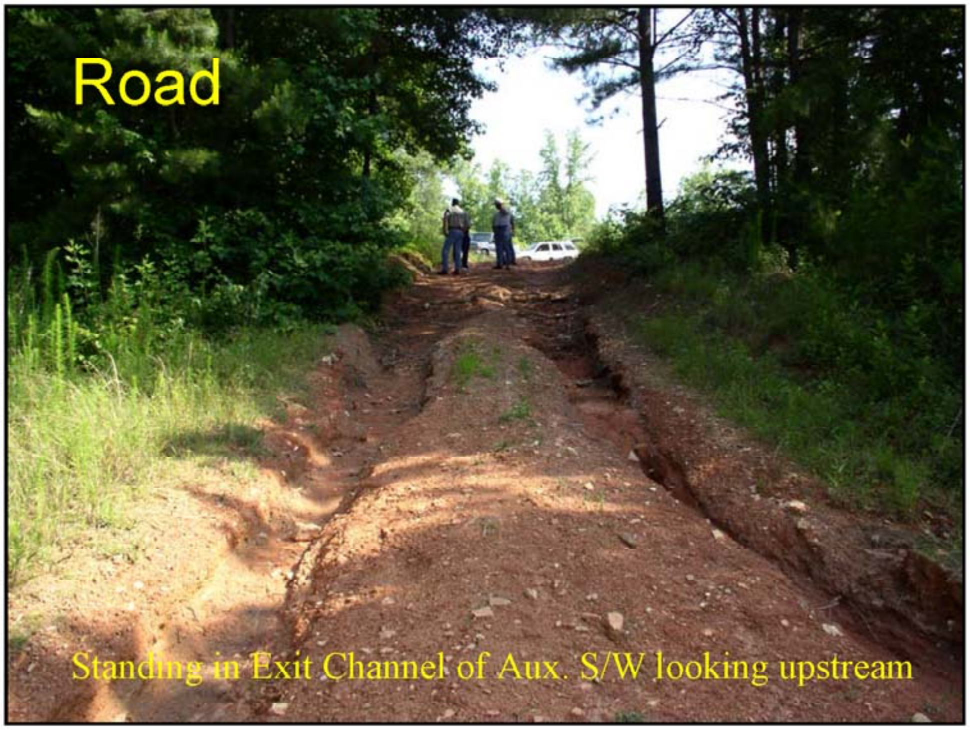

Hp on spillway = 0.5'
Standing in entrance of Aux. S/W looking at front slope of dam – good vegetation
Mud line

Standing in entrance of Aux. S/W
looking upstream – good vegetation

Vegetation in crest not good.
Hay bales in control section
Standing in entrance to Aux. S/W looking downstream


Almost no vegetation.
Standing in control section looking downstream

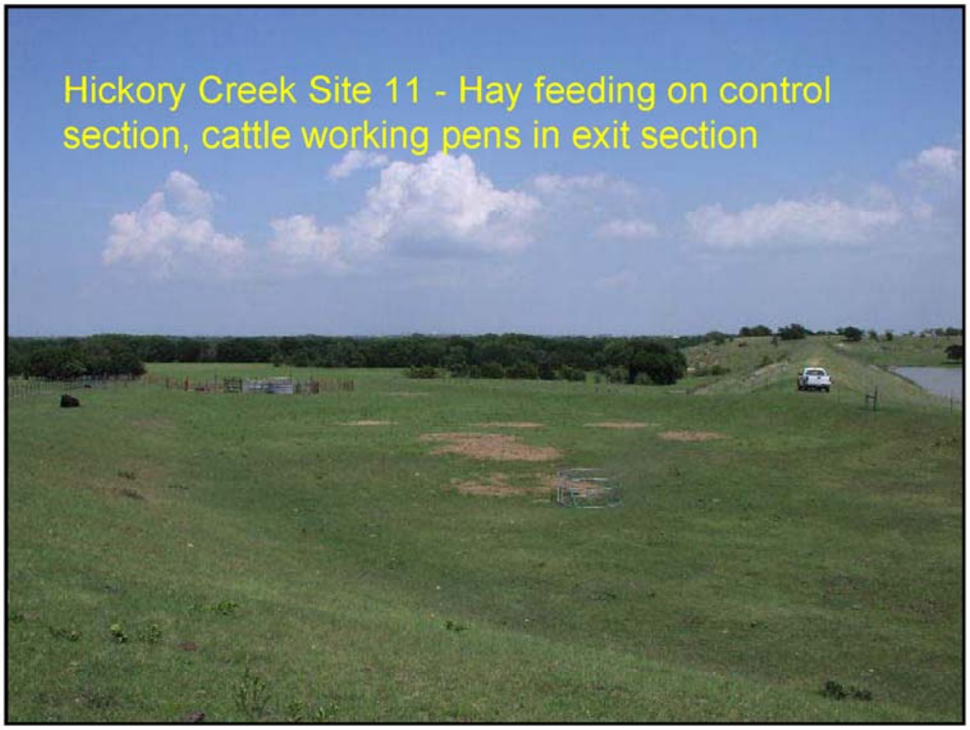

Control Section
Standing in Aux. S/W looking upstream

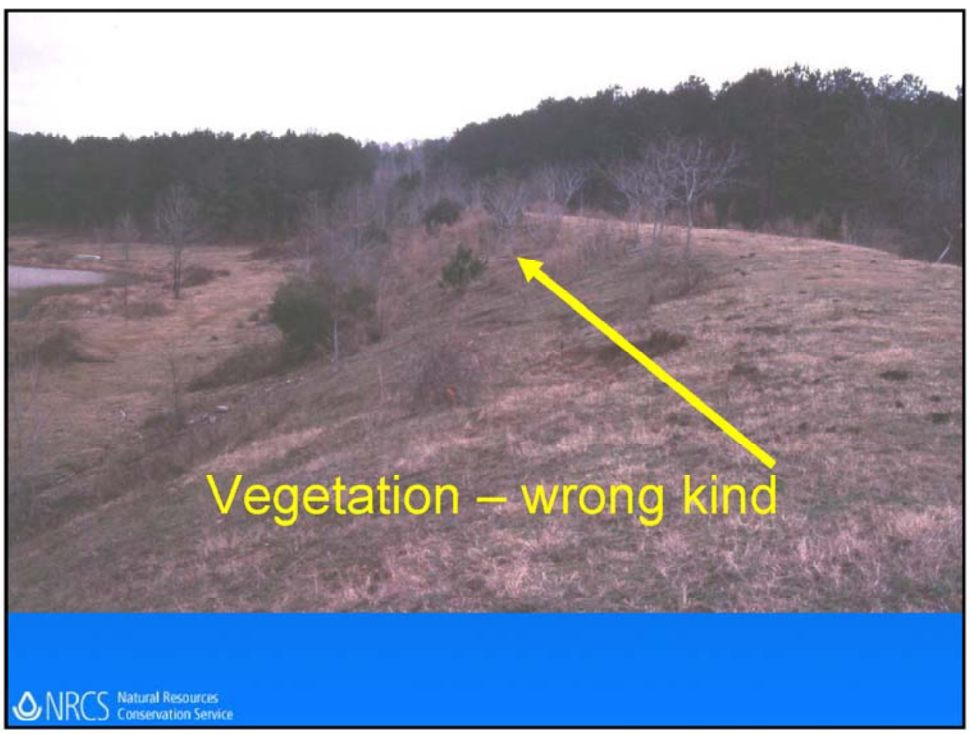

Road
Standing in Exit Channel of Aux. S/W looking upstream

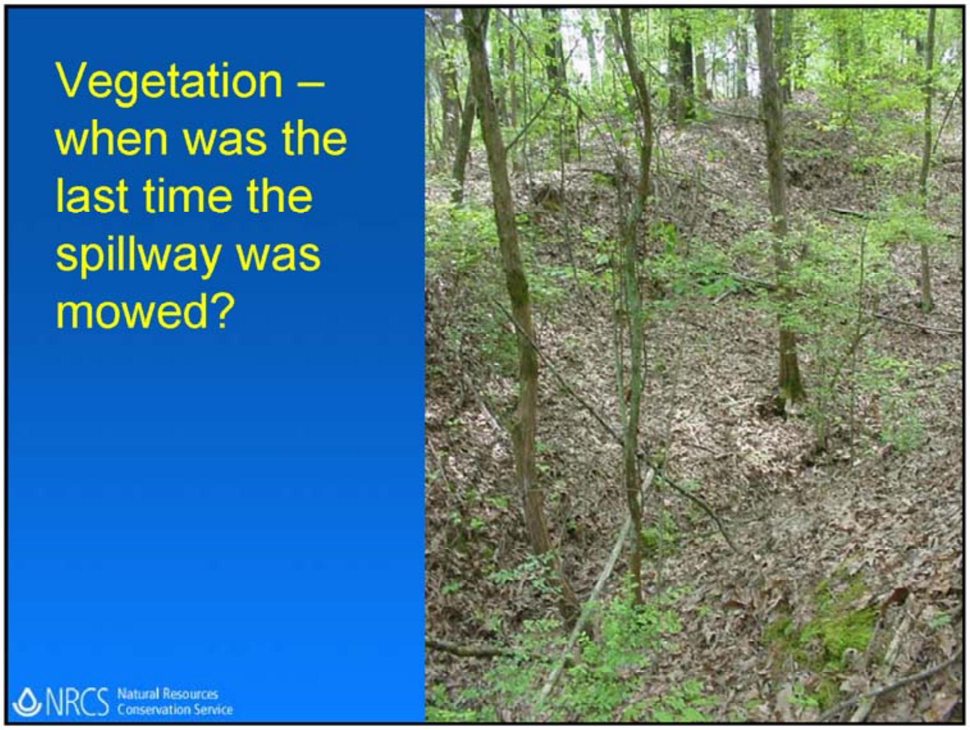

FEB 13 2002

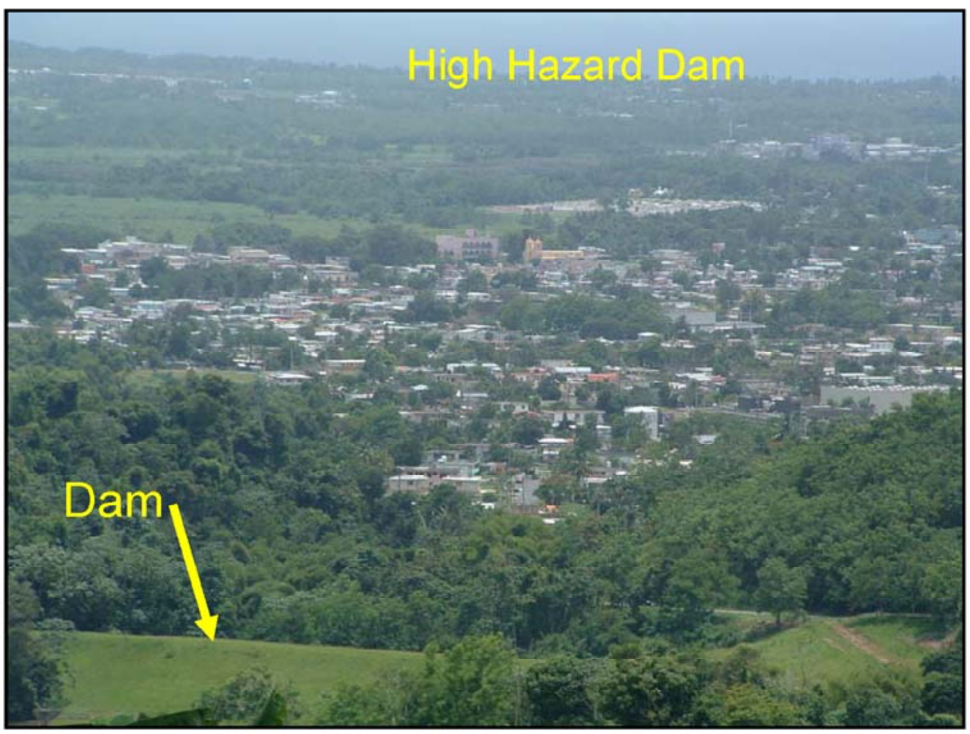

FEB 13 2002

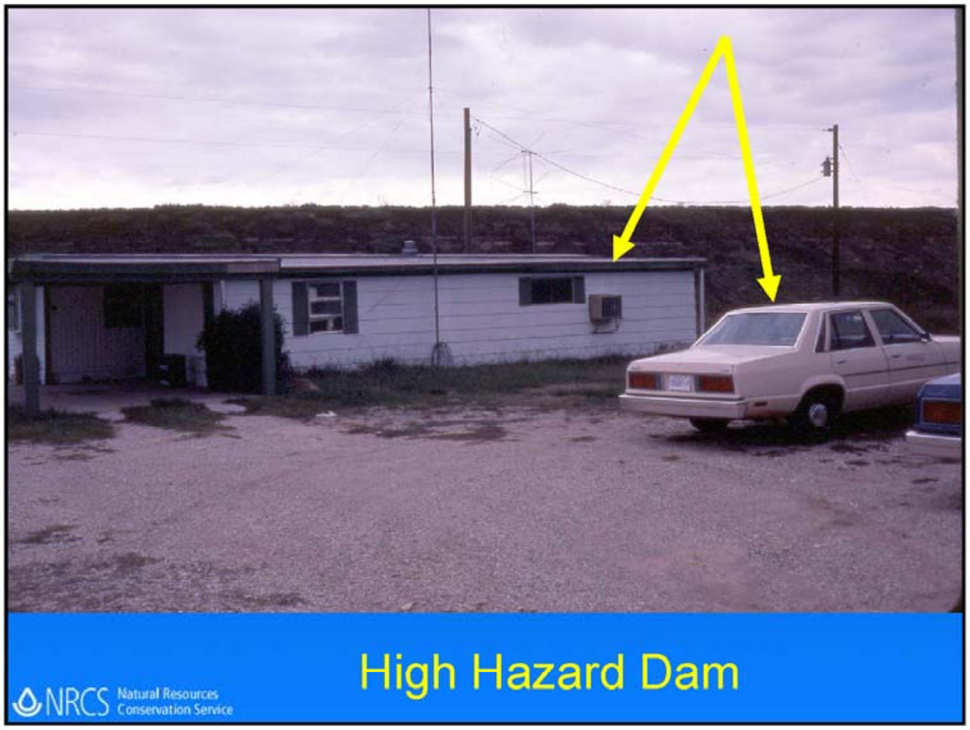

FEB 13 2002


Hickory Creek Site 11 - Hay feeding on control section, cattle working pens in exit section

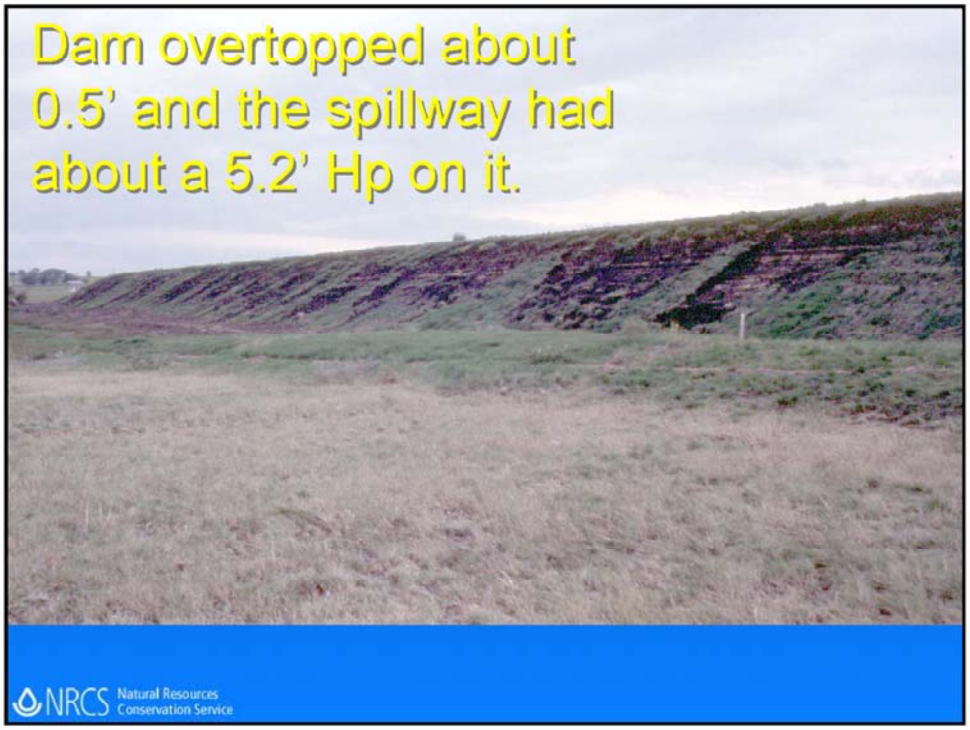

Vegetation – wrong kind
NRCS Natural Resources Conservation Service


Vegetation – when was the last time the spillway was mowed?
NRCS Natural Resources Conservation Service


High Hazard Dam
Dam


High Hazard Dam
NRCS Natural Resources Conservation Service

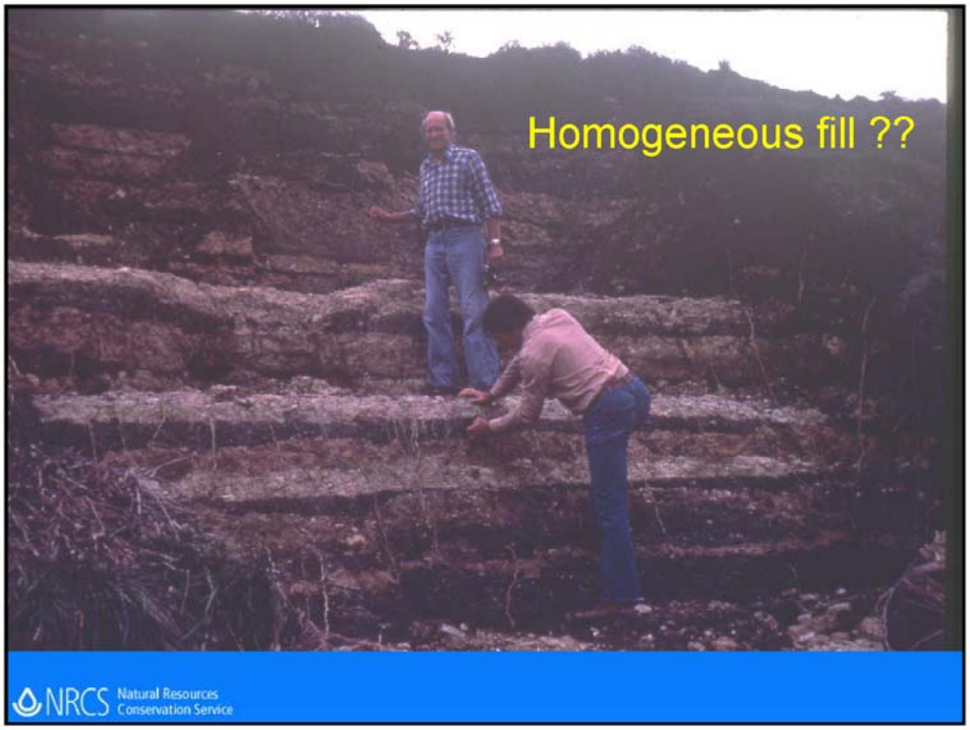

Same Car and House
NRCS Natural Resources Conservation Service


Dam overtopped about 0.5' and the spillway had about a 5.2' Hp on it.
NRCS Natural Resources Conservation Service

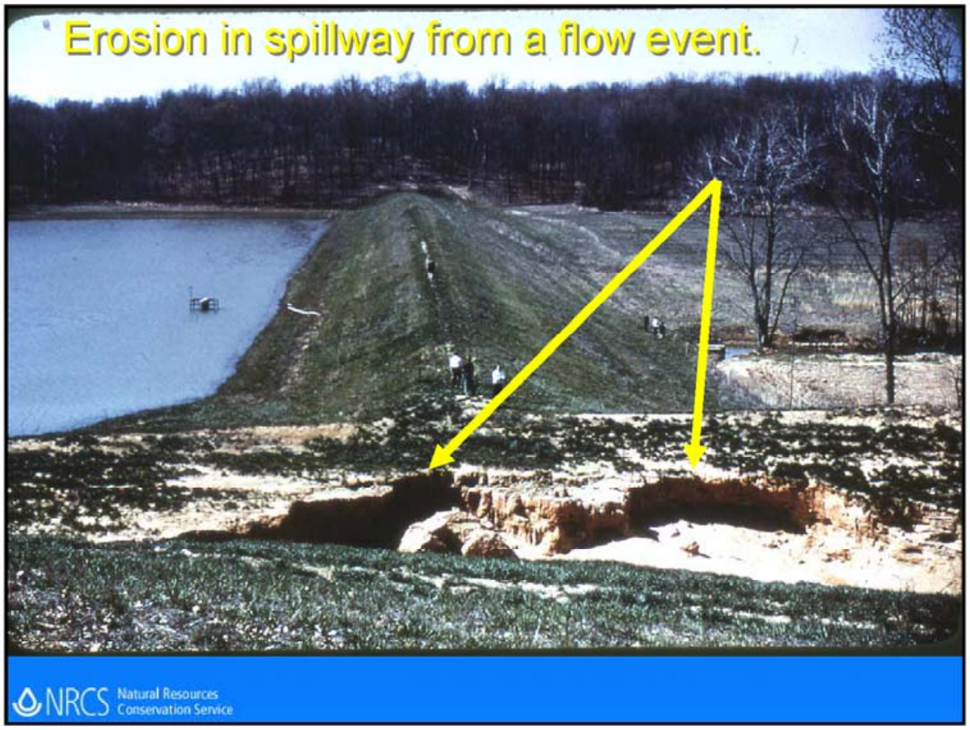

5.2' Hp on crest of this spillway – little or no damage
NRCS Natural Resources Conservation Service

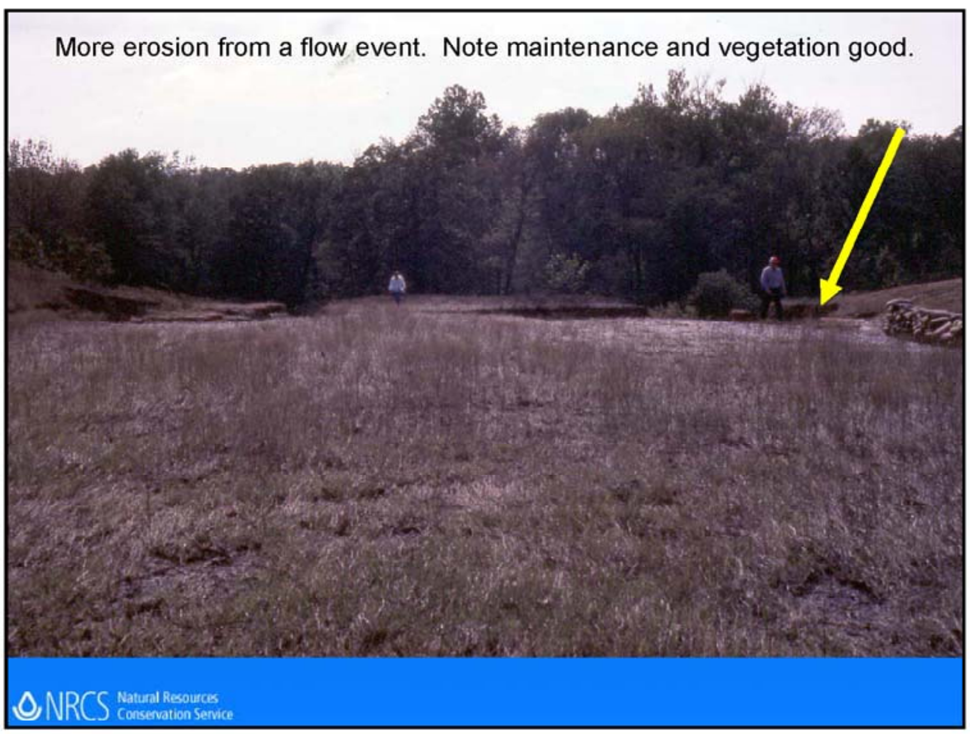

Same spillway after the flow event. Minor damage.
NRCS Natural Resources Conservation Service


Damage to dam from overtopping – about 0.5'
NRCS Natural Resources Conservation Service


Homogeneous fill ??
NRCS Natural Resources Conservation Service


Spillway with debris from flow event and vegetation.
2001 8 8


Erosion in spillway from a flow event.
NRCS Natural Resources Conservation Service


More erosion from a flow event. Note maintenance and vegetation good.
NRCS Natural Resources Conservation Service

Headcut erosion from flow event.

NRCS Natural Resources Conservation Service

The End

Presentation 13:
Earth Spillways — State of Practice and Research Needs

Spillway Design 101

- Determine routed discharge flow
- Size channel for desired flow
  - Broad Crested Weir ($Q = c\,L\,H^{3/2}$)
  - Manning's equation
  - HEC-RAS (HEC-2)
- Check channel flow velocity
  - NRCS Bulk length procedure (SITES)
  - HEC-RAS
- Armor (concrete, rock) or enlarge

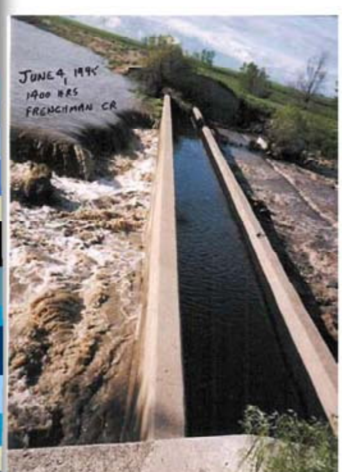
Bulk Length / Sill Walls

-soil type

-time of flow

-depth of wall/ width

Frenchman Creek



Burgess #1

Discharge co-efficient

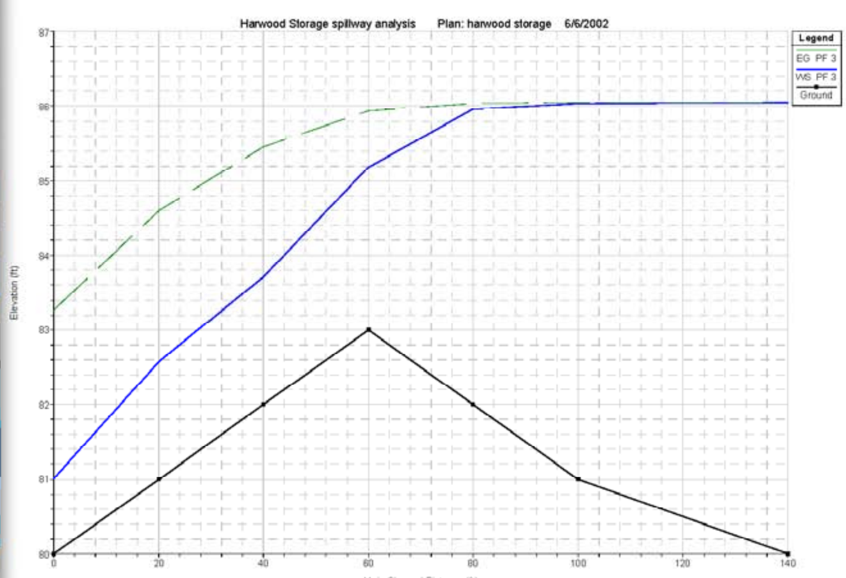
$$Q = c\ L\ H^{3/2}$$

What is correct value for "c";

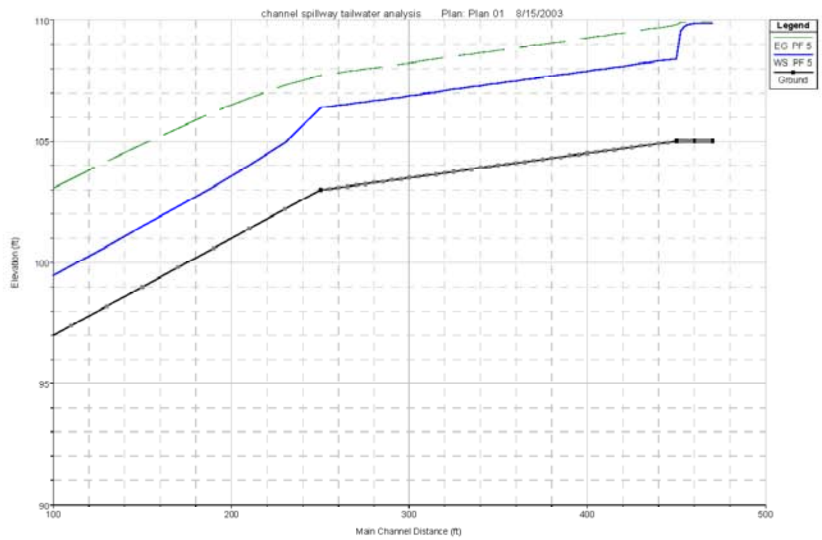
-broad crested weir? (approx. 2.6-3.1)

-Uniform flow using Manning's eq.?

-Tailwater analysis -> C = approx. 1.5 – 4.1 !!



C = 2.5



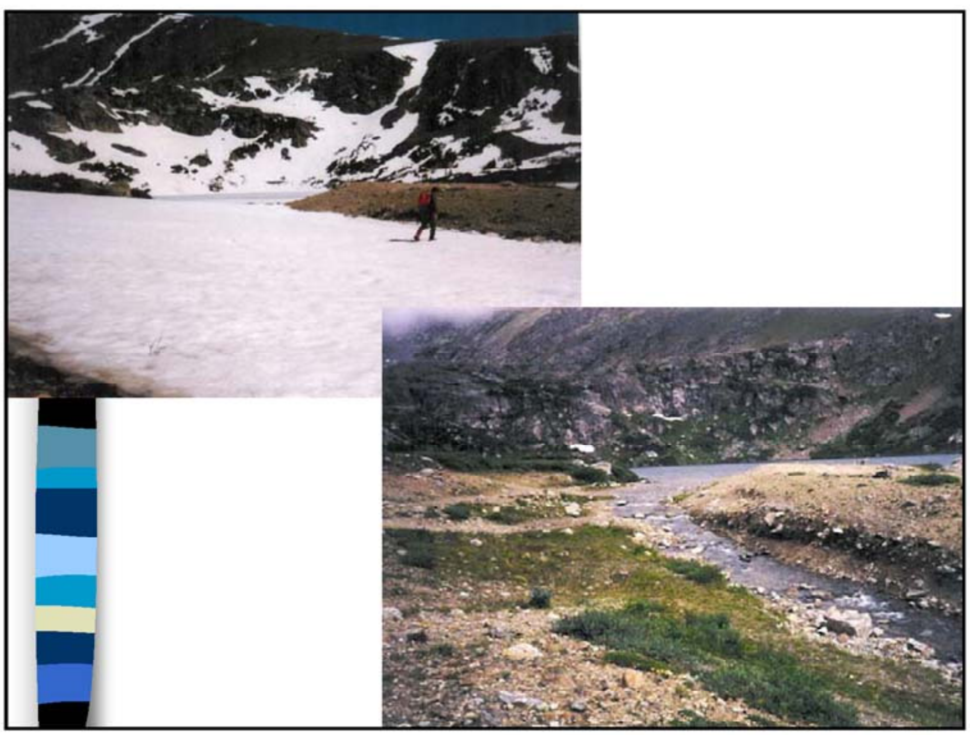
C = 4.0

Ice/ Snow blockage

-snow depth

-melting/ clearing

Design to keep spillway open despite snow cover?



Precipitation in High Mountain Regions

There has been some research to date suggesting that high mountains, and orographic effects do not correlate with published HMR data (Jarrett). Other research indicates "rain shadow" effects (Henz, Tomlinson).

Research Needs:

- Design criteria for:
  - Flow capacity; C factor, bulk length
  - Sill wall; depth, spacing
  - Headcutting
- Ice/ Snow blockage, and melting
- HMR design indices for orographic effects

Presentation 14:
Issues and Research Needs Related to Hydraulics for State Regulated Dams

Issues and Research Needs Related to Hydraulics for State Regulated Dams

By

Francis E. Fiegle II, P.E.

Georgia Safe Dams Program

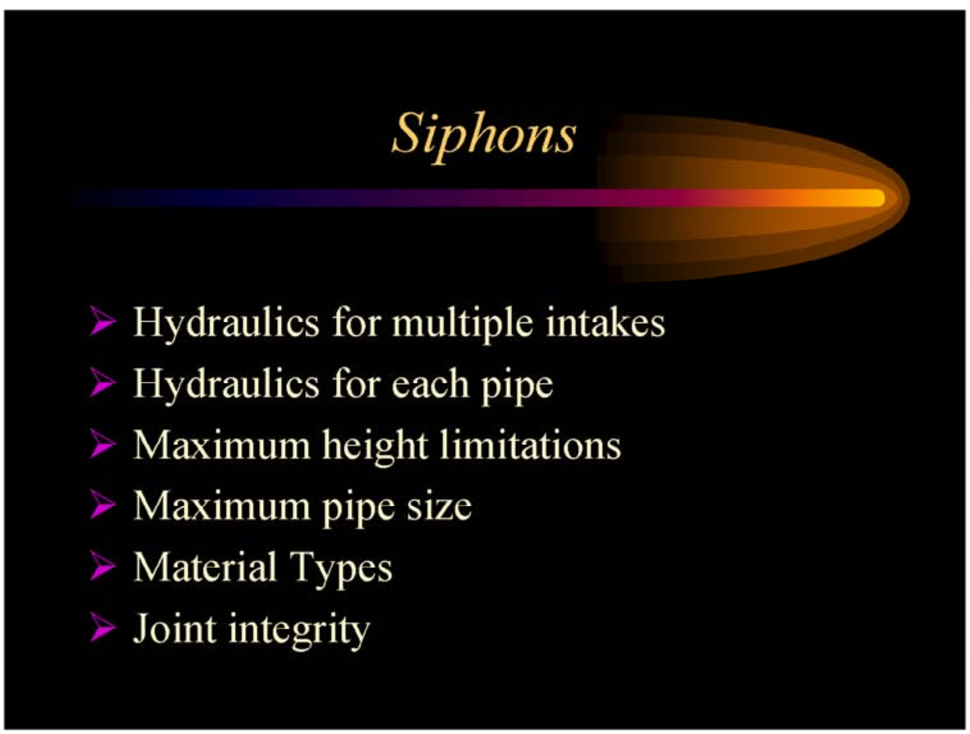
Issues and Research Needs Related to Hydraulics for State Regulated Dams

States regulate over 90 % of the dams listed on the National Inventory of Dams.

State Survey

30 states responded

- Types of spillways?
- PVC siphon spillways?
- Ice and snow effects on hydraulics?
- Skimming flows on stepped spillways?
- Questions about hydraulics of spillways?
- Adequate training?
- What are the issues?



Siphons
Hydraulics for multiple intakes
Hydraulics for each pipe
Maximum height limitations
Maximum pipe size
Material Types
Joint integrity

Ice and Snow

- Hydraulic changes due to ice
- Cost effective designs to minimize ice jams and icing impacts
- Ice/snow removal without site visits (especially small dams)

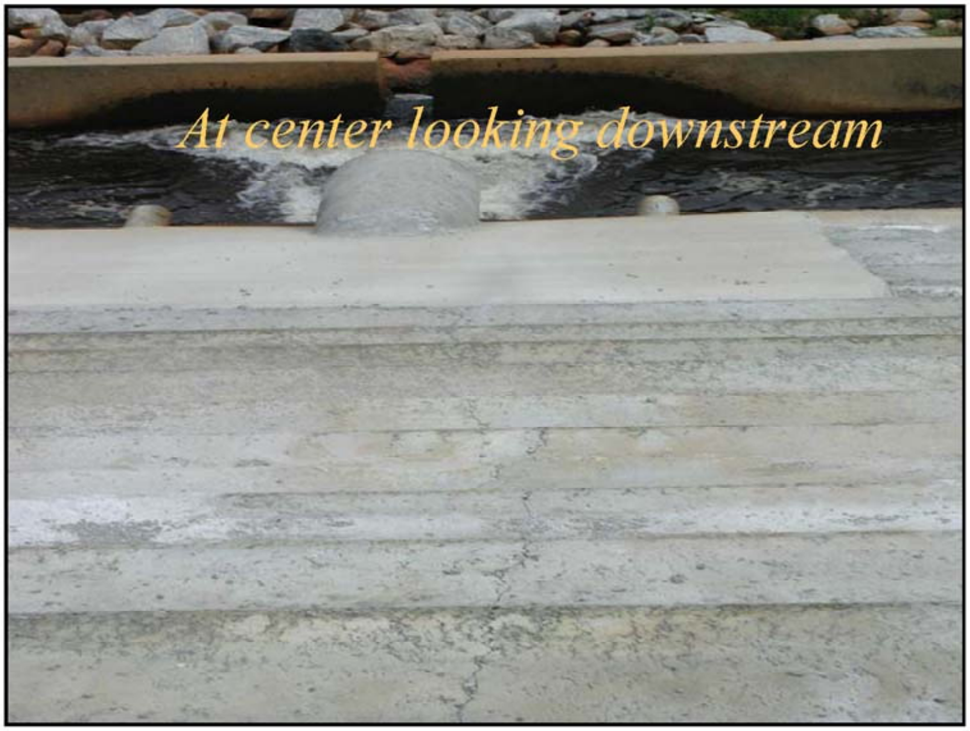
Drop Structures

- Slugging flows in deep conduits (prevention)
- Loading of pipe/drop structure due to slugging flows
- Rational approach to air demand & minimum air pressure in outlet pipes
- Deflector plates in drop structures (are they necessary)

Stepped Spillways (RCC)

- Changing hydraulics due to weathering of steps
- Skimming flows at high volume flows
- Hydraulic Jumps in stilling basins (Have we forgotten lessons learned in concrete chute design?)
- Cracking in steps/stilling basins

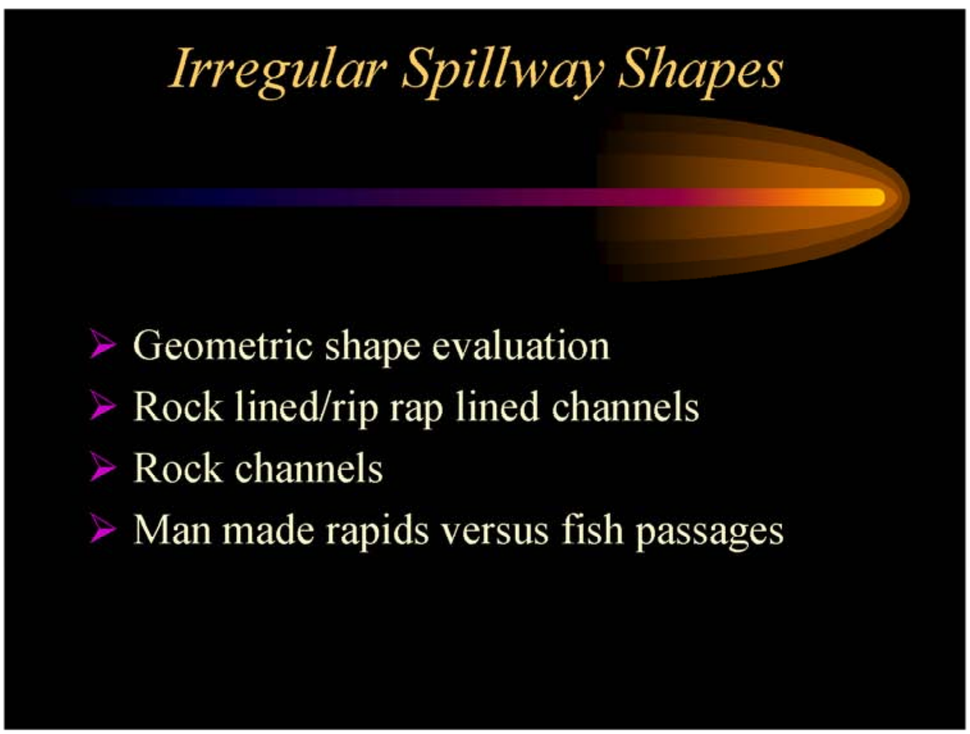
Looking upstream@ center
towards ogee crest from
downstream



Concrete Blocks

- Performance during extreme floods
- Debris flows
- Long term material performance

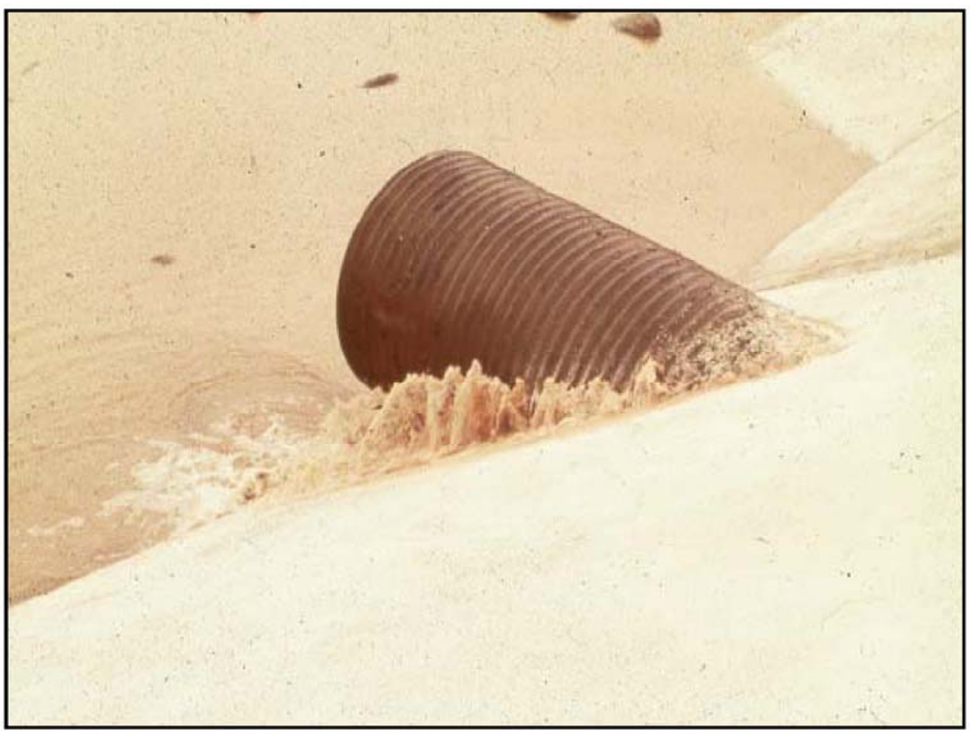

Hydraulic Coefficients
Overstated coefficient capacities
Better software
Realistic and relevant evaluations



Irregular Spillway Shapes
Geometric shape evaluation
Rock lined/rip rap lined channels
Rock channels
Man made rapids versus fish passages

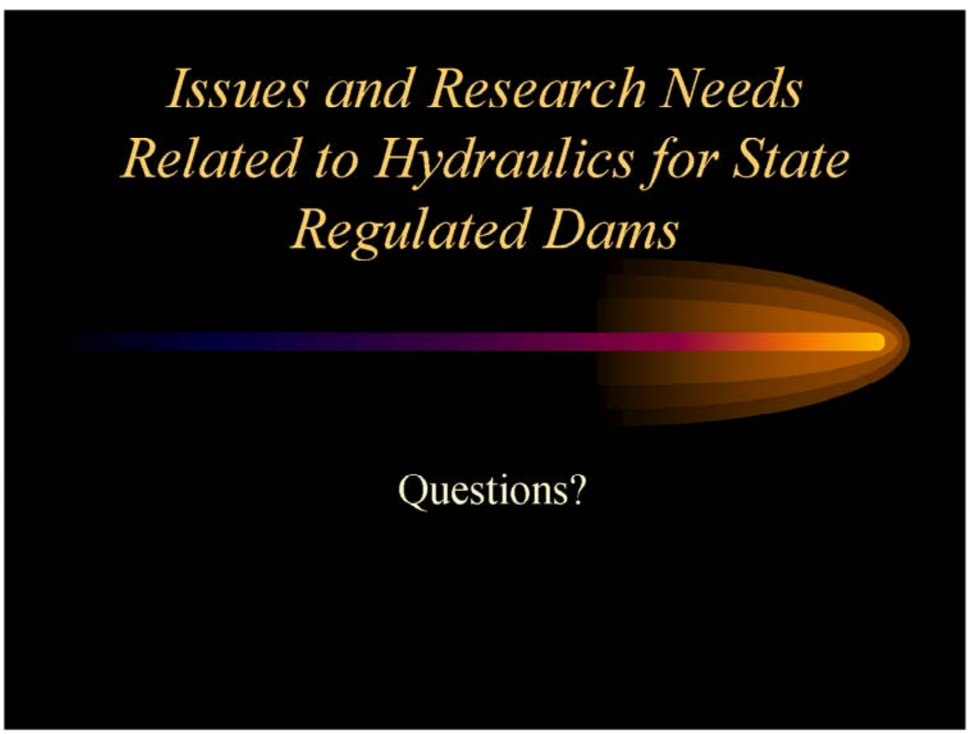
Miscellaneous

- Corrugated metal pipe life
- Overtopping of earth dams
- Rip rap / concrete drop structure design
- Flash boards that do not fail
- Application of earthquake loading forces with hydraulic and other loading conditions. When?



Research Results Need to be Relevant and Reliable

The results need to be proven in the field in long term applications. Small dam owners do not have the financial capability to do the same upgrade twice.

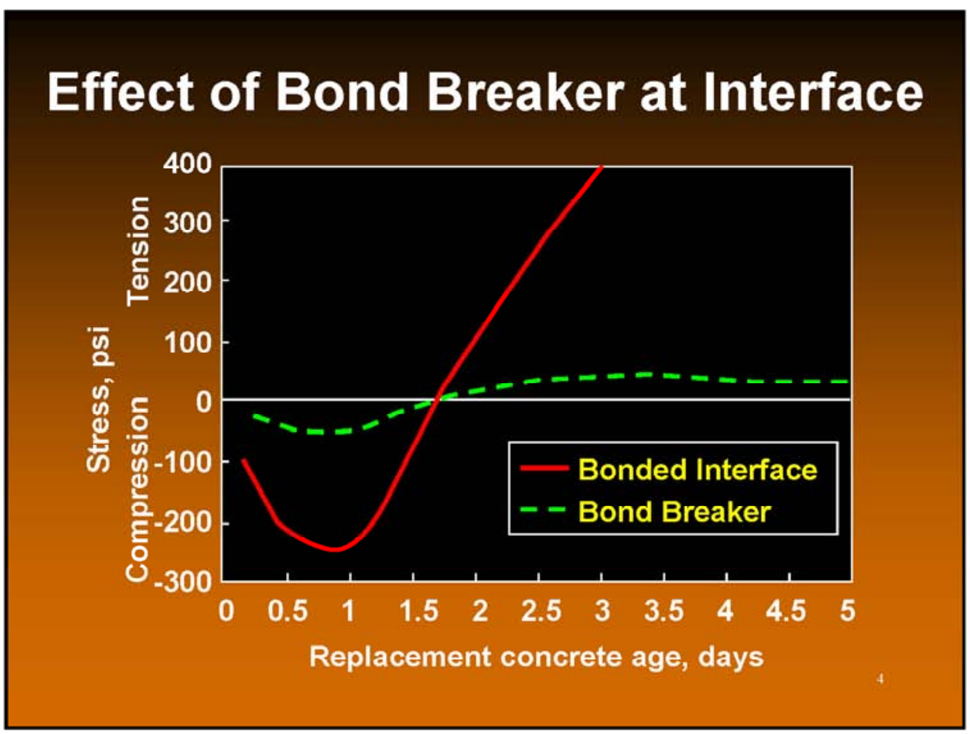

Issues and Research Needs Related to Hydraulics for State Regulated Dams
Questions?

Presentation 15:
Concrete Spillway Repairs


Spillway Repairs
Jim McDonald
Consulting Engineer
Clinton, MS


Premature Repair Failures

Repair/Substrate Compatibility
Definition - The capacity of two or more entities to combine or remain together without undesirable aftereffects: mutual tolerance.
SHOTCRETE
Incompatible
Compatible
3



Effect of Bond Breaker at Interface
Stress, psi
Tension
Compression
400
300
200
100
0
-100
-200
-300
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Replacement concrete age, days
Bonded Interface
Bond Breaker
4

Effect Of Restraint

Performance Criteria

Cement-Based Materials

12 Repair Materials

Field Performance Tests

Laboratory Tests

Correlation

Dimensional Compatibility

6

Performance Criteria

Laboratory Tests

- Drying Shrinkage
  - –Unrestrained
  - –Restrained
- Modulus of elasticity
- Creep
- Thermal expansion
- Strength

7

Performance Criteria

Field Tests

- 3 exposure sites (FL, IL, & AZ)
- 3 repairs with each of the 12 materials
- Conduct restrained shrinkage tests
- Monitor performance

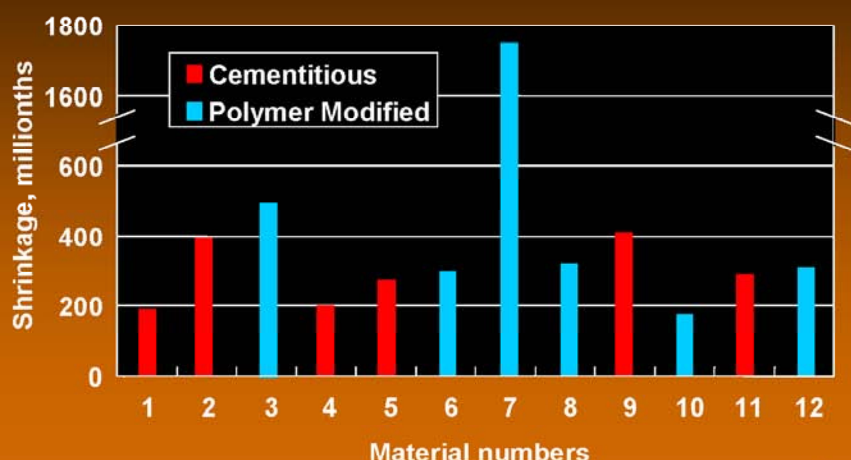
8

Field Exposure Tests

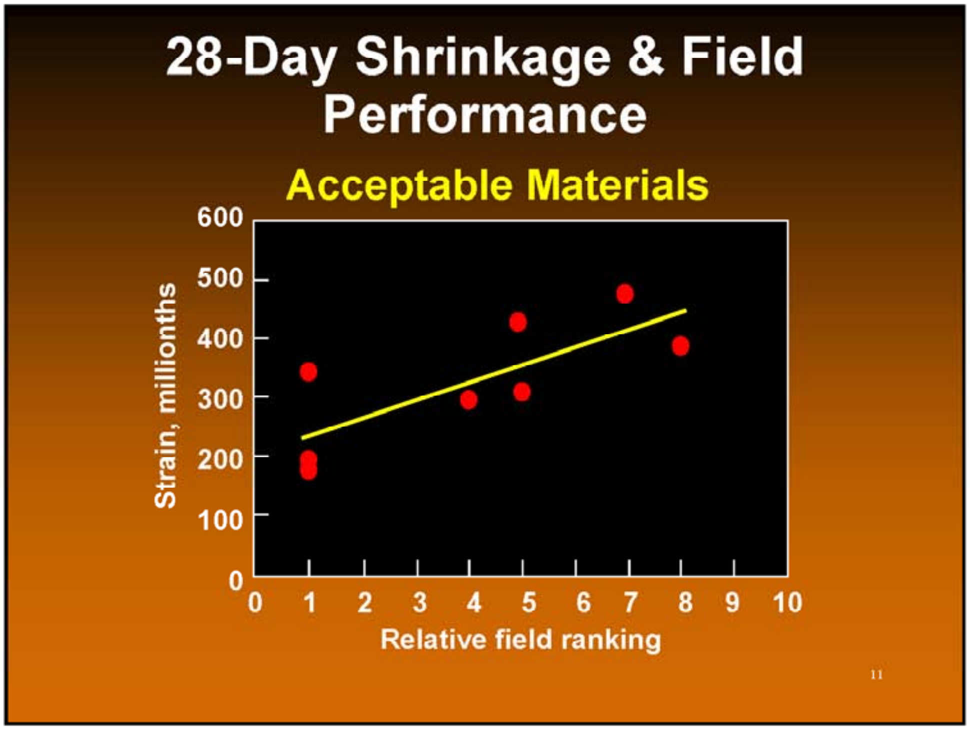
Relative Performance Ratings

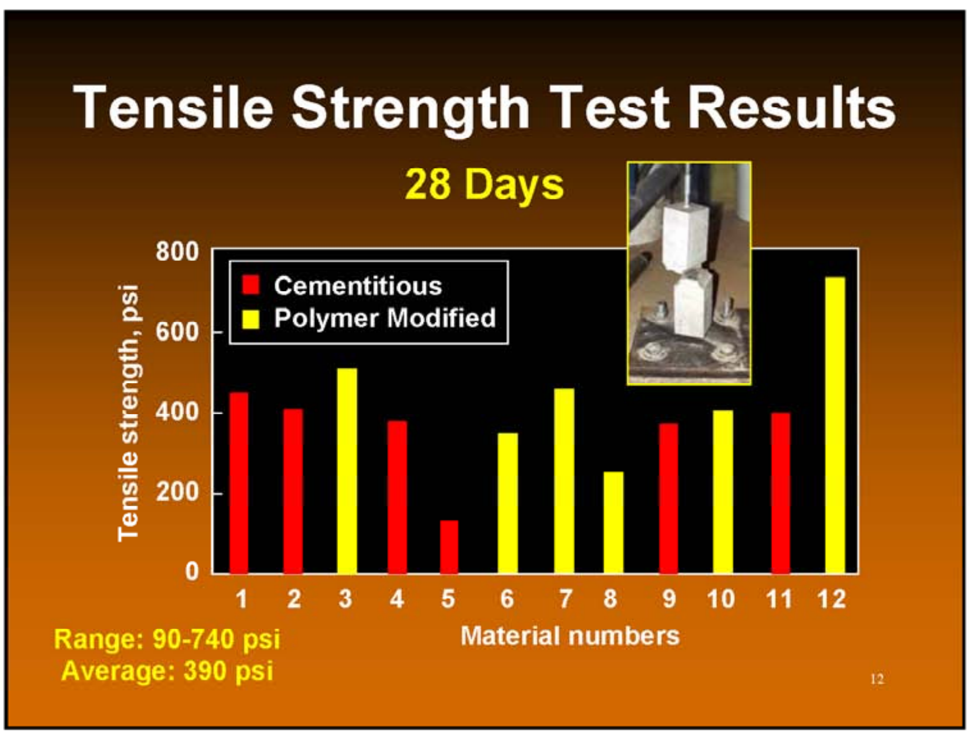
Drying Shrinkage

50% RH, 28 Days



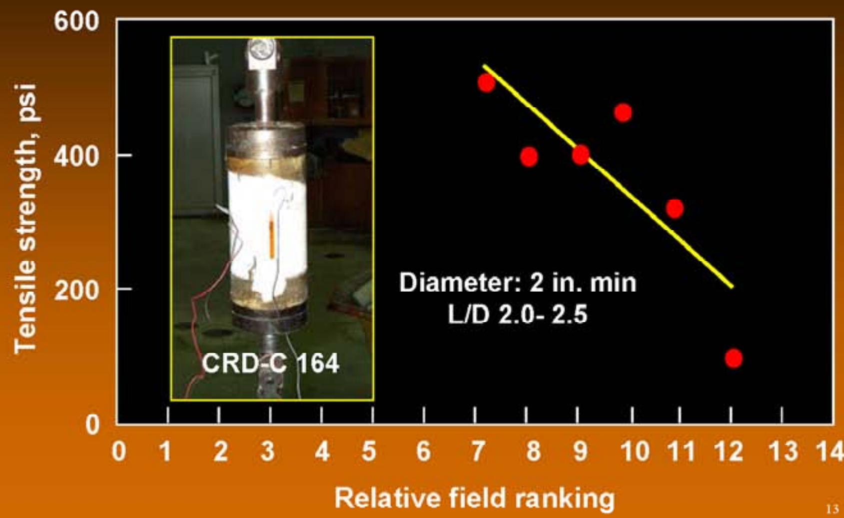
10


28-Day Shrinkage & Field Performance
Acceptable Materials
Strain, millionths
0
100
200
300
400
500
600
0 1 2 3 4 5 6 7 8 9 10
Relative field ranking
11


Tensile Strength Test Results
28 Days
Cementitious
Polymer Modified
Tensile strength, psi
0
200
400
600
800
1 2 3 4 5 6 7 8 9 10 11 12
Material numbers
Range: 90-740 psi
Average: 390 psi
12

Tensile Strength & Field Performance

Marginal and Unsatisfactory Materials



Performance Criteria for Cement-Based Repair Materials*

Property	Test Method	Requirement
Tensile strength, min	CRD-C 164	400 psi
Modulus of elasticity, max	ASTM C 469	3.5×10^6 psi
Thermal coefficient, max	CRD-C 39	7 millionths/deg F
Drying shrinkage, max	ASTM C 157 (Modified)	
28 days		400 millionths
1 year		1,000 millionths
Restrained shrinkage	Ring Method	
Cracks		None < 14 days
Implied strain (1 yr), max		1,000 millionths

* http://www.wes.army.mil/SL/HPMS/bulletins.htm

14

Laboratory/Field Correlation

Satisfactory Performance

Field Rank	Mat'l No.	Tensile Strength, (>400)	Modulus of Elasticity (<3.5)	Thermal Coefficient (<7)	Drying Shrinkage: 28 Days (<400)	Drying Shrinkage: Peak (<1,000)	Ring Test: 1st Crack (>14)	Ring Test: Implied Strain (<1,000)
1	1	451	2.8	5.8	178	366	6	667
1	4	348	3.8	8.3	201	703	140	560
1	11	390	5.9	7.6	339	641	14	810
4	12	742	3.0	9.3	293	634	None	0
5	8	215	2.7	9.2	305	1,109	8	1,222
5	9	323	2.7	6.9	429	877	23	955

15

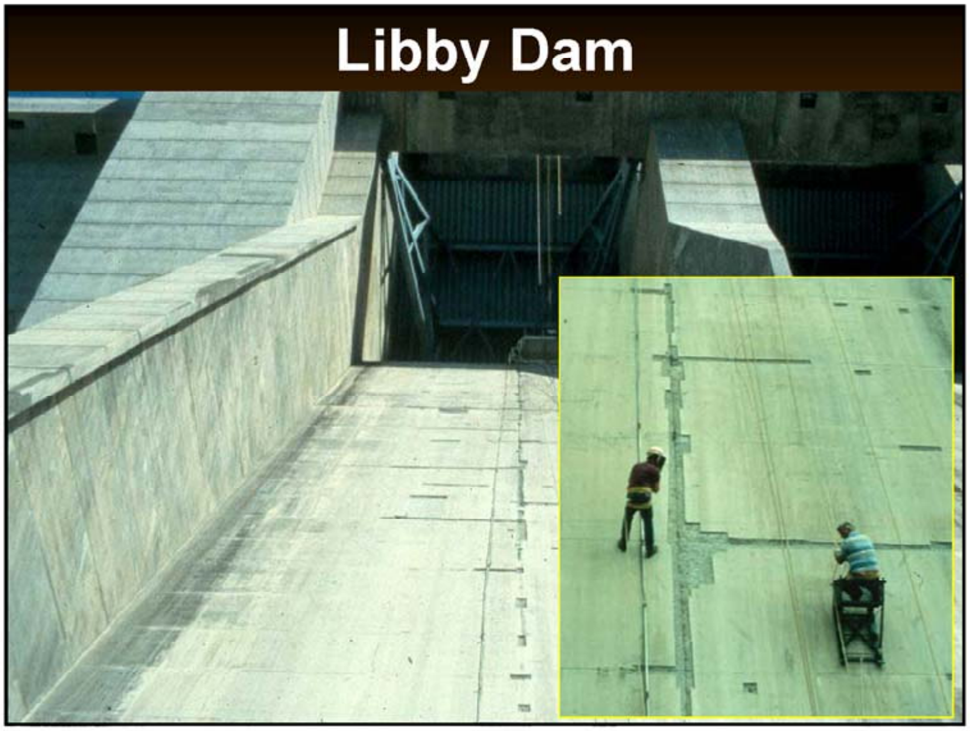
HPM&S

High-Performance Materials and Systems Research Program

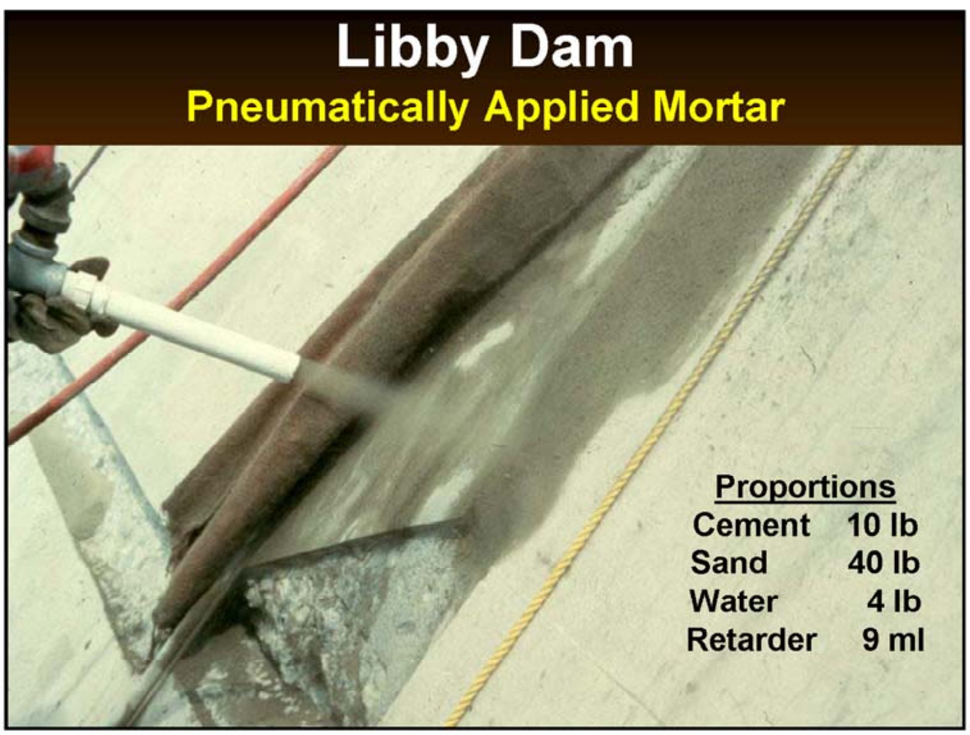
http://www.wes.army.mil/SL/HPMS/bulletins.htm

"Performance Criteria for Dimensionally Compatible Repair Materials" (Jan 2000) 0.4 MB, PDF file
[Key words: cement-based materials, concrete repair, drying shrinkage, performance criteria, tensile strength]

16



Libby Dam



Libby Dam
Pneumatically Applied Mortar
Proportions
Cement 10 lb
Sand 40 lb
Water 4 lb
Retarder 9 ml

Libby Dam

Mortar Gun

- Easily assembled from readily available material
- Only a few critical dimensions
- Can be operated by personnel without extensive training
- EM 1110-2-2002, Evaluation and Repair of Concrete

Libby Dam

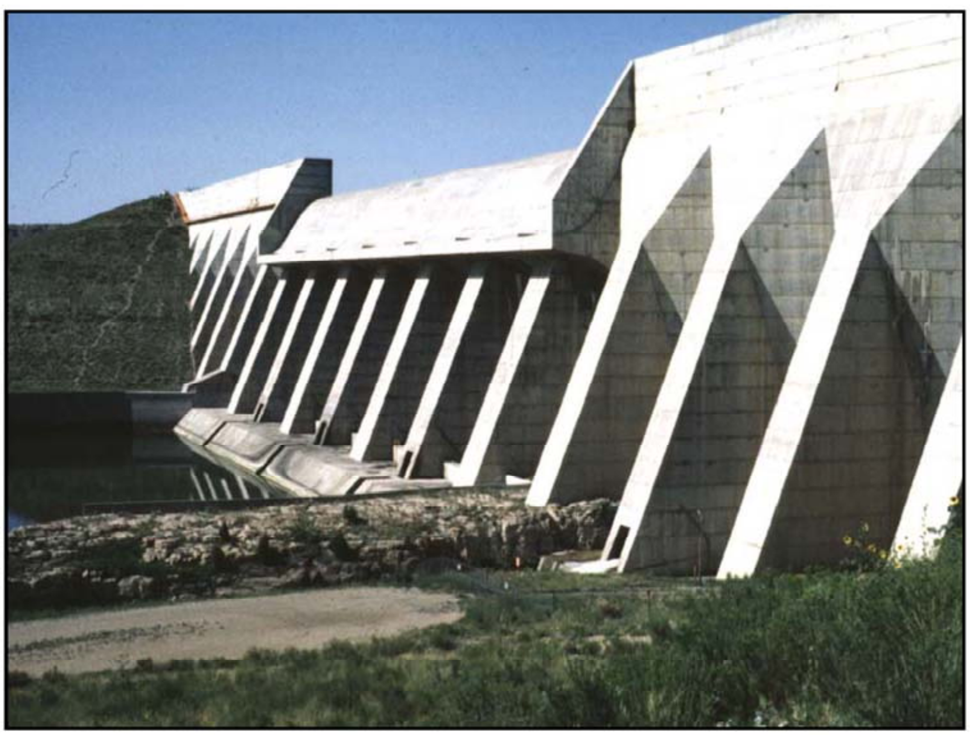

Research Needs
• Tools to reduce O&M costs and extend functional life of existing water-resource infrastructure
– Sustainable repair technology
– Innovative repair materials that satisfy compatibility requirements
– Underwater concrete repair
– Inspection techniques

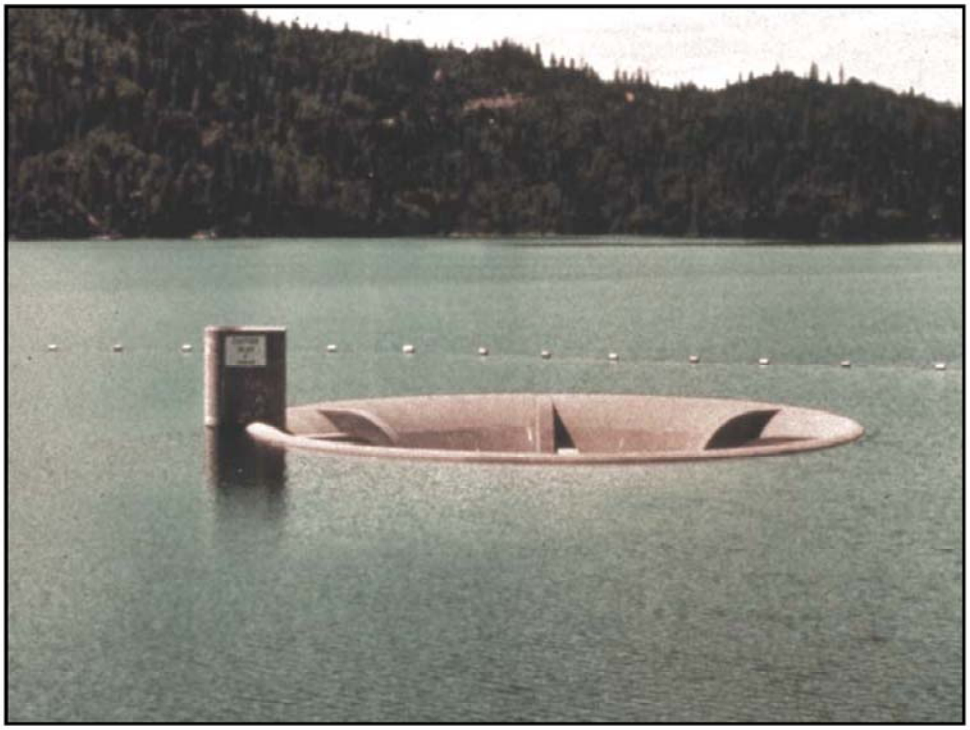

Research Needs
• Reliable NDT equipment/procedures to evaluate gate anchorage systems
– Detect corrosion activity and determine rate
– Determine stress levels, particularly post-tensioned systems
• Materials and methods to mitigate ASR in existing mass concrete structures
• Capture corporate knowledge and promote technology infusion into the field

Presentation 16:
Inspection of Concrete Spillways —
Gated and Uncontrolled

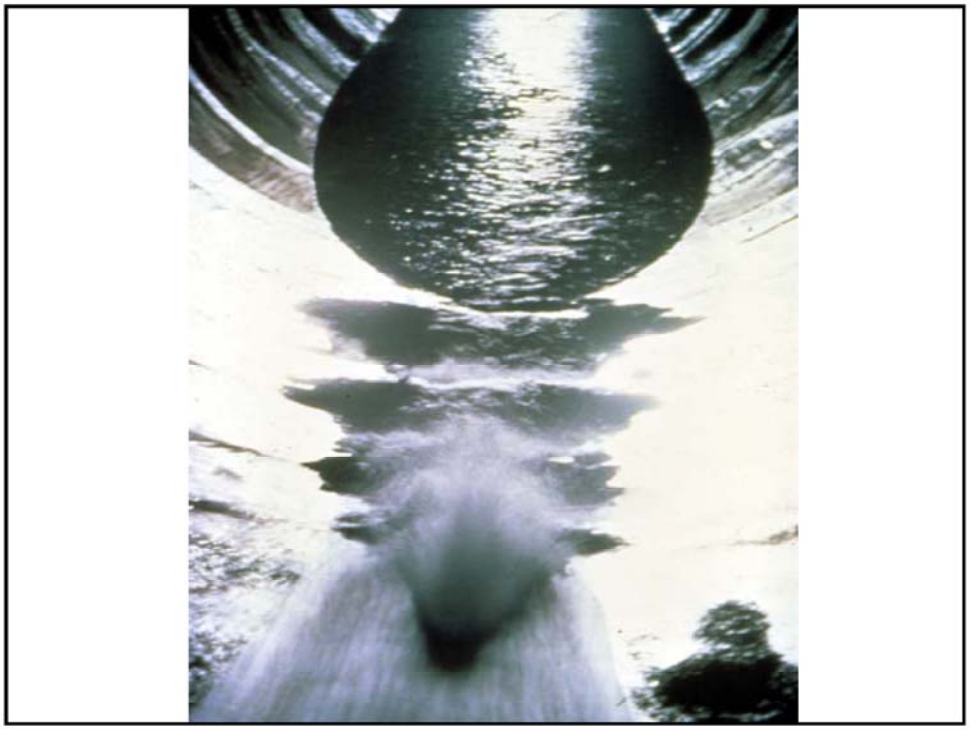
Inspection of Spillways

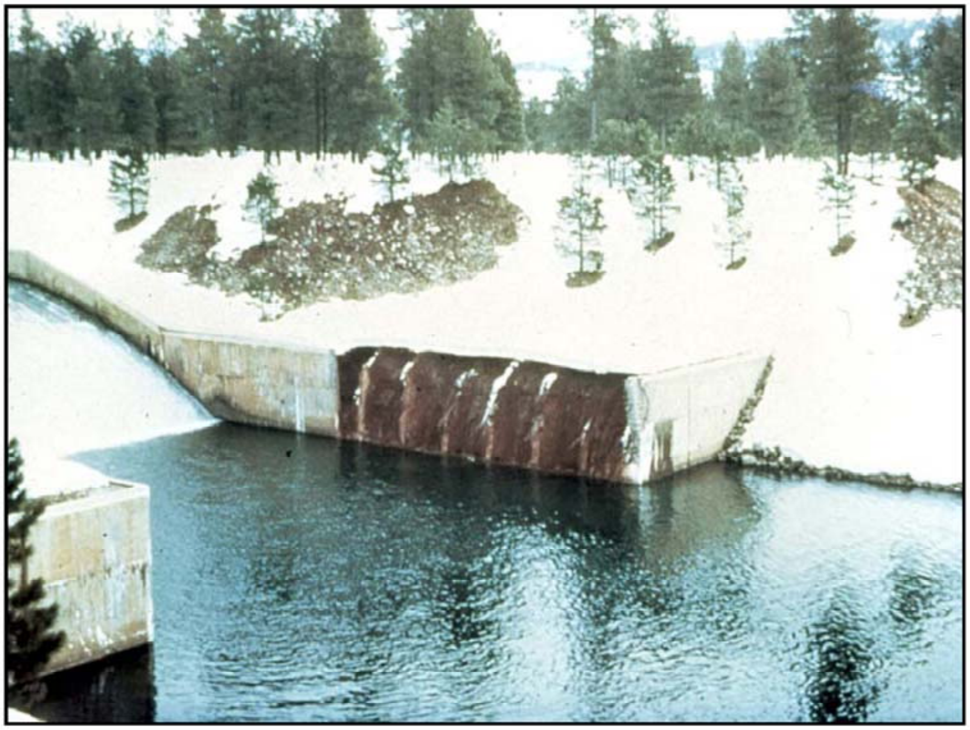
Gated
and
Uncontrolled





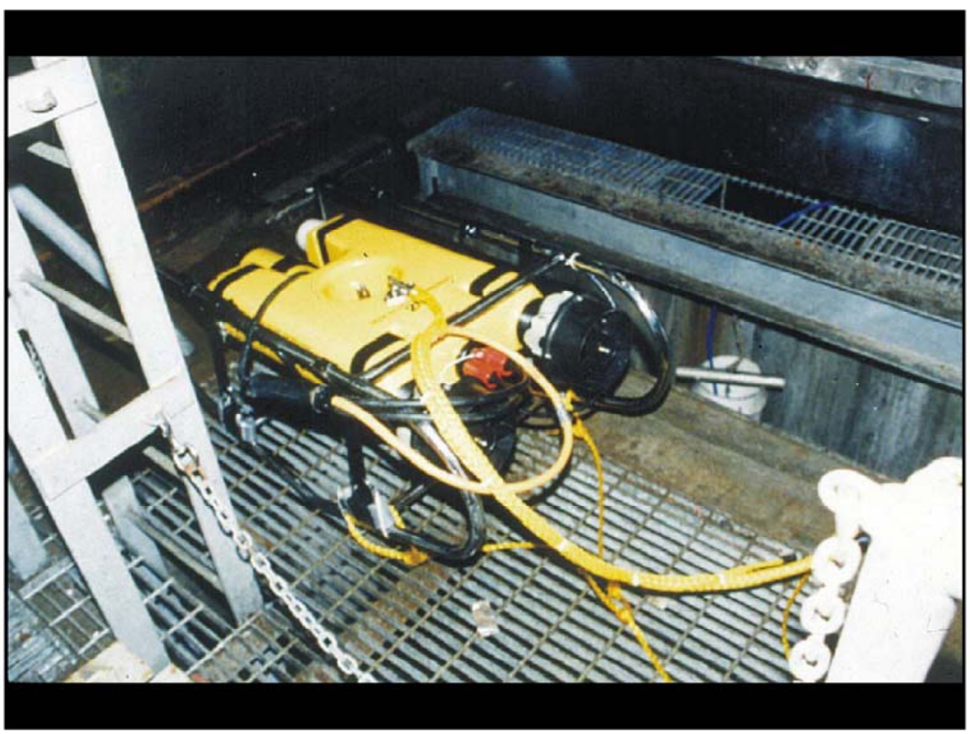
Chutes, Tunnels, & Stilling Basins



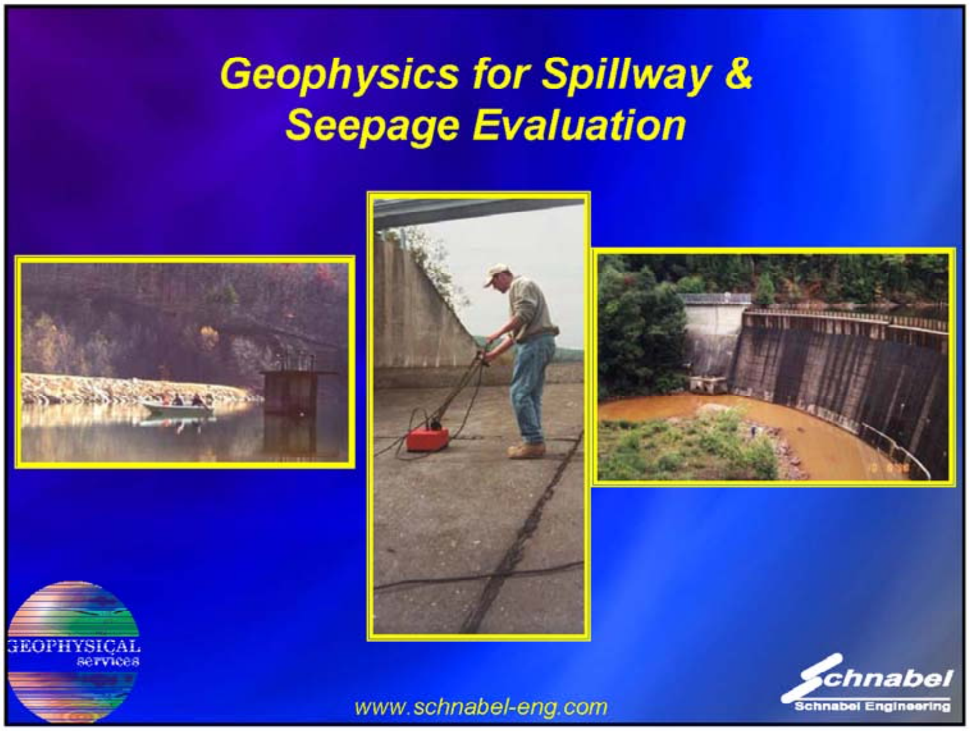


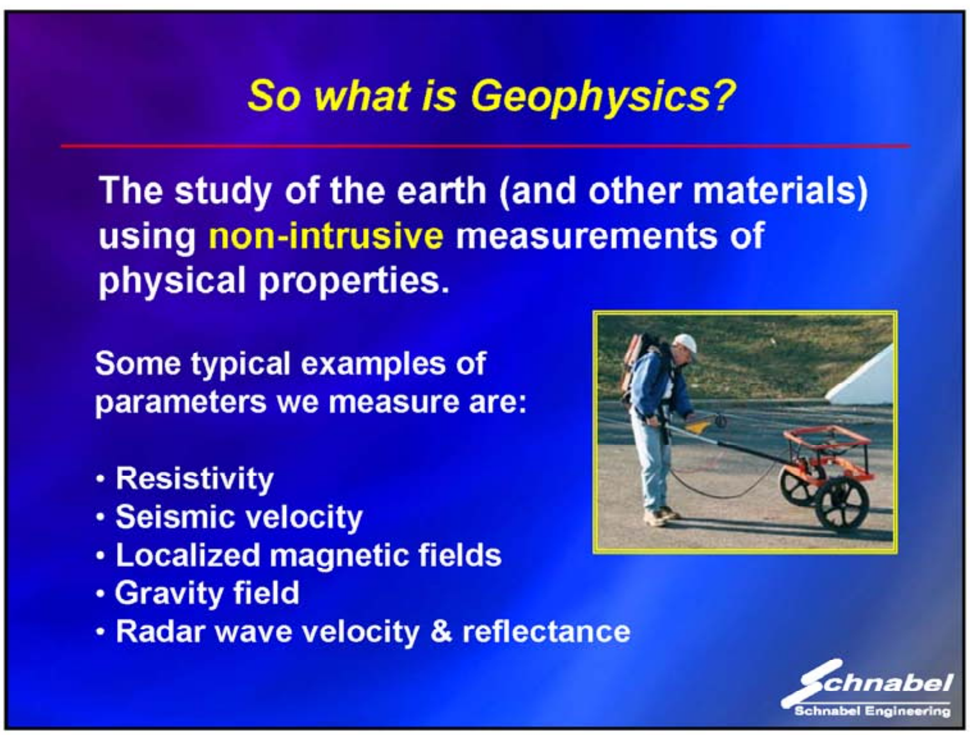
Inspection

Techniques



Presentation 17: Geophysics for Spillway and Seepage Evaluation


Geophysics for Spillway &
Seepage Evaluation
GEOPHYSICAL
services
www.schnabel-eng.com
Schnabel
Schnabel Engineering


So what is Geophysics?
The study of the earth (and other materials) using non-intrusive measurements of physical properties.
Some typical examples of parameters we measure are:
• Resistivity
• Seismic velocity
• Localized magnetic fields
• Gravity field
• Radar wave velocity & reflectance
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How is Geophysics Helpful?

- Non-Invasive "Screening" Tool
- Does not Generate Waste (Environmental)
- Supplements Subsurface Data Between Borings
- Help Subsurface Characterization by "Seeing the Big Picture"
- Quickly Search for Specific Targets
- Trace What is Not Easily Seen (Water Seepage)
- In-Situ Estimation of Engineering Properties of Subsurface Earth Materials

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Some of Our Common Tools

- Resistivity Sounding and Imaging (2-D & 3-D)
- Electromagnetics (EM)
- Ground Penetrating Radar (GPR)
- Magnetics
- Induced Potential (IP)
- Spontaneous Potential (SP)
- Seismic Techniques
- Microgravity

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What Can you Do with Geophysics?

- Trace Seepage through Embankment Dams/ Ponds
- Define Limits of Voids underneath Spillway Slabs
- Determine Shear Wave Velocities for Seismic Design
- Karst Investigations
- Detect Abandoned Mines
- Map Voids and Sinkhole Potential
- Subsurface Stratigraphy
- Define Depth of Fill
- Characterize Geologic Structure
- Determine Depth to Bedrock
- Determine Depth to Non-rippable Bedrock
- Map Contaminant Plumes
- Locate steel Reinforcing in Concrete Slabs
- Locate Underground Storage Tanks (USTs)
- Define Limits of Abandoned Landfills
- Confirm Fractures in Bedrock for Groundwater Well Siting
- Assess Concrete Quality
- Monitor Vibrations from Blasting/ Construction/ Demolition
- Define GW Well Capture Zones in Fractured Bedrock
- Locate Buried Metallic Debris
- ....

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Performing Geophysical Investigations

Investigation Design → Data Collection → Data Reduction → Analysis → Interpretation

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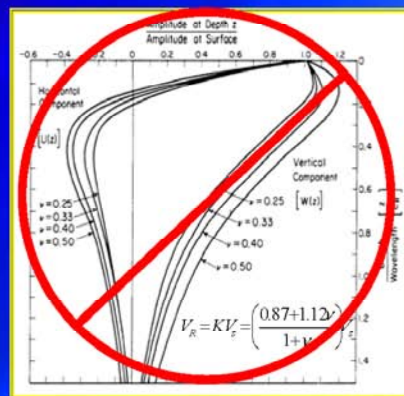
Object of This Presentation

NOT to teach the theory of geophysics;

RATHER, to provide examples where geophysics is used to provide valuable information.



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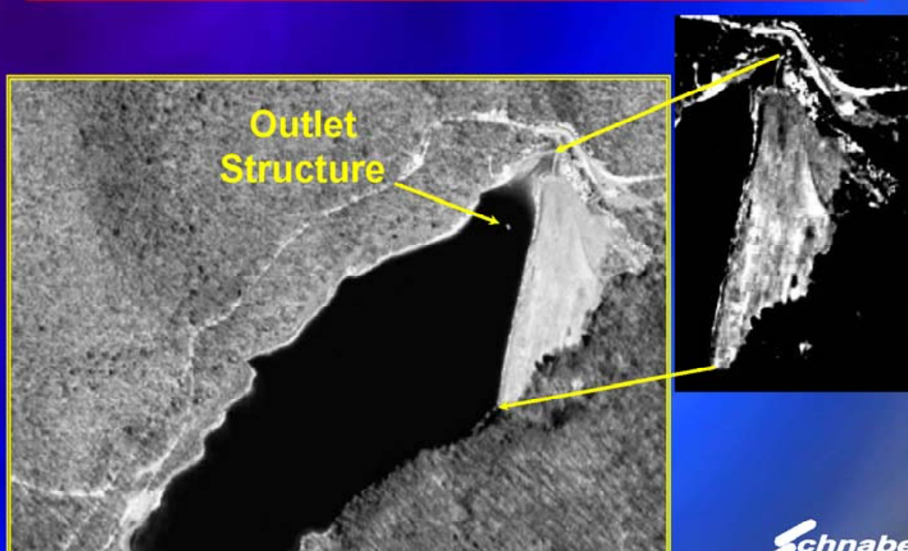
Example 1, Moore's Creek Dam, Lexington, VA



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Sinkhole in downstream face above spillway conduit
Boil at Toe of Dam
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Geophysical Investigation to Define Seepage Pathways
Complimentary Geophysical Techniques
• Self Potential (SP)
(measures voltages from water moving through porous medium)
• Two-Dimensional Resistivity
(measures low resistivity zones caused by increased water saturation)
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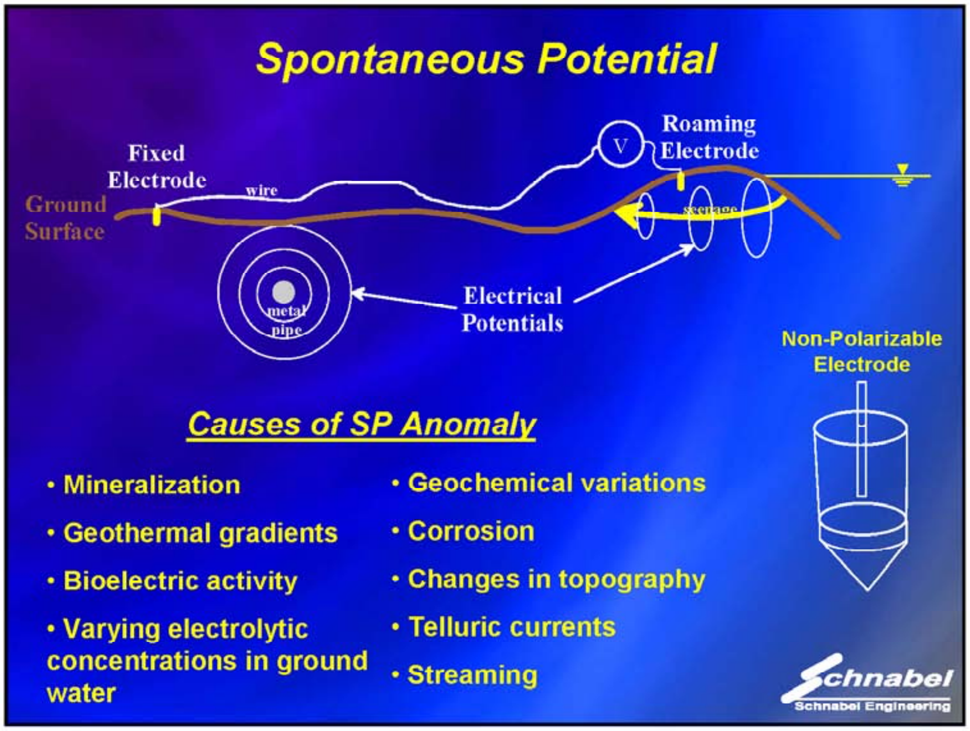
Spontaneous Potential
Fixed
Electrode
wire
Ground
Surface
Roaming
Electrode
V
seepage
metal
pipe
Electrical
Potentials
Non-Polarizable
Electrode
Causes of SP Anomaly
• Mineralization
• Geothermal gradients
• Bioelectric activity
• Varying electrolytic concentrations in ground water
• Geochemical variations
• Corrosion
• Changes in topography
• Telluric currents
• Streaming
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Plan View of the Dam
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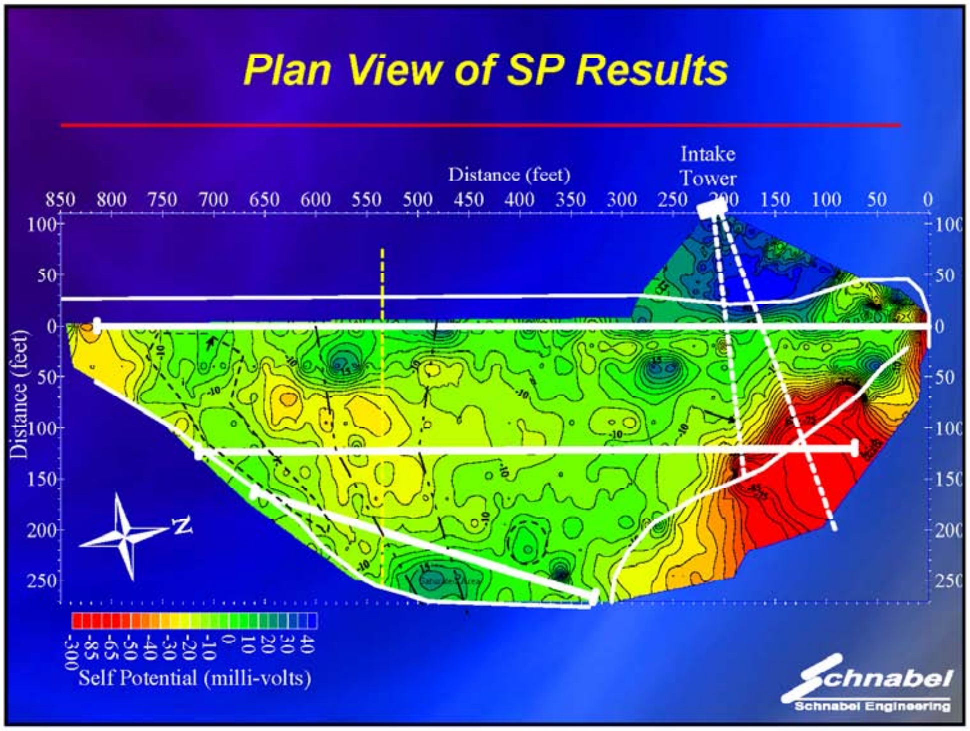
Plan View of SP Results
Intake Tower
Distance (feet)
Distance (feet)
Self Potential (milli-volts)
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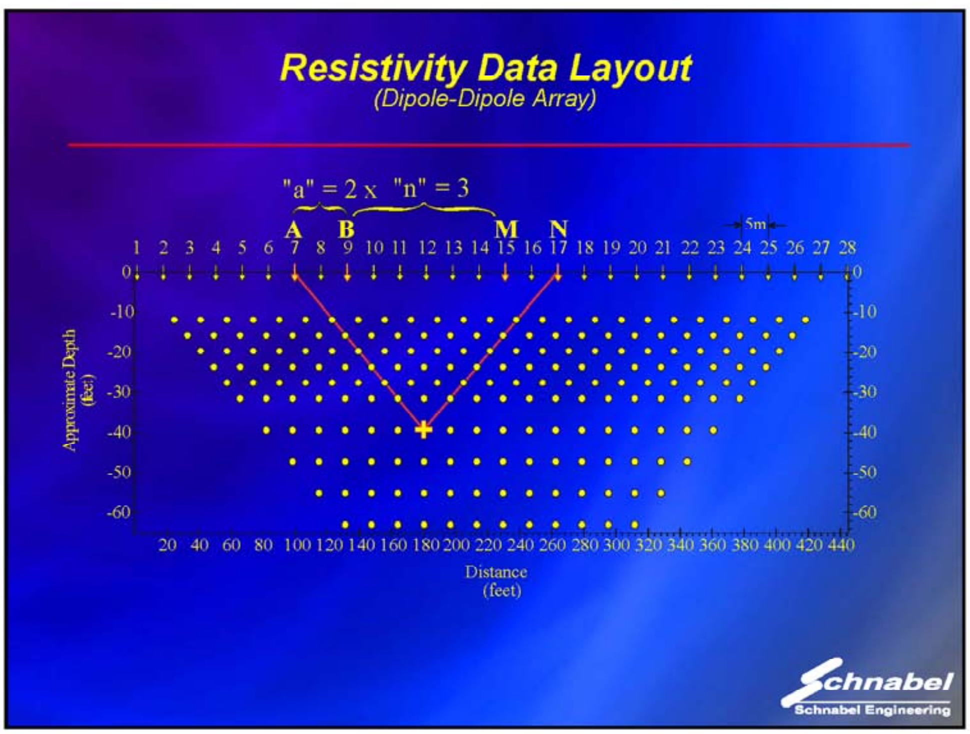
Resistivity Data Layout
(Dipole-Dipole Array)
"a" = 2 x "n" = 3
A B M N
5m
Approximate Depth (feet)
Distance (feet)
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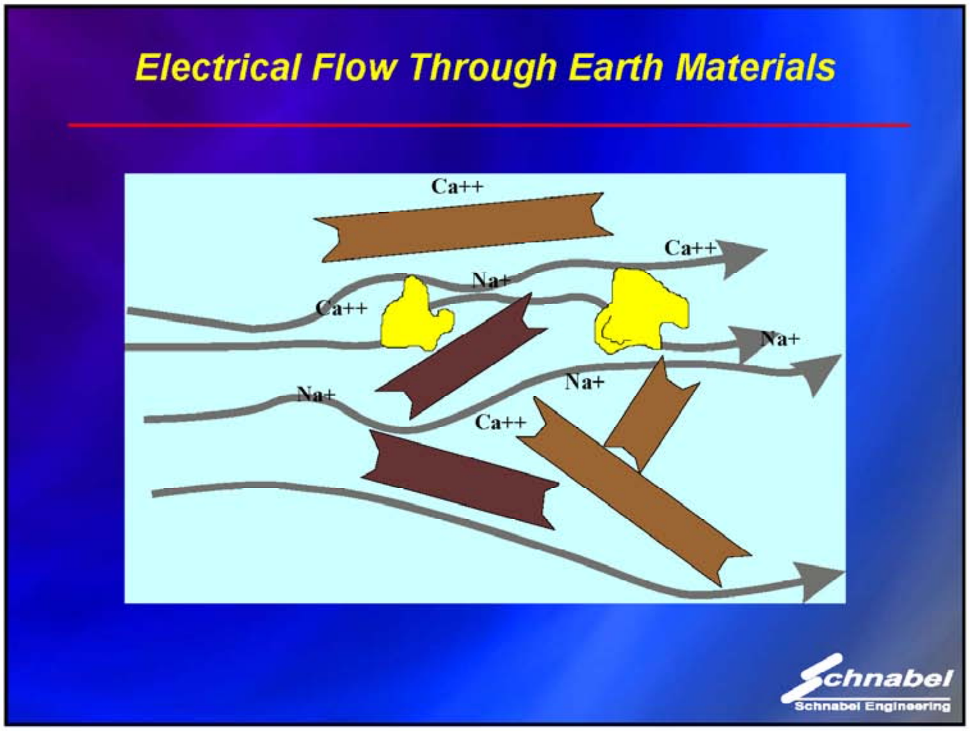
Electrical Flow Through Earth Materials
Ca++
Ca++
Na+
Ca++
Na+
Na+
Na+
Ca++
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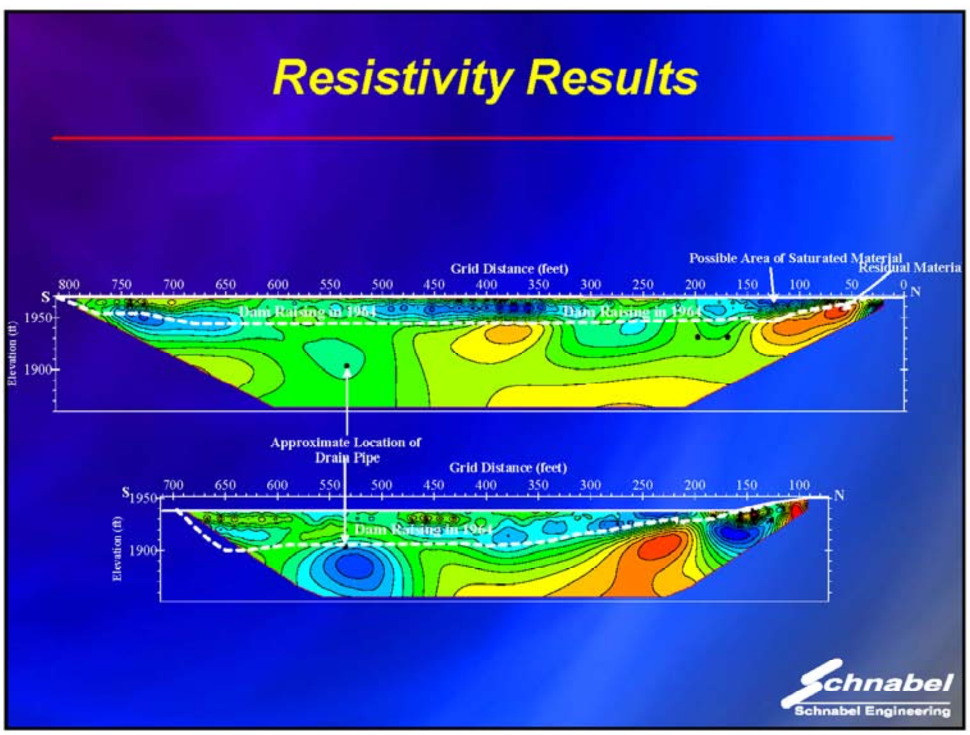
Resistivity Results
Grid Distance (feet)
Possible Area of Saturated Material
Residual Materia
Dam Raising in 1964
Dam Raising in 1964
Elevation (ft)
Approximate Location of Drain Pipe
Grid Distance (feet)
Dam Raising in 1964
Elevation (ft)
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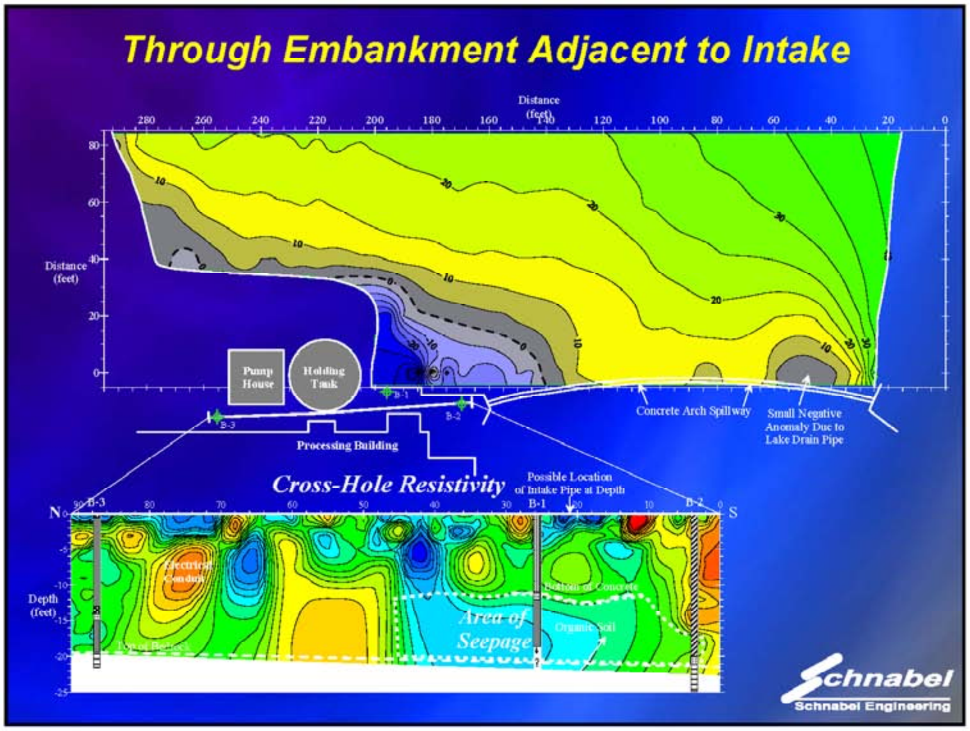
Example 2: SP On Water, Chagrin Falls, OH

Seepage Through or Around Spillway?



Through Embankment Adjacent to Intake
Distance (feet)
Distance (feet)
Pump House
Holding Tank
Processing Building
Concrete Arch Spillway
Small Negative Anomaly Due to Lake Drain Pipe
Cross-Hole Resistivity
Possible Location of Intake Pipe at Depth
N
S
B-3
B-1
B-2
Depth (feet)
Area of Seepage
Organic Soil
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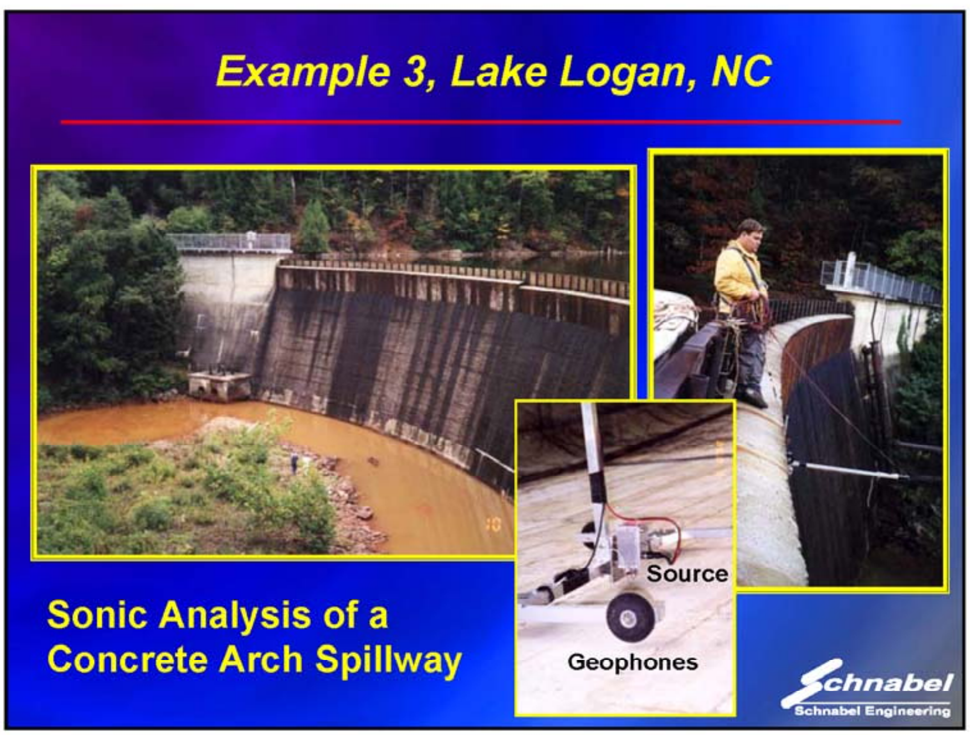

Example 3, Lake Logan, NC
Sonic Analysis of a Concrete Arch Spillway
Source
Geophones
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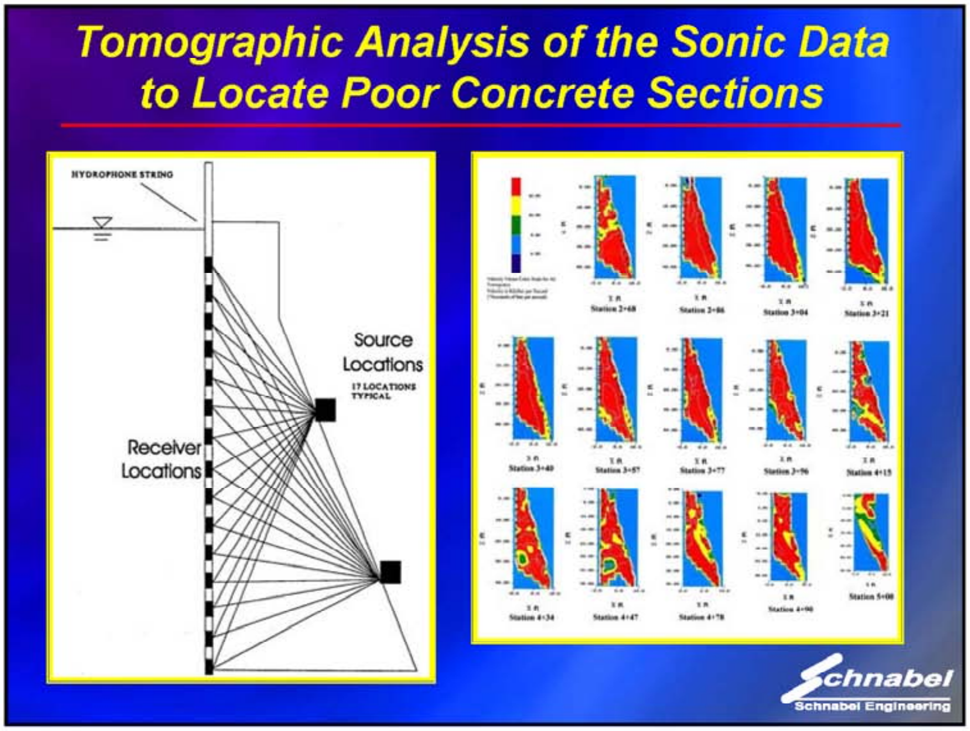
Tomographic Analysis of the Sonic Data
to Locate Poor Concrete Sections
HYDROPHONE STRING
Source
Locations
17 LOCATIONS
TYPICAL
Receiver
Locations
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Example 4, Concrete Spillway Slabs
Finding Voids
Under Spillways
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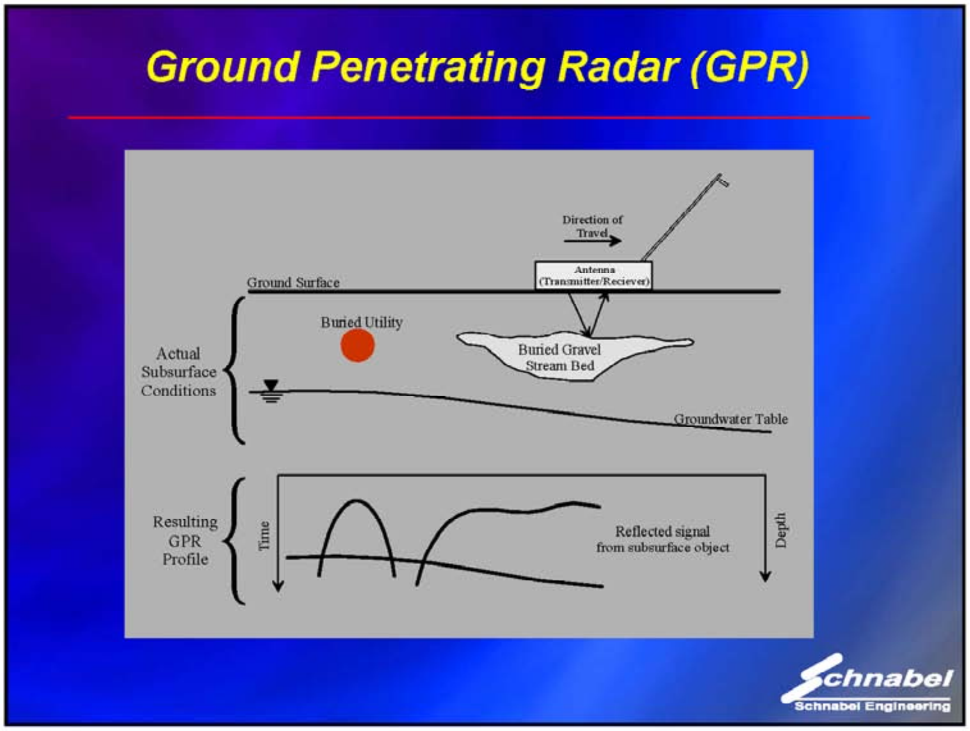
Ground Penetrating Radar (GPR)
Direction of Travel
Antenna (Transmitter/Reciever)
Ground Surface
Buried Utility
Buried Gravel Stream Bed
Actual Subsurface Conditions
Groundwater Table
Resulting GPR Profile
Time
Reflected signal from subsurface object
Depth
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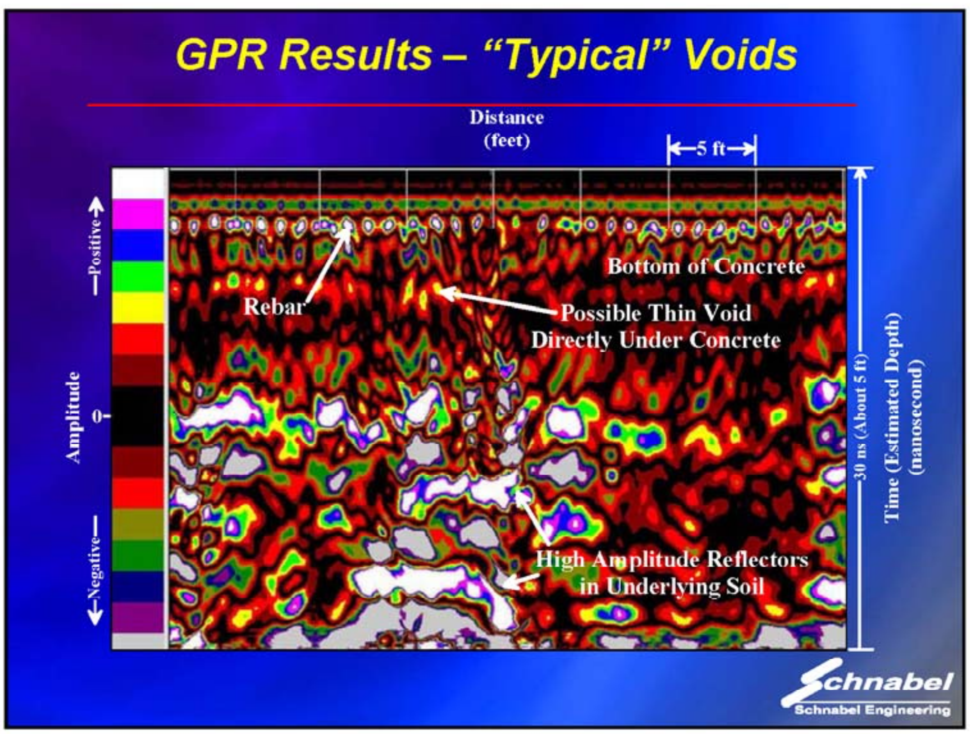
GPR Results – "Typical" Voids
Distance (feet)
5 ft
Positive
Amplitude
0
Negative
Rebar
Bottom of Concrete
Possible Thin Void Directly Under Concrete
High Amplitude Reflectors in Underlying Soil
30 ns (About 5 ft)
Time (Estimated Depth) (nanosecond)
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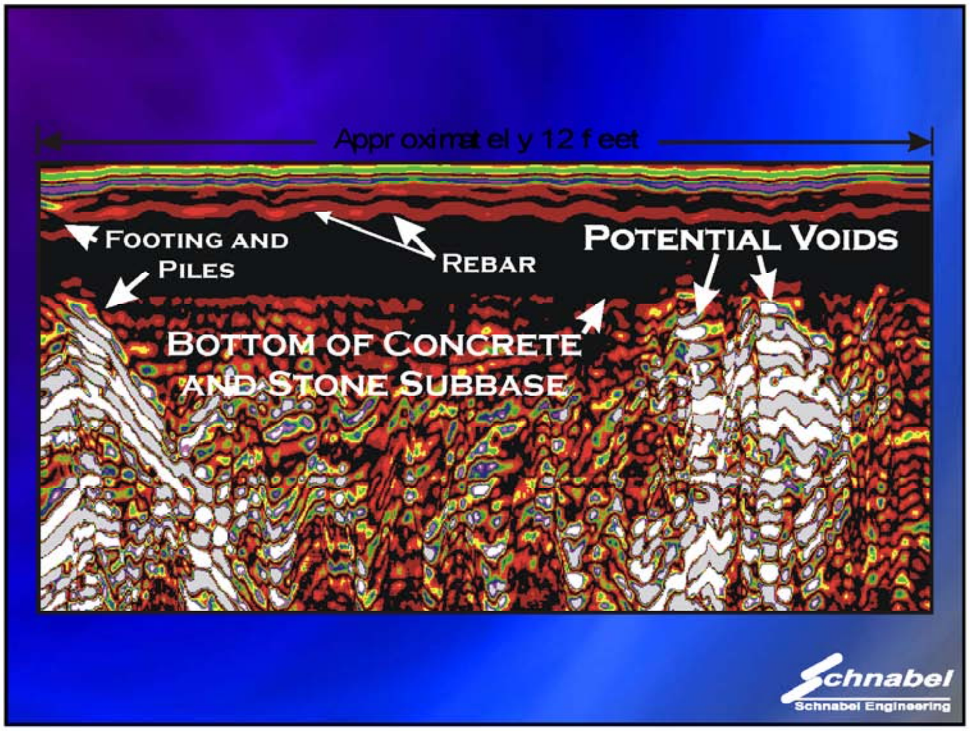
Approximately 12 feet
Footing and Piles
Rebar
Potential Voids
Bottom of Concrete and Stone Subbase
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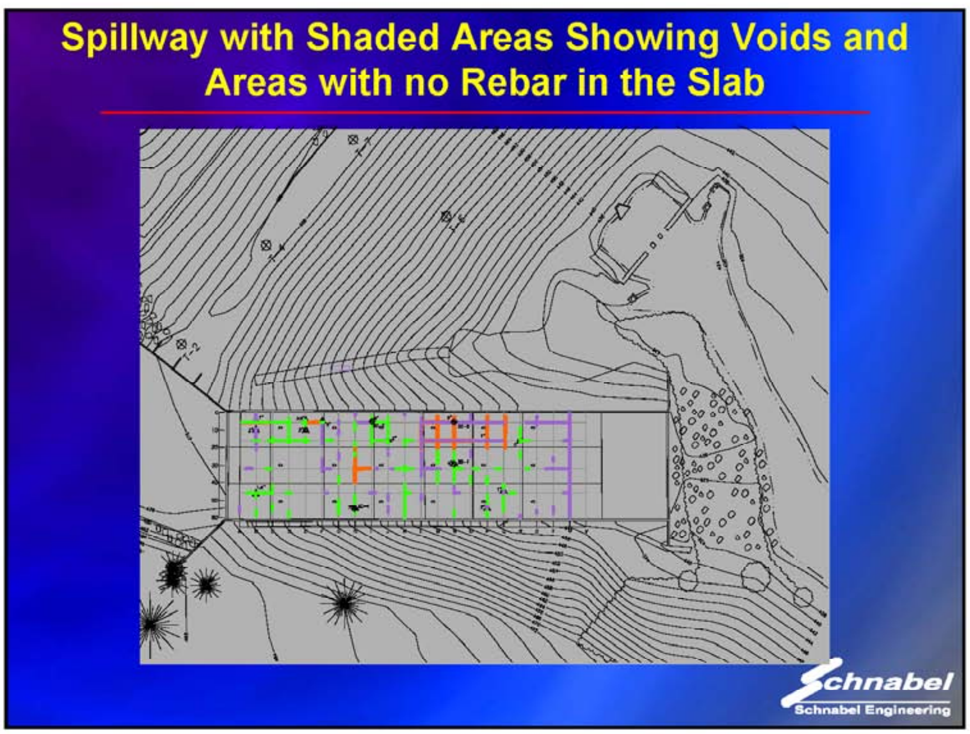
Spillway with Shaded Areas Showing Voids and Areas with no Rebar in the Slab
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GEOPHYSICS

- Will NOT solve every problem.
- Each method has strong and weak points, therefore often best when several complimentary methods are used.
- Can be extremely useful and cost effective if used properly to "see the big picture", or to search for "targets".
- Necessary to understand geophysical principles, geology, construction methods and design, and what the client wants in order to provide USEFUL interpretations and subsurface characterization.

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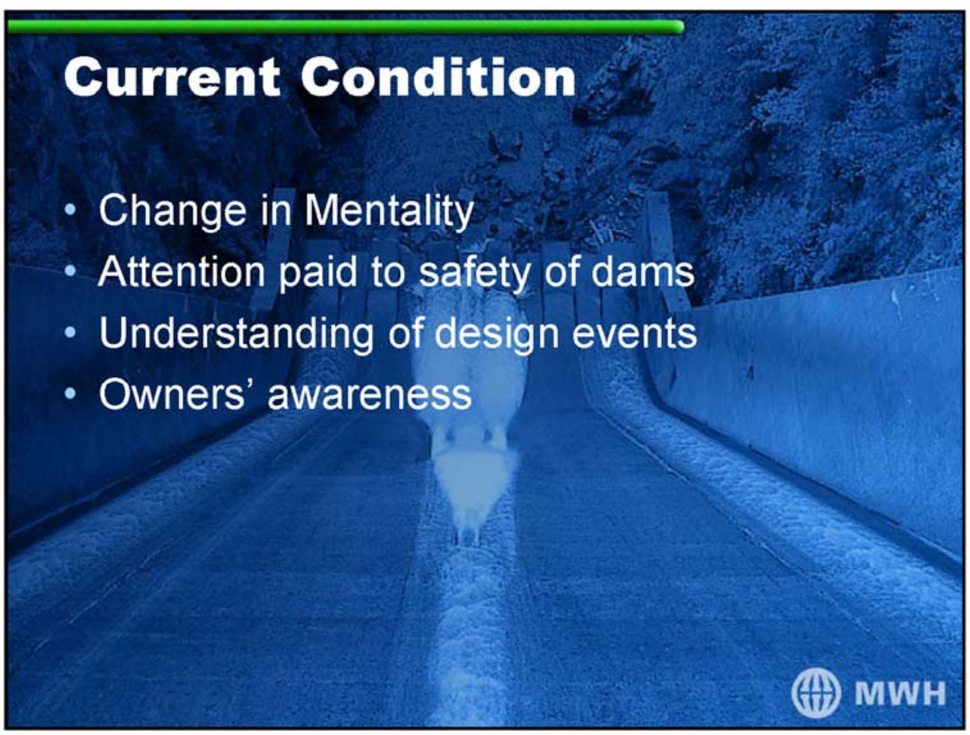
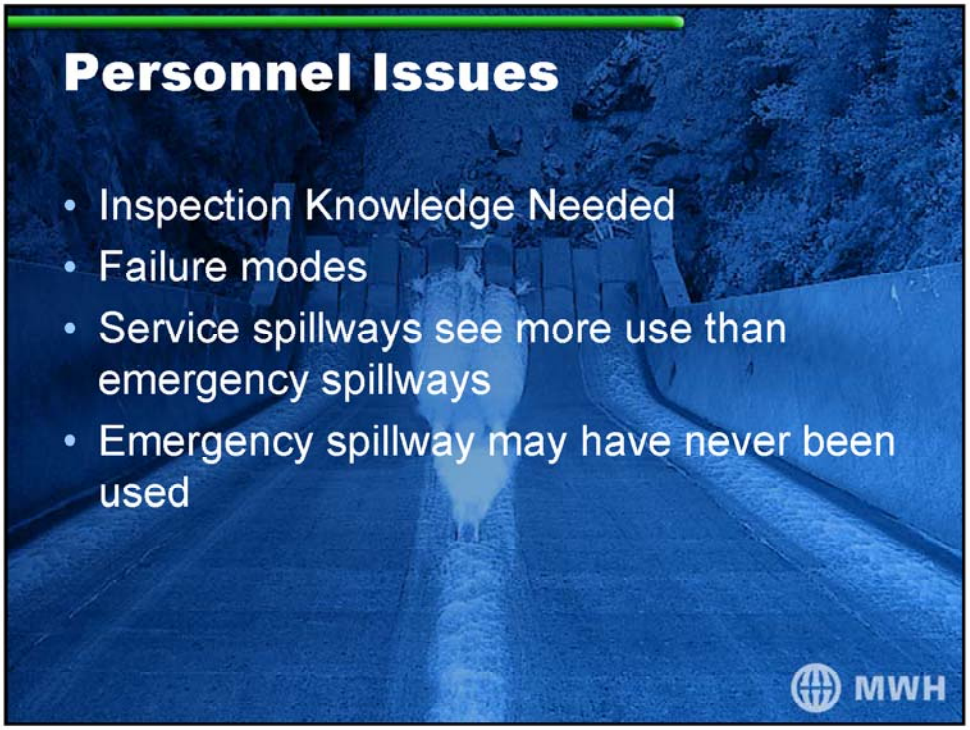
Presentation 18:
Inspection, Maintenance, and Monitoring of Service and Emergency Spillways

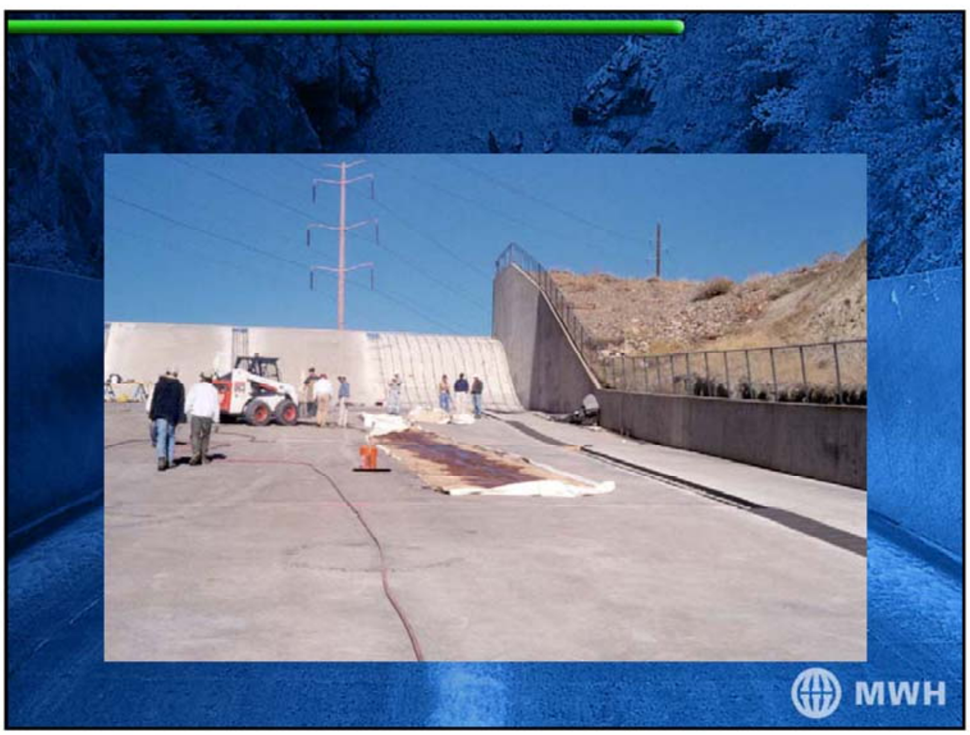

MWH
Inspection, Maintenance and Monitoring of Service and Emergency Spillways
Daniel L. Johnson
MWH Americas


Current Condition
• Change in Mentality
• Attention paid to safety of dams
• Understanding of design events
• Owners' awareness
MWH

Levels of Experience

- Rarity of large flood events
- Denver snowstorm of 1913
- Big Thompson Flood of 1976
- South Platte Flood of 1965
- Events do occur and spillways are leading cause of failures


Personnel Issues
• Inspection Knowledge Needed
• Failure modes
• Service spillways see more use than emergency spillways
• Emergency spillway may have never been used
MWH

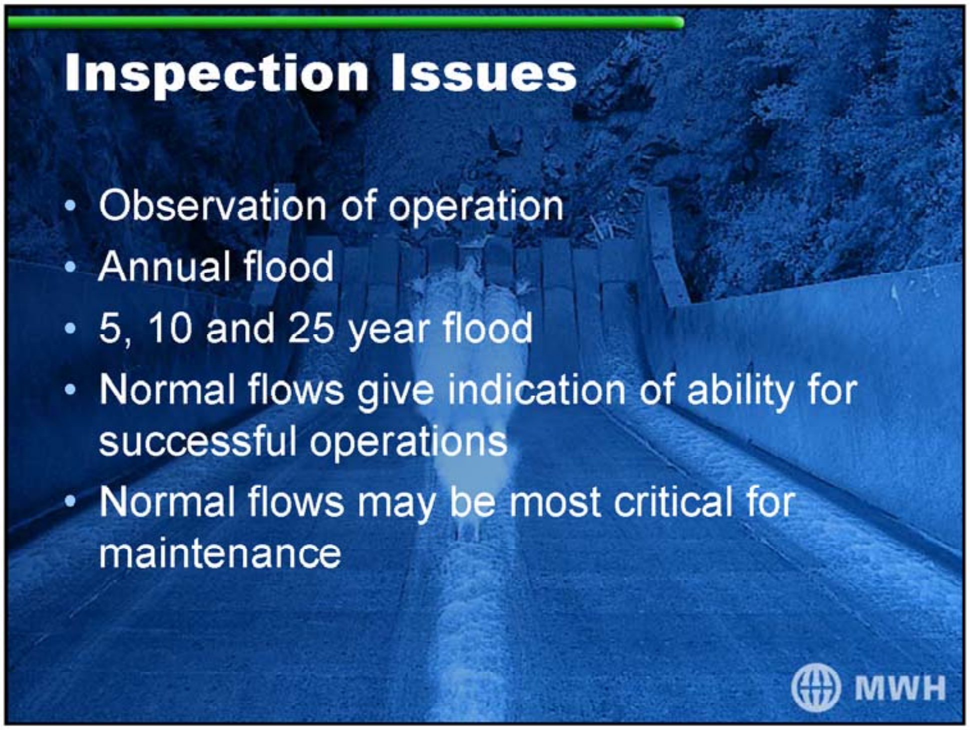

MWH

Inspection Issues

- Capability to meet design criteria
- Conditions and components for successful operation
  - Located on abutment
  - Located on dam
- Condition assessment
- Changes with time

MWH

MWH


Inspection Issues
• Observation of operation
• Annual flood
• 5, 10 and 25 year flood
• Normal flows give indication of ability for successful operations
• Normal flows may be most critical for maintenance
MWH


Maintenance
• Maintenance is typically not frequent
• Emergency spillway may be forgotten
• Repairs are necessary to maintain in as-designed condition
• Concrete
– Movement, foundation erosion, toe and head erosion
• Earth
– Slope protection, erosion of channel, abutments, toe, head
• Deleterious materials
MWH

Special Issue

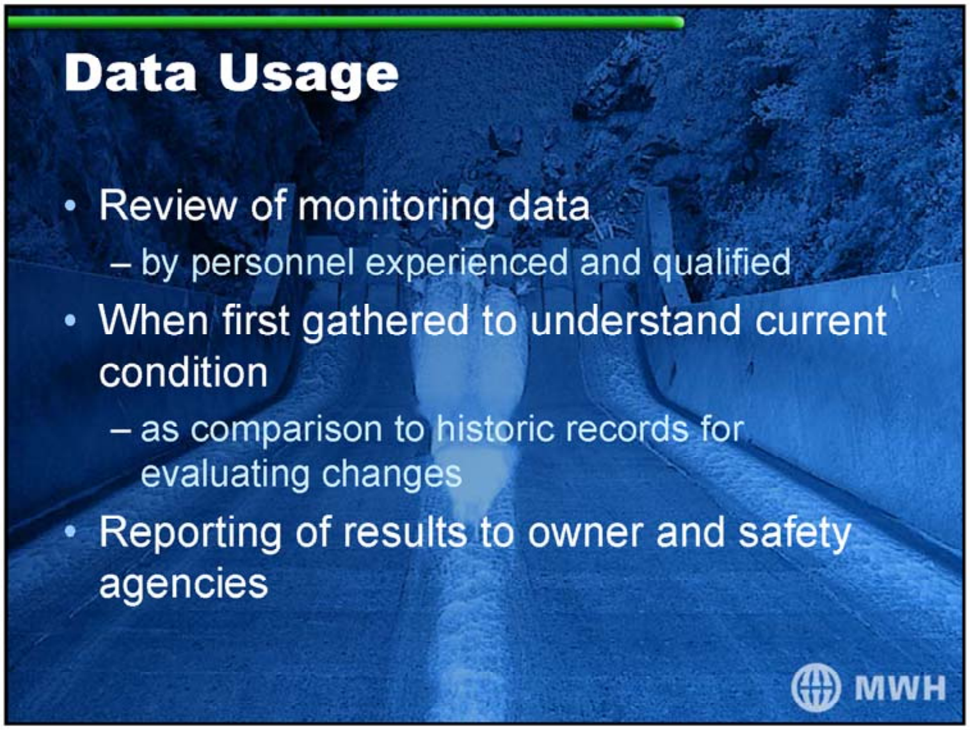
- Over-the-dam spillways need additional attention
- Frequent use as they are cost effective using RCC
- Induces new failure mode
- Increases frequency of emergency spillway usage

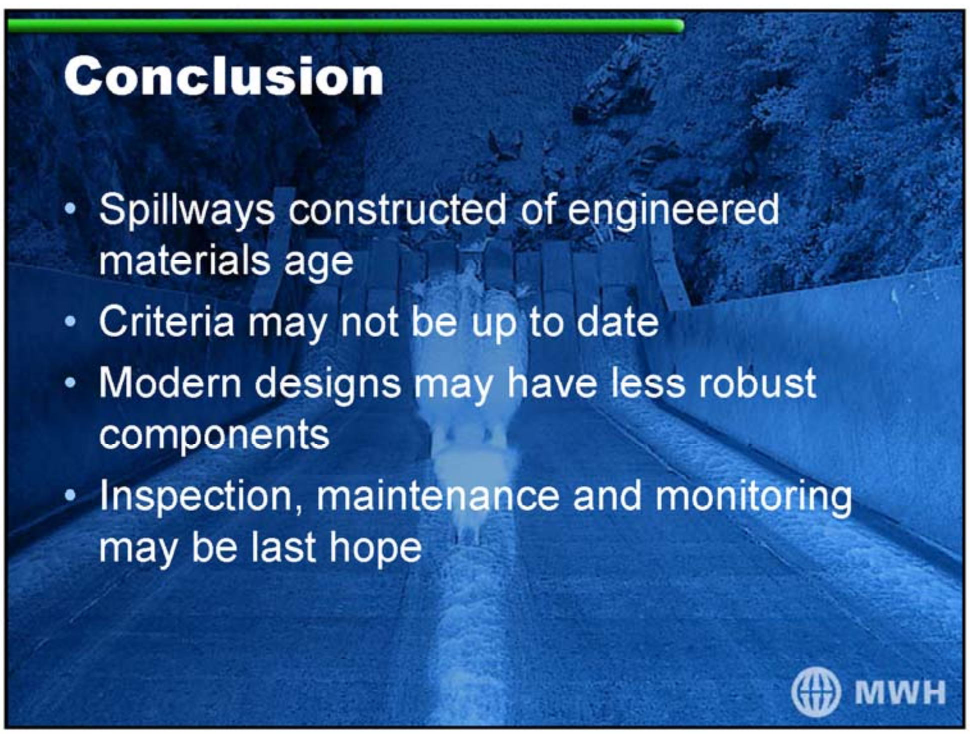
MWH

Monitoring

- Monitoring is needed
  - to estimate performance
  - to set a maintenance/rehabilitation plan
- Measurements of
  - movement, cracking, deterioration, aging issues
- Documentation of
  - surveys, photos, checklists and notes

MWH


Data Usage
• Review of monitoring data
– by personnel experienced and qualified
• When first gathered to understand current condition
– as comparison to historic records for evaluating changes
• Reporting of results to owner and safety agencies
MWH


Conclusion
• Spillways constructed of engineered materials age
• Criteria may not be up to date
• Modern designs may have less robust components
• Inspection, maintenance and monitoring may be last hope
MWH

Presentation 19:
Unlined Spillway Erosion Risk Assessment

Unlined Spillway Erosion Risk Assessment

Johannes Wibowo
Evelyn Villanueva
Don Yule
Darrel Temple

Unlined Spillway Erosion Risk Assessment

Problem Statements:

- Spillway erosion analysis encounters variable nature of geometry, geologic material and unpredictable flood events.
- Dam Safety Portfolio Analysis needs a tool to determine the probability of spillway damage.

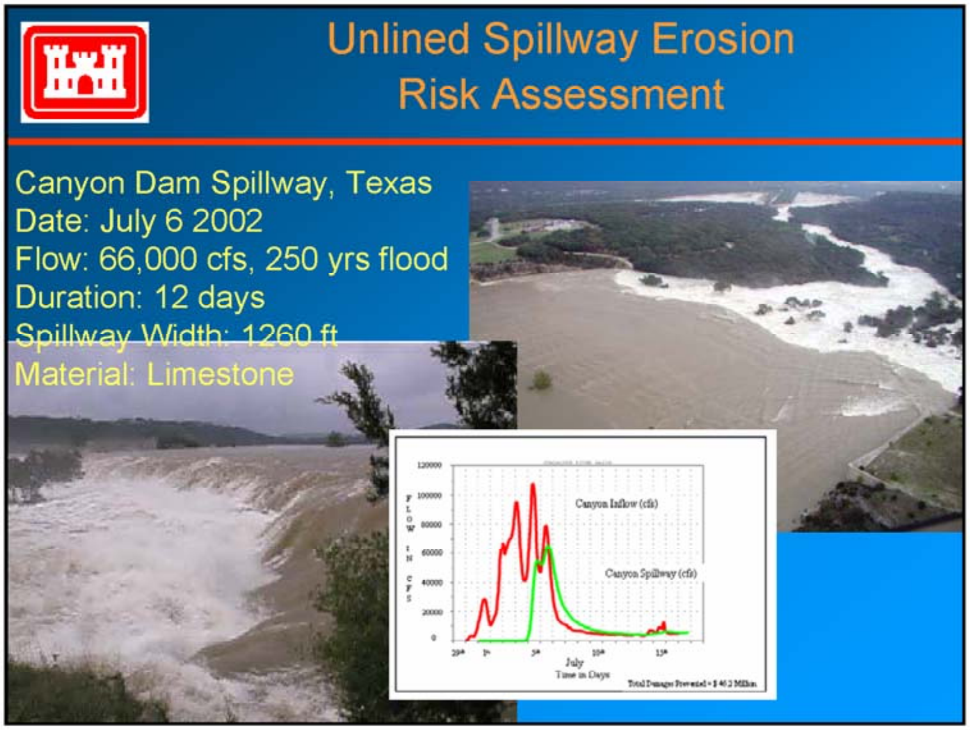
Unlined Spillway Erosion Risk Assessment

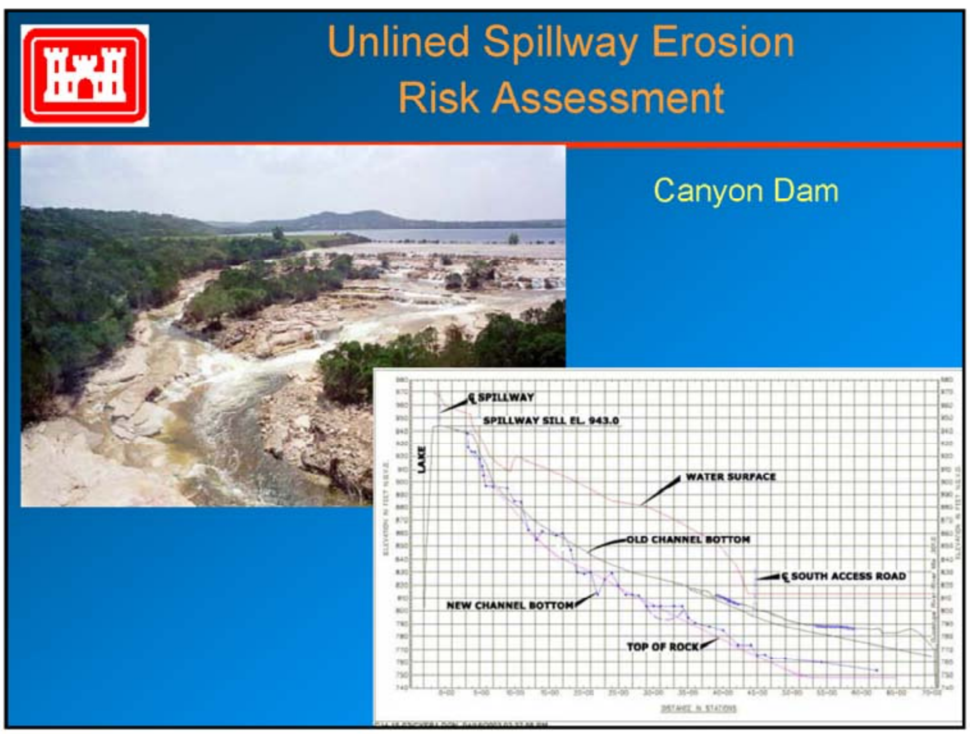
RESEARCH OBJECTIVES:

- Develop a tool to assess the probability of damage on unlined spillway erosion
- Develop a tool to prioritize unlined spillway/channel remediation projects

Unlined Spillway Erosion Risk Assessment

DMAD spillway shortly after failure (1982)


Unlined Spillway Erosion
Risk Assessment
Canyon Dam Spillway, Texas
Date: July 6 2002
Flow: 66,000 cfs, 250 yrs flood
Duration: 12 days
Spillway Width: 1260 ft
Material: Limestone
Canyon Inflow (cfs)
Canyon Spillway (cfs)
July
Time in Days


Unlined Spillway Erosion
Risk Assessment
Canyon Dam
SPILLWAY
SPILLWAY SILL EL. 943.0
LAKE
WATER SURFACE
OLD CHANNEL BOTTOM
SOUTH ACCESS ROAD
NEW CHANNEL BOTTOM
TOP OF ROCK

Unlined Spillway Erosion
Risk Assessment

Risk Assessment

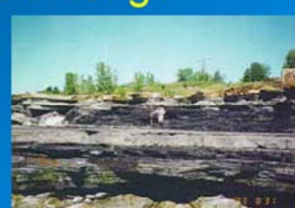
Process of Answering Three Questions:

1. What can go wrong?
2. What is the likelihood it will go wrong?
3. What are the consequences if it does go wrong?

Unlined Spillway Erosion
Risk Assessment

1 What Can Go Wrong?

Local Scouring



Headcut Erosion

Spillway Breach

Dam Breach

Unlined Spillway Erosion Risk Assessment

2 What Is The Likelihood It Will Go Wrong?

- Uncertainty of Flood Event
- Uncertainty of Material Parameters
- Uncertainty of Performance of the Unlined Spillway

Unlined Spillway Erosion Risk Assessment

3 What Are the Consequences If It Does Go Wrong?

- Spillway Partial Damage
  - Lightly Damaged
  - Moderately Damaged
  - Severely Damaged
- Spillway Breach
  - Population at Risk
  - Loss of Economic Value

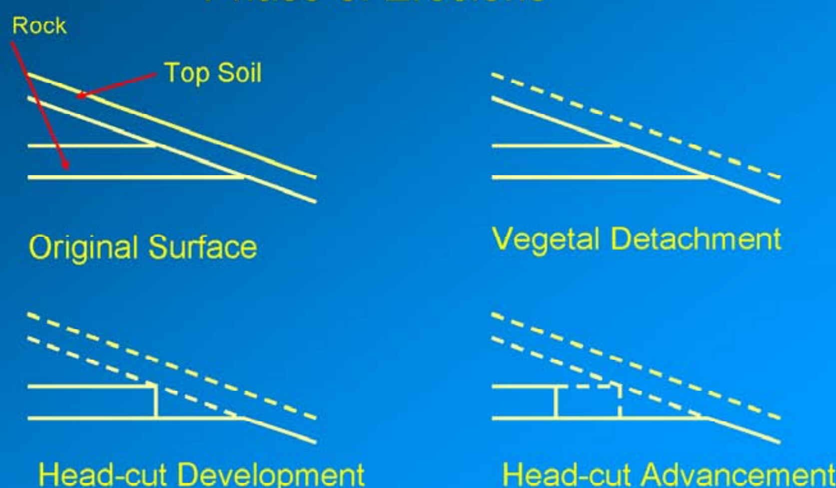
Unlined Spillway Erosion Risk Assessment

Spillway Erosion Models

- USDA (Temple et al., 1994)
- Modified USDA (KCD,1995; ERDC, 2002)
- Annandale (1995)
- REMR (WES, 1998)

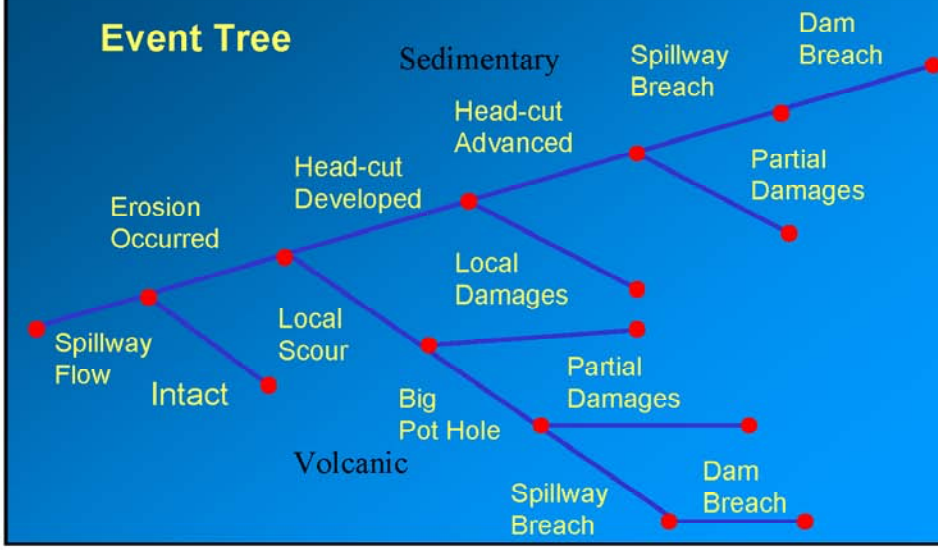
Unlined Spillway Erosion Risk Assessment

Phase of Erosions



Unlined Spillway Erosion Risk Assessment

Event Tree



Unlined Spillway Erosion Risk Assessment

Development of Head-cut

Load: Hydrograph

Governing Equations:

$$\tau_e = \gamma\left(d + \Delta d\right)S$$

$$\frac{d\varepsilon}{dt} = k_d\left[\tau_e - \tau_c\right]$$

Unlined Spillway Erosion Risk Assessment

Parameters

τ_e = effective stress

γ = unit weight of water

d = normal depth of flow

S = surface slope

$d\varepsilon/dt$ = erosion rate

k_d = detachment rate coefficient

τ_c = threshold stress

Unlined Spillway Erosion Risk Assessment

Head-cut Advance

Load: Hydrograph

Governing Equations:

$$\frac{dx}{dt} = \begin{cases} C(A - A_0) & (A - A_0) > 0 \\ 0 & (A - A_0) \leq 0 \end{cases}$$

dx/dt = Rate of headcut advance

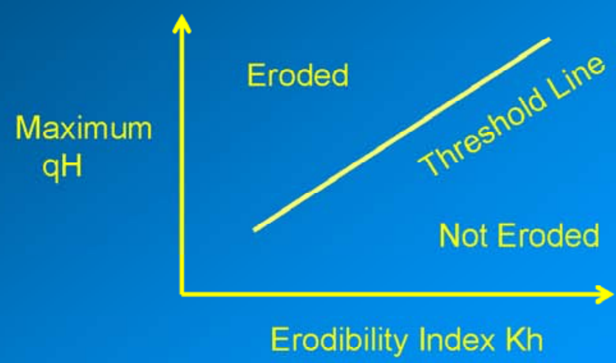
C = Empirical parameter

A = Hydraulic attack

A_0 = Threshold level

Unlined Spillway Erosion Risk Assessment

Erosion Model - Threshold Line



Unlined Spillway Erosion Risk Assessment

Erodibility Index (K_h)

$$K_h = M_s * K_b * K_d * J_s$$

M_s = Material Strength Number
K_b = Block Size Number
K_d = Joint Shear Strength Number
J_s = Joint Orientation Number

Unlined Spillway Erosion Risk Assessment

Maximum Hydraulic Attack

E = ☎ * q * H

E = Maximum Hydraulic Attack

☎ = Unit weight of water

q = Unit discharge

H = Energy line drop

Unlined Spillway Erosion Risk Assessment

Logistic Regression

- Regression for Binary Outcomes
  - Occurrence (Erosion)
  - Non-Occurrence (No Erosion)
- User of Logistic Regression Method
  - Medical
  - Business
- Probabilistic Liquefaction Analysis

Unlined Spillway Erosion Risk Assessment

Logistic Regression

- Odds ratio $\frac{p}{1 - p}$
- Logit transformation

$$Ln\left[\frac{p}{1-p}\right] = b_0 + b_1 x$$

$$p = \frac{1}{1 + \exp\left[-\left(b_0 + b_1 x\right)\right]}$$

p = probability of occurrence

b_0, b_1 = regression parameters

x = independent variable

Unlined Spillway Erosion Risk Assessment

Multiple Logistic Regression

$$p = \frac{1}{1 + \exp\left[-\left(b_0 + b_1 x_1 + b_2 x_2 + .. + b_n x_n\right)\right]}$$

p = probability of occurrence

b_0, b_1, b_2, .., b_n = regression parameters

x_1, x_2, .., x_n, = independent variables

Unlined Spillway Erosion Risk Assessment

Multiple Logistic Regression for Spillway Erosion

$$p = \frac{1}{1 + \exp\left[-\left(b_0 + b_1 K_h + b_2 qH\right)\right]}$$

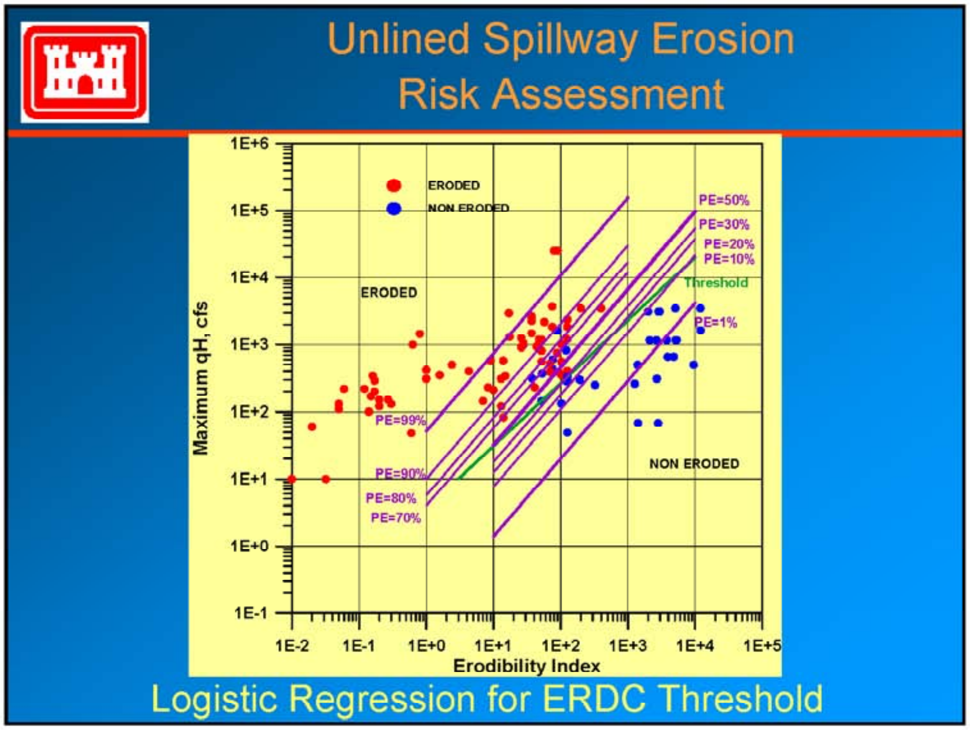
K_h = Erosion Index, Material Resistance
qH = Maximum qH, Hydraulic Attack

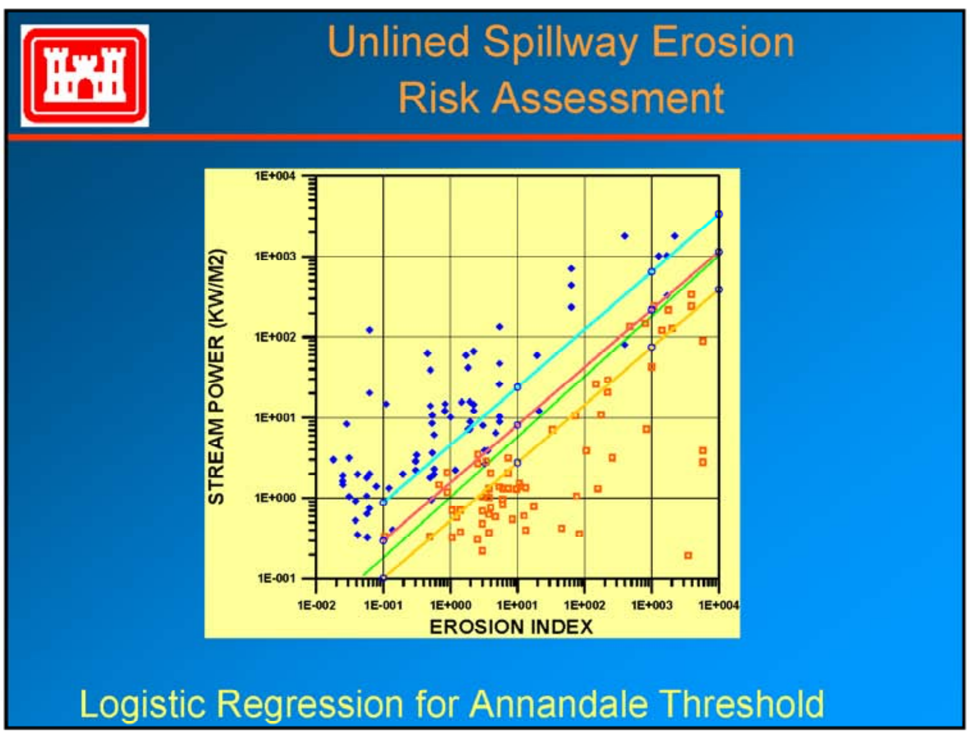
Unlined Spillway Erosion Risk Assessment

Result of Multiple Logistic Regression

$$p_e = \frac{1}{1 + \exp\left[-\left(1.171 - 3.9 K_h + 3.364\, qH\right)\right]}$$

p_e = probability of erosion
K_h = Erosion Index, Material Resistance
qH = Maximum qH, Hydraulic Attack


Unlined Spillway Erosion
Risk Assessment
ERODED
NON ERODED
PE=50%
PE=30%
PE=20%
PE=10%
Threshold
PE=1%
PE=99%
PE=90%
PE=80%
PE=70%
NON ERODED
Maximum qH, cfs
Erodibility Index
1E+6
1E+5
1E+4
1E+3
1E+2
1E+1
1E+0
1E-1
1E-2
1E-1
1E+0
1E+1
1E+2
1E+3
1E+4
1E+5
Logistic Regression for ERDC Threshold


Unlined Spillway Erosion
Risk Assessment
STREAM POWER (KW/M2)
EROSION INDEX
1E+004
1E+003
1E+002
1E+001
1E+000
1E-001
1E-002
1E-001
1E+000
1E+001
1E+002
1E+003
1E+004
Logistic Regression for Annandale Threshold

Unlined Spillway Erosion Risk Assessment

Independent Variables

- Hydrograph
  - Peak unit discharges (cfs/ft)
  - Flood durations (hrs)
- Spillway Geometry
  - Lengths (ft)
  - Slopes (degrees)
- Material Index
  - Erosion Indexes

Unlined Spillway Erosion Risk Assessment

Ordinal Logistic Regression

Sj = F (Material, Peak Discharge, Duration, Average_Slope, and Length)

Data: Case Histories (USDA and COE)

Damage Levels:

No Damage	0 - 0.05%
Lightly Damage	0.06 – 15%
Moderately Damage	16 – 40%
Severely Damage	41 – 75%
Breach	76 – 100%

Unlined Spillway Erosion Risk Assessment

Ordinal Logistic Regression

Sj = -1.515 Log_Kh + 8.635 Log_q – 1.581Log_Dura
+ 0.807 Slope_av + 3.975 Log_Length

Probability Formulation:

No Damage	= 1/(1+ exp(Sj-k1))
Lightly Damage	= 1/(1+ exp(Sj-k2)) - 1/(1+ exp(Sj-k1))
Moderately Damage	= 1/(1+ exp(Sj-k3)) - 1/(1+ exp(Sj-k2))
Severely Damage	= 1/(1+ exp(Sj-k4)) - 1/(1+ exp(Sj-k3))
Breach	= 1 – 1/(1+ exp(Sj-k4))

k1,k2, k3, and k4 = boundary parameters from regression

Unlined Spillway Erosion Risk Assessment

Input	Tuttle Cr., KS Ls-Sh G/J	Painted Rock, AZ		Saylorville, IA Ss-Sh, 91	Buck_Doe, MO
Unit Disch. (cfs/ft)	112.1	41.8		104.4	163.5
Duration (hours)	120	576		216	3
Erosion Index, K_h	17	5340	28	103	0.01
Ave. Slope (deg)	1.4	1.32	14.04	1	7.2
Length (ft)	2200	520	230	1340	155
Probability Output					
No Damage	0.001	0.990	0.000	0.029	0.000
Lightly	0.019	0.009	0.002	0.275	0.000
Moderate	0.305	0.001	0.047	0.609	0.000
Severe	0.629	0.000	0.639	0.085	0.003
Breach	0.046	0.000	0.312	0.002	0.997

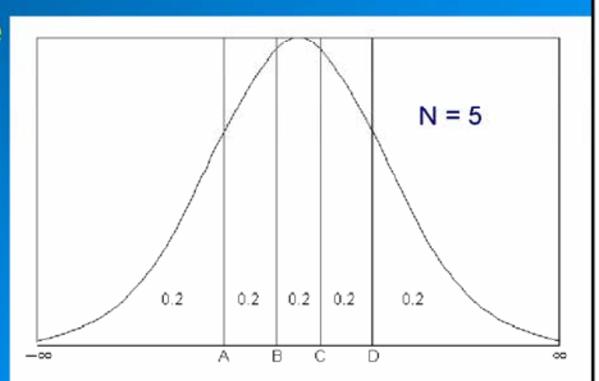
Unlined Spillway Erosion Risk Assessment

	The Dalles, OR Q=2,290,000 cfs	Bluestone. WV Q=430,000 cfs
Erosion Index (Kh)	1960	2734
Stream Power (Kw/m2)	125.4	22.3
Probability of Erosion	0.012	0.000

Unlined Spillway Erosion Risk Assessment

Simulation Using USDA Model

- Monte Carlo
- Latin Hyper-Cube



Unlined Spillway Erosion Risk Assessment

LHC Simulation

Variables:

Materials
Hydrographs

Damage Levels:

No Damage	0 - 0.05%
Lightly Damage	0.06 – 15%
Moderately Damage	16 – 40%
Severely Damage	41 – 75%
Breach	76 – 100%

Unlined Spillway Erosion Risk Assessment

Prioritizing Process

Ranking the outcome:

$$Risk = P_{occurrence} * P_{failure} * Consequences$$

Unlined Spillway Erosion Risk Assessment

Future Research

- Erosion Index needs to be refined
- Geophysical Exploration will be useful for volcanic areas
- Effect of spillway channel geometry (curving, narrowing)
- Three dimensional erosion (side erosion)

Appendix D

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Inspection, Maintenance and Monitoring of Service and Emergency Spillways - Johnson

NONE

Unlined Spillway Erosion Risk Assessment - Koester

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Appendix E

Individual Topic Voting Results

This appendix is a compilation of each topic difficulty and benefit result shown graphically. Each topic is shown side by side with benefit on the left and difficulty on the right of the figure box. The ratings were 1=not very beneficial, 10= very beneficial; 1=low difficulty or easy to accomplish, 10=high difficulty or very hard to accomplish. The numbers of votes received for each level of benefit or difficulty are shown across the bottom of each graph The bars show the results of voting graphically in terms of percent votes for each level divided by the total number of votes received. The mean is also shown for the category giving the voting distribution.

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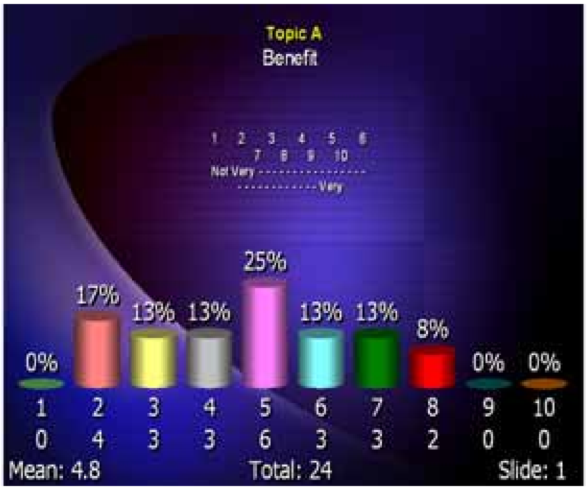
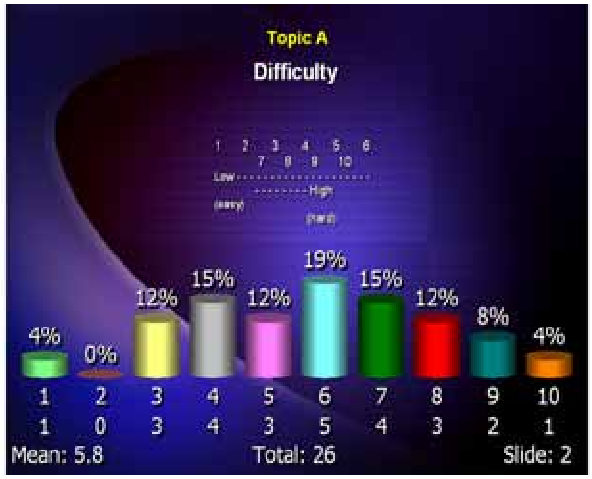
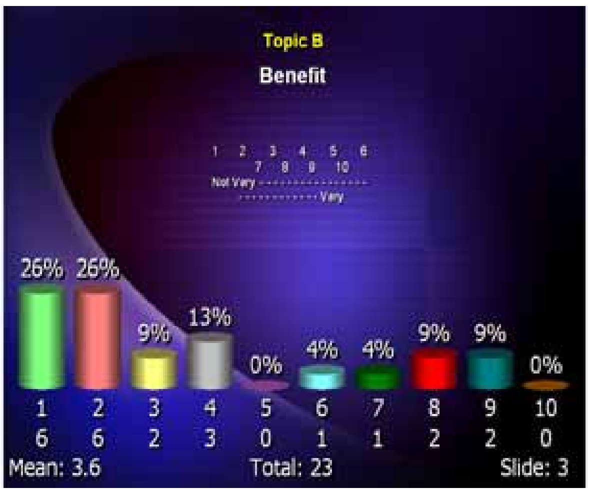
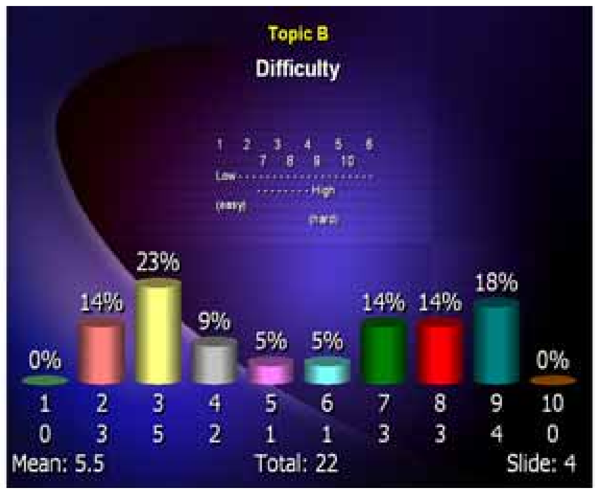
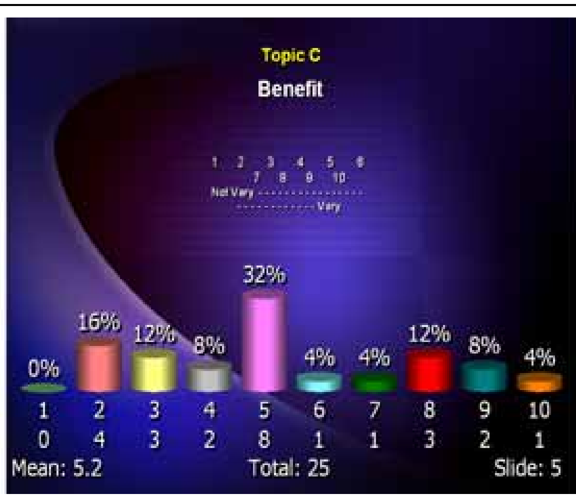
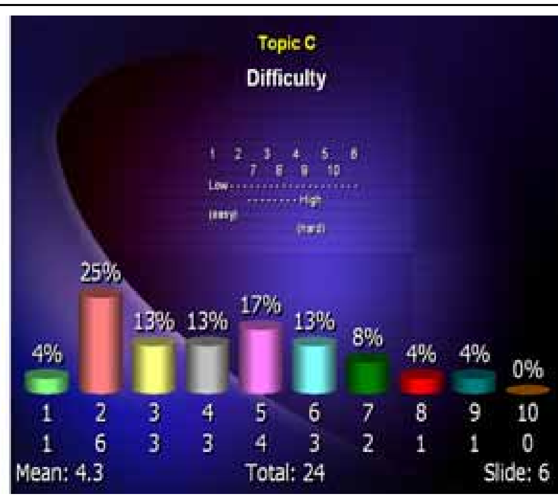

Topic A
Benefit
1 2 3 4 5 6 7 8 9 10
Not Very ---------------------------- Very
0% 17% 13% 13% 25% 13% 13% 8% 0% 0%
1 2 3 4 5 6 7 8 9 10
0 4 3 3 6 3 3 2 0 0
Mean: 4.8
Total: 24
Slide: 1

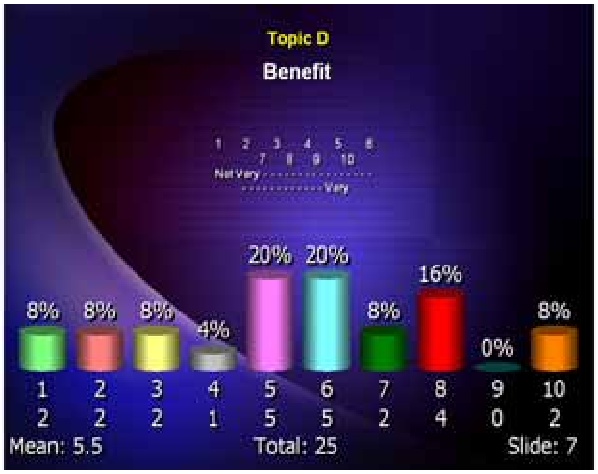

Topic A
Difficulty
1 2 3 4 5 6 7 8 9 10
Low ---------------------------- High
(easy)
(hard)
4% 0% 12% 15% 12% 19% 15% 12% 8% 4%
1 2 3 4 5 6 7 8 9 10
1 0 3 4 3 5 4 3 2 1
Mean: 5.8
Total: 26
Slide: 2

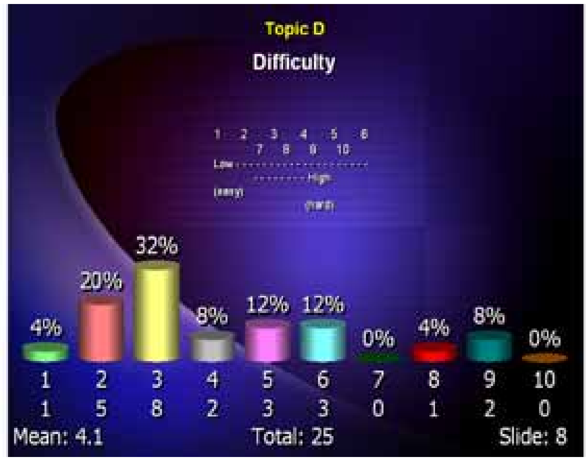

Topic B
Benefit
1 2 3 4 5 6 7 8 9 10
Not Very ---------------------------- Very
26% 26% 9% 13% 0% 4% 4% 9% 9% 0%
1 2 3 4 5 6 7 8 9 10
6 6 2 3 0 1 1 2 2 0
Mean: 3.6
Total: 23
Slide: 3

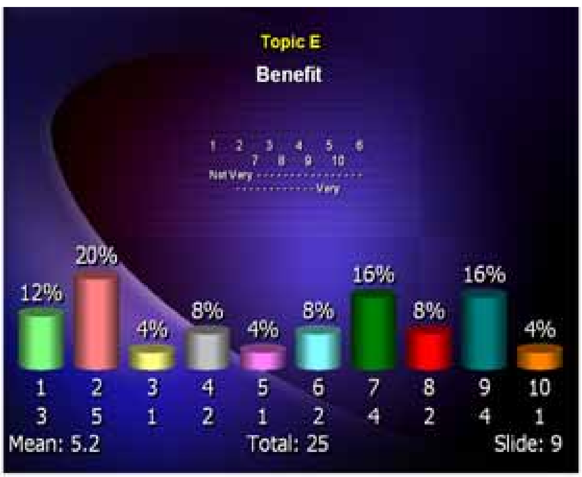

Topic B
Difficulty
1 2 3 4 5 6 7 8 9 10
Low ---------------------------- High
(easy)
(hard)
0% 14% 23% 9% 5% 5% 14% 14% 18% 0%
1 2 3 4 5 6 7 8 9 10
0 3 5 2 1 1 3 3 4 0
Mean: 5.5
Total: 22
Slide: 4

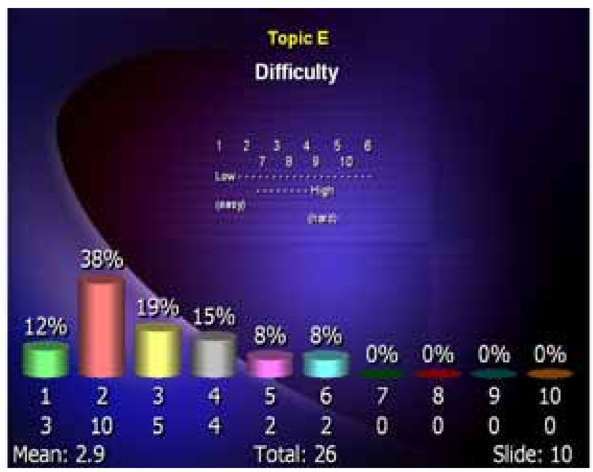

Topic C
Benefit
1 2 3 4 5 6 7 8 9 10
Not Very ---------------------------- Very
0% 16% 12% 8% 32% 4% 4% 12% 8% 4%
1 2 3 4 5 6 7 8 9 10
0 4 3 2 8 1 1 3 2 1
Mean: 5.2
Total: 25
Slide: 5

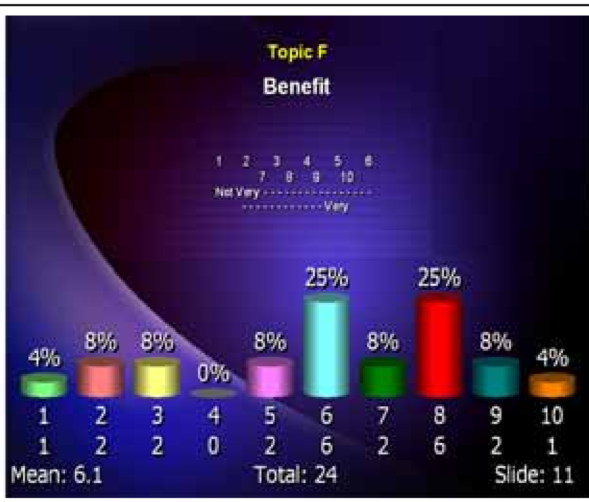

Topic C
Difficulty
1 2 3 4 5 6 7 8 9 10
Low ---------------------------- High
(easy)
(hard)
4% 25% 13% 13% 17% 13% 8% 4% 4% 0%
1 2 3 4 5 6 7 8 9 10
1 6 3 3 4 3 2 1 1 0
Mean: 4.3
Total: 24
Slide: 6

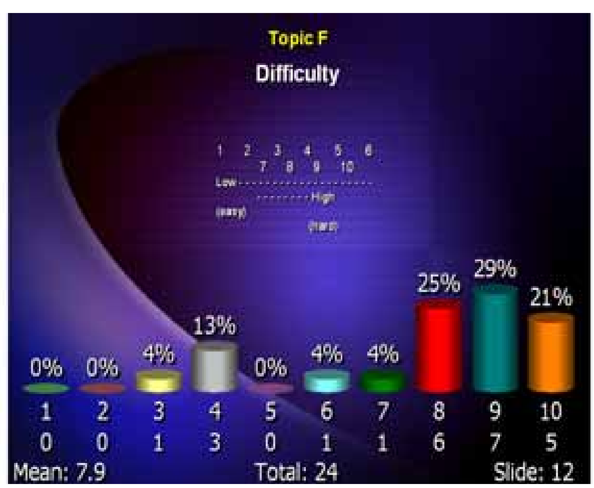

Topic D
Benefit
1 2 3 4 5 6 7 8 9 10
Not Very
Very
8% 8% 8% 4% 20% 20% 8% 16% 0% 8%
1 2 3 4 5 6 7 8 9 10
2 2 2 1 5 5 2 4 0 2
Mean: 5.5
Total: 25
Slide: 7

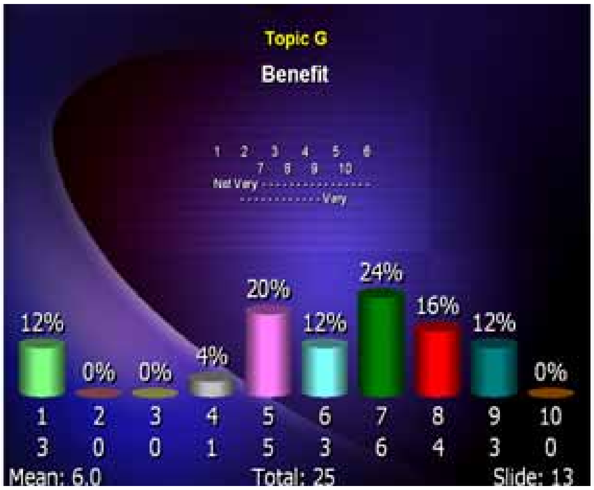

Topic D
Difficulty
1 2 3 4 5 6 7 8 9 10
Low
High
(easy)
(hard)
4% 20% 32% 8% 12% 12% 0% 4% 8% 0%
1 2 3 4 5 6 7 8 9 10
1 5 8 2 3 3 0 1 2 0
Mean: 4.1
Total: 25
Slide: 8

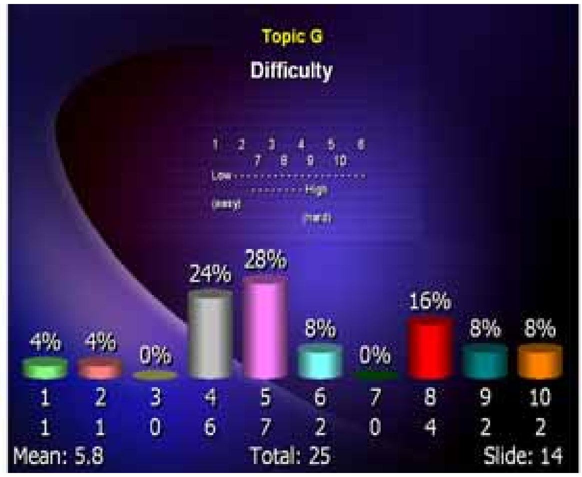

Topic E
Benefit
1 2 3 4 5 6 7 8 9 10
Not Very
Very
12% 20% 4% 8% 4% 8% 16% 8% 16% 4%
1 2 3 4 5 6 7 8 9 10
3 5 1 2 1 2 4 2 4 1
Mean: 5.2
Total: 25
Slide: 9

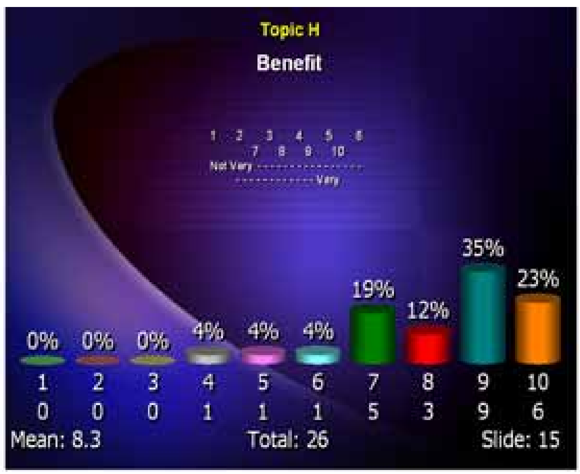

Topic E
Difficulty
1 2 3 4 5 6 7 8 9 10
Low
High
(easy)
(hard)
12% 38% 19% 15% 8% 8% 0% 0% 0% 0%
1 2 3 4 5 6 7 8 9 10
3 10 5 4 2 2 0 0 0 0
Mean: 2.9
Total: 26
Slide: 10

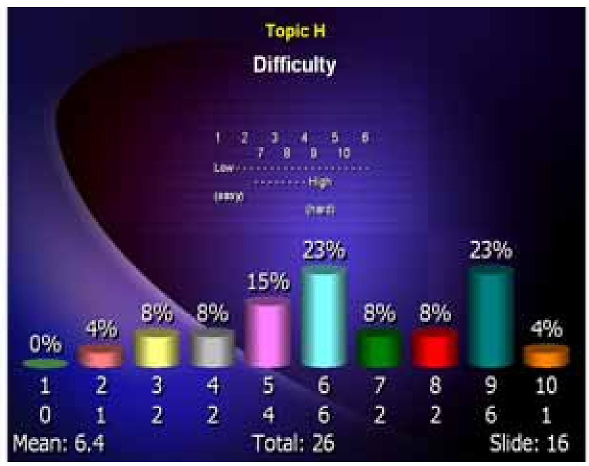

Topic F
Benefit
1 2 3 4 5 6 7 8 9 10
Not Very
Very
4% 8% 8% 0% 8% 25% 8% 25% 8% 4%
1 2 3 4 5 6 7 8 9 10
1 2 2 0 2 6 2 6 2 1
Mean: 6.1
Total: 24
Slide: 11

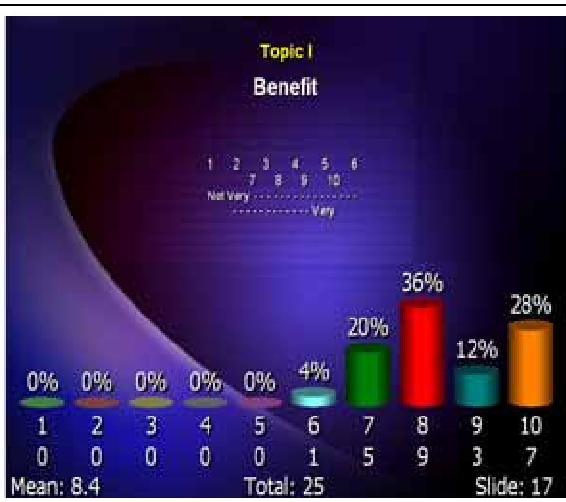

Topic F
Difficulty
1 2 3 4 5 6 7 8 9 10
Low
High
(easy)
(hard)
0% 0% 4% 13% 0% 4% 4% 25% 29% 21%
1 2 3 4 5 6 7 8 9 10
0 0 1 3 0 1 1 6 7 5
Mean: 7.9
Total: 24
Slide: 12

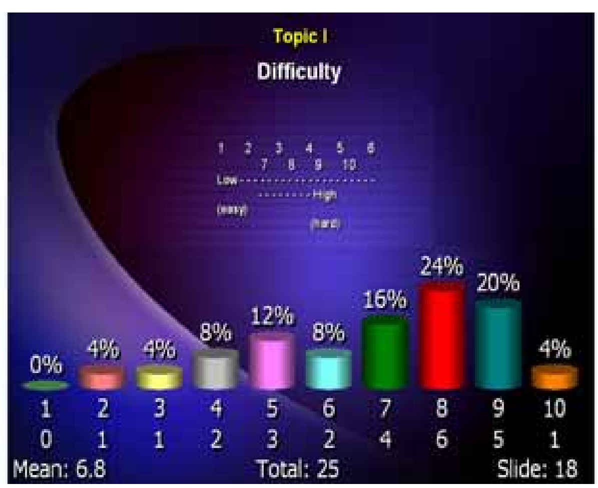

Topic G
Benefit
Not Very
Very
12% 0% 0% 4% 20% 12% 24% 16% 12% 0%
1 2 3 4 5 6 7 8 9 10
3 0 0 1 5 3 6 4 3 0
Mean: 6.0
Total: 25
Slide: 13

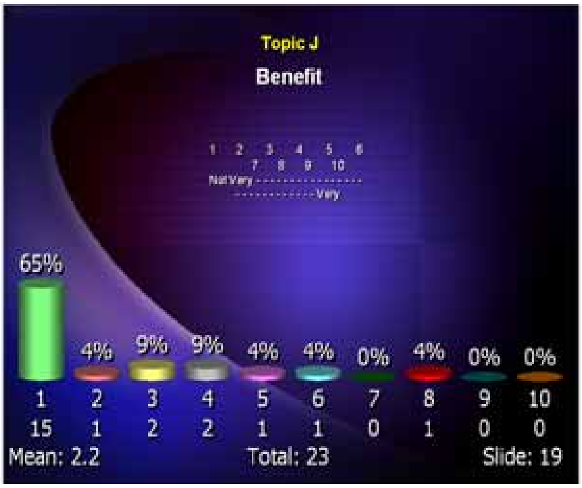

Topic G
Difficulty
Low
High
(easy)
(hard)
4% 4% 0% 24% 28% 8% 0% 16% 8% 8%
1 2 3 4 5 6 7 8 9 10
1 1 0 6 7 2 0 4 2 2
Mean: 5.8
Total: 25
Slide: 14

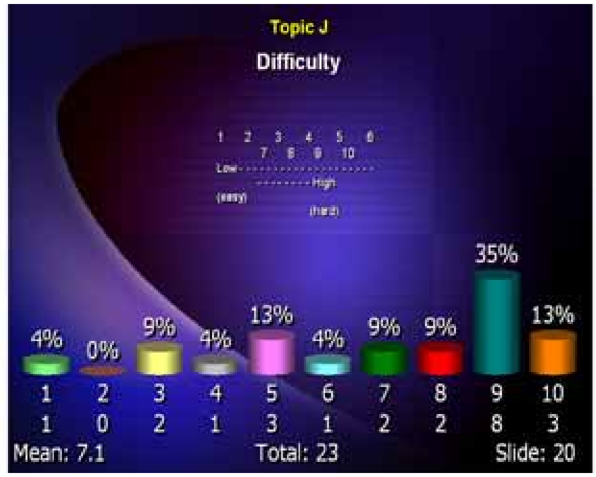

Topic H
Benefit
Not Very
Very
0% 0% 0% 4% 4% 4% 19% 12% 35% 23%
1 2 3 4 5 6 7 8 9 10
0 0 0 1 1 1 5 3 9 6
Mean: 8.3
Total: 26
Slide: 15


Topic H
Difficulty
Low
High
(easy)
(hard)
0% 4% 8% 8% 15% 23% 8% 8% 23% 4%
1 2 3 4 5 6 7 8 9 10
0 1 2 2 4 6 2 2 6 1
Mean: 6.4
Total: 26
Slide: 16


Topic I
Benefit
Not Very
Very
0% 0% 0% 0% 0% 4% 20% 36% 12% 28%
1 2 3 4 5 6 7 8 9 10
0 0 0 0 0 1 5 9 3 7
Mean: 8.4
Total: 25
Slide: 17


Topic I
Difficulty
Low
High
(easy)
(hard)
0% 4% 4% 8% 12% 8% 16% 24% 20% 4%
1 2 3 4 5 6 7 8 9 10
0 1 1 2 3 2 4 6 5 1
Mean: 6.8
Total: 25
Slide: 18


Topic J
Benefit
65% 4% 9% 9% 4% 4% 0% 4% 0% 0%
1 2 3 4 5 6 7 8 9 10
15 1 2 2 1 1 0 1 0 0
Mean: 2.2
Total: 23
Slide: 19


Topic J
Difficulty
4% 0% 9% 4% 13% 4% 9% 9% 35% 13%
1 2 3 4 5 6 7 8 9 10
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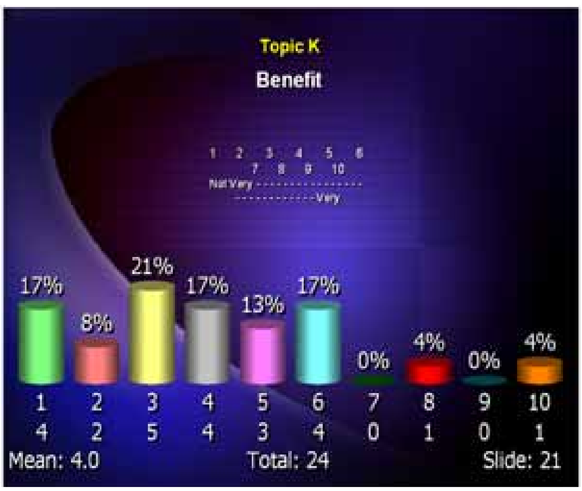
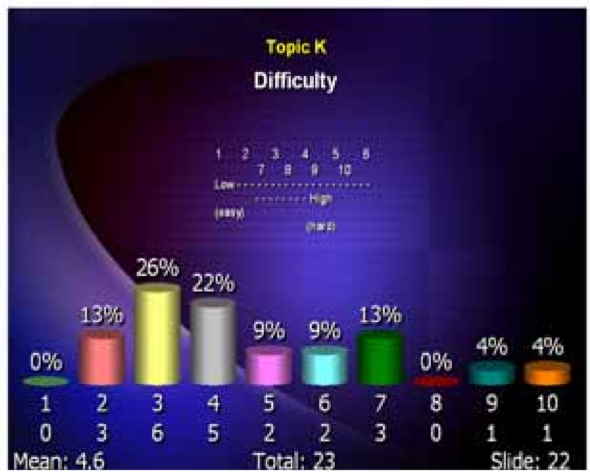
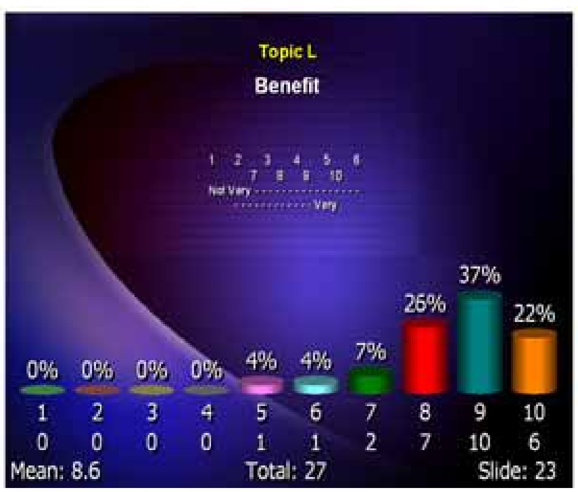
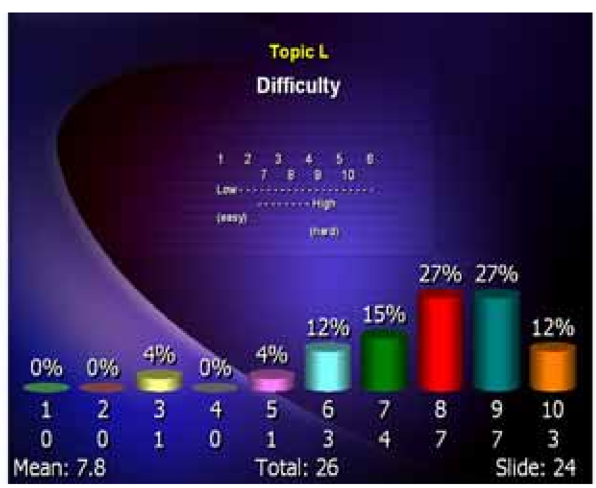
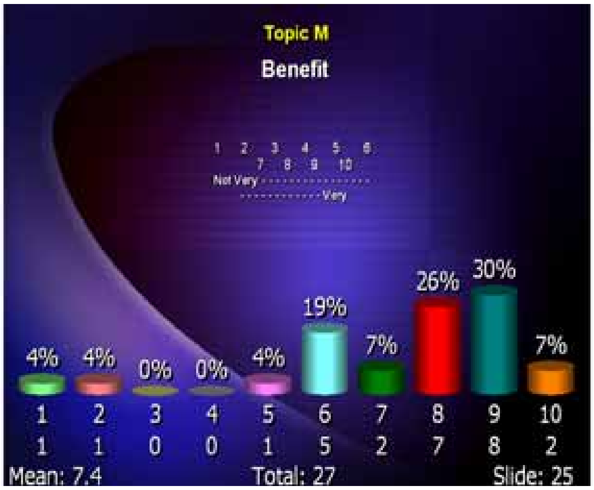
Mean: 7.1
Total: 23
Slide: 20

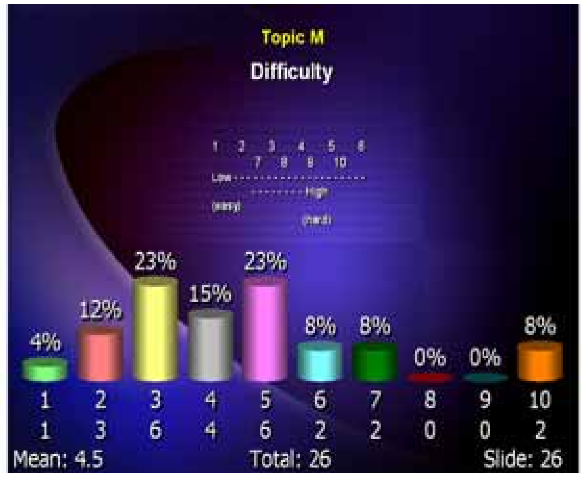

Topic K
Benefit
17% 8% 21% 17% 13% 17% 0% 4% 0% 4%
1 2 3 4 5 6 7 8 9 10
4 2 5 4 3 4 0 1 0 1
Mean: 4.0
Total: 24
Slide: 21

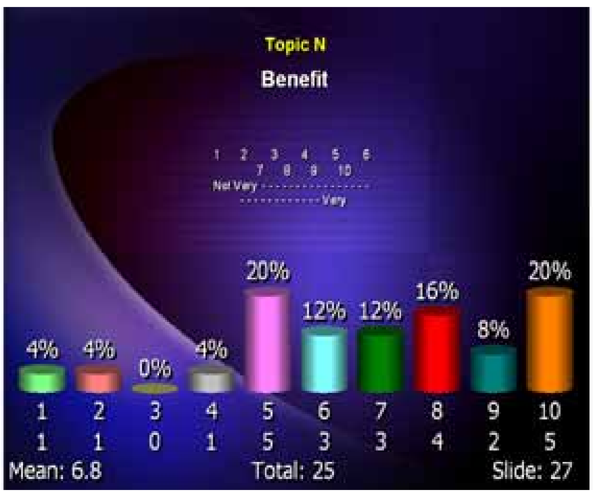

Topic K
Difficulty
0% 13% 26% 22% 9% 9% 13% 0% 4% 4%
1 2 3 4 5 6 7 8 9 10
0 3 6 5 2 2 3 0 1 1
Mean: 4.6
Total: 23
Slide: 22

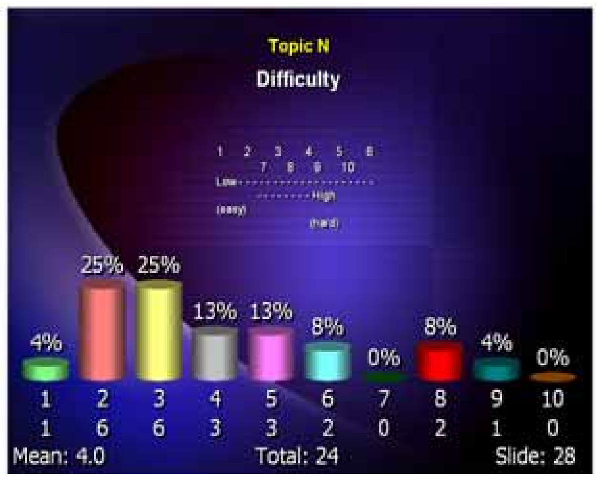

Topic L
Benefit
0% 0% 0% 0% 4% 4% 7% 26% 37% 22%
1 2 3 4 5 6 7 8 9 10
0 0 0 0 1 1 2 7 10 6
Mean: 8.6
Total: 27
Slide: 23


Topic L
Difficulty
0% 0% 4% 0% 4% 12% 15% 27% 27% 12%
1 2 3 4 5 6 7 8 9 10
0 0 1 0 1 3 4 7 7 3
Mean: 7.8
Total: 26
Slide: 24


Topic M
Benefit
4% 4% 0% 0% 4% 19% 7% 26% 30% 7%
1 2 3 4 5 6 7 8 9 10
1 1 0 0 1 5 2 7 8 2
Mean: 7.4
Total: 27
Slide: 25


Topic M
Difficulty
4% 12% 23% 15% 23% 8% 8% 0% 0% 8%
1 2 3 4 5 6 7 8 9 10
1 3 6 4 6 2 2 0 0 2
Mean: 4.5
Total: 26
Slide: 26


Topic N
Benefit
4% 4% 0% 4% 20% 12% 12% 16% 8% 20%
1 2 3 4 5 6 7 8 9 10
1 1 0 1 5 3 3 4 2 5
Mean: 6.8
Total: 25
Slide: 27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Difficulty
4% 25% 25% 13% 13% 8% 0% 8% 4% 0%
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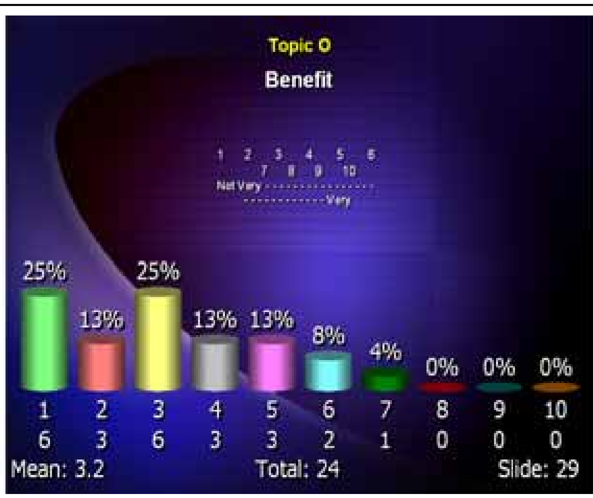
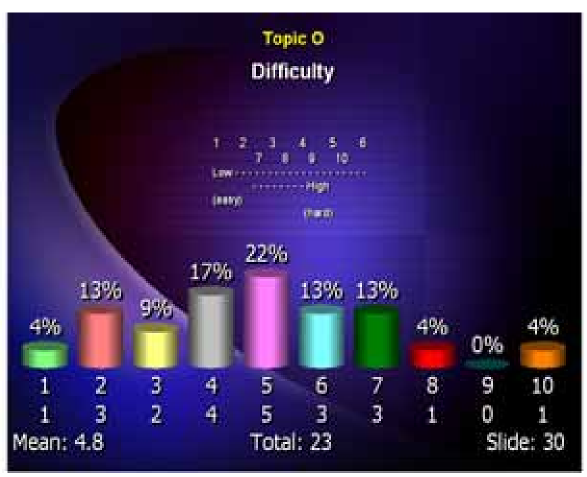
Mean: 4.0
Total: 24
Slide: 28


Topic O
Benefit
25% 13% 25% 13% 13% 8% 4% 0% 0% 0%
1 2 3 4 5 6 7 8 9 10
6 3 6 3 3 2 1 0 0 0
Mean: 3.2
Total: 24
Slide: 29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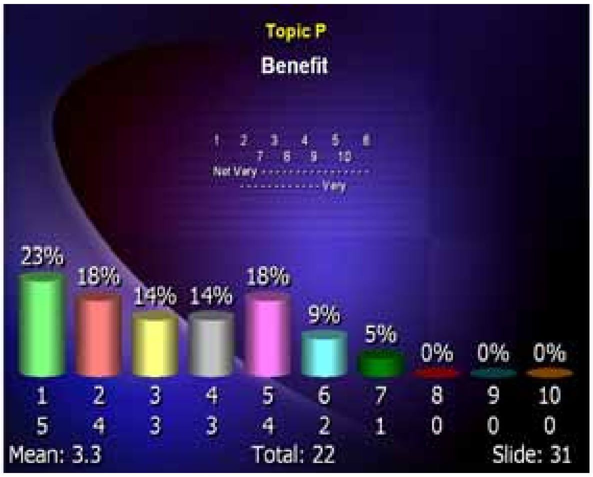
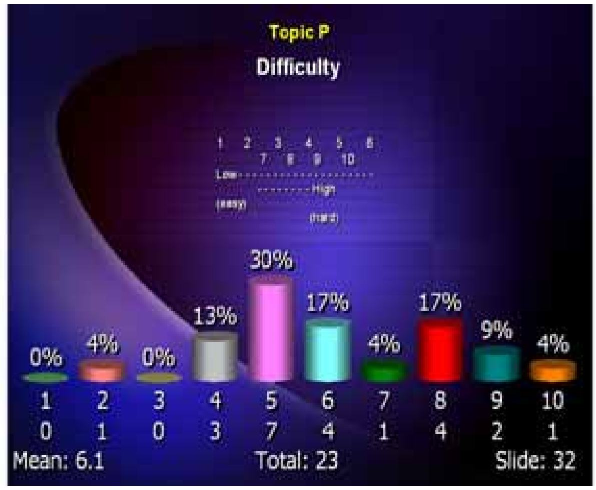
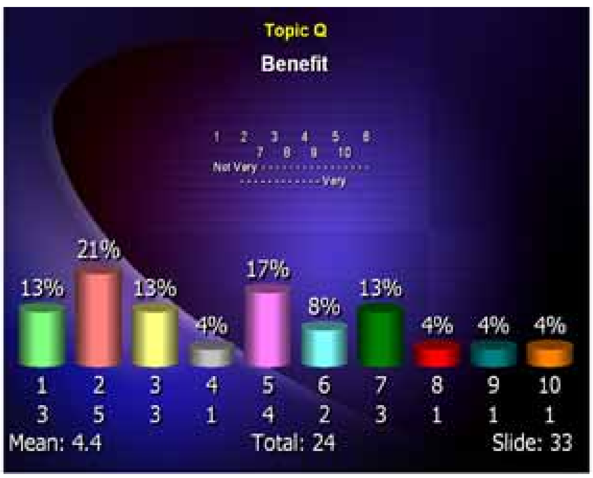
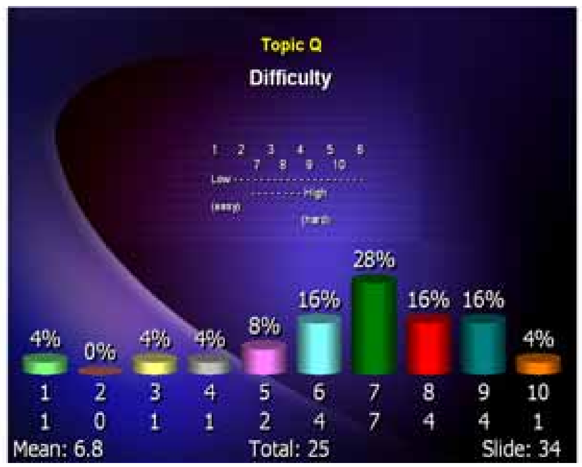
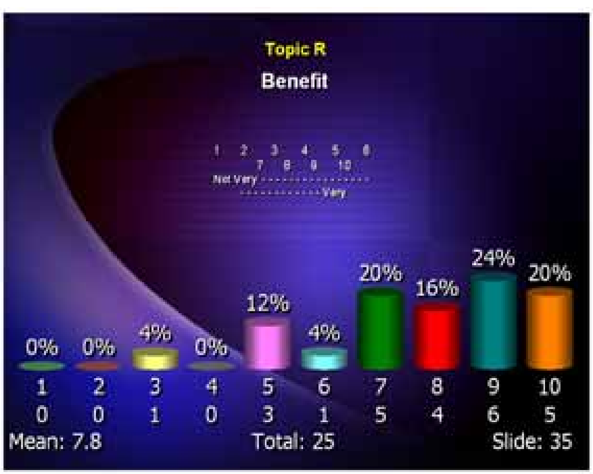
Difficulty
4% 13% 9% 17% 22% 13% 13% 4% 0% 4%
1 2 3 4 5 6 7 8 9 10
1 3 2 4 5 3 3 1 0 1
Mean: 4.8
Total: 23
Slide: 30

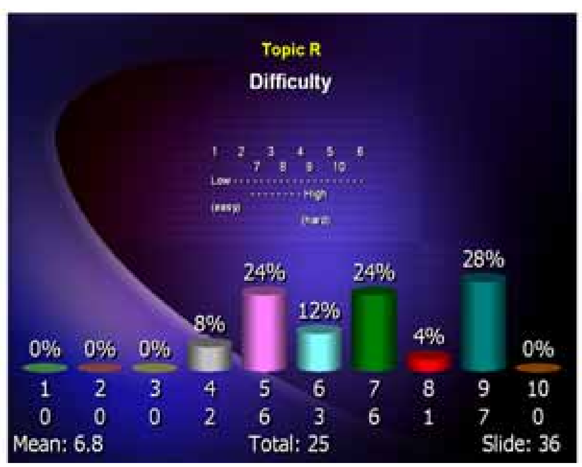

Topic P
Benefit
23% 18% 14% 14% 18% 9% 5% 0% 0% 0%
1 2 3 4 5 6 7 8 9 10
5 4 3 3 4 2 1 0 0 0
Mean: 3.3
Total: 22
Slide: 31

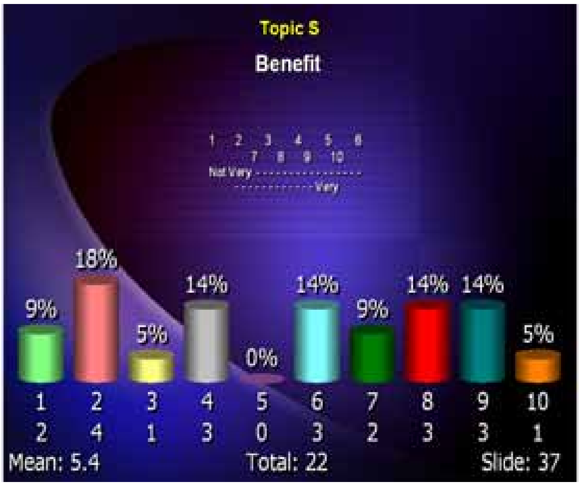

Topic P
Difficulty
0% 4% 0% 13% 30% 17% 4% 17% 9% 4%
1 2 3 4 5 6 7 8 9 10
0 1 0 3 7 4 1 4 2 1
Mean: 6.1
Total: 23
Slide: 32

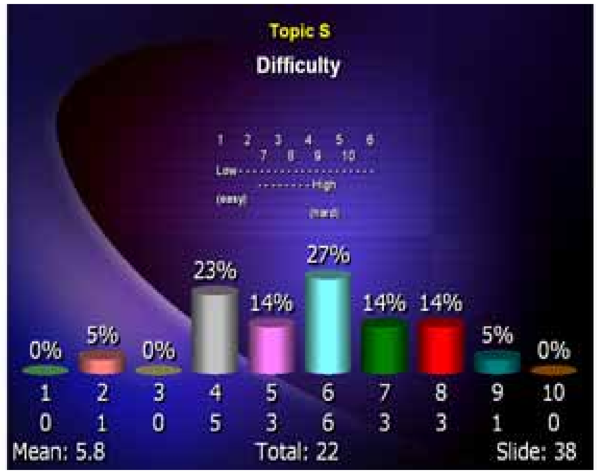

Topic Q
Benefit
13% 21% 13% 4% 17% 8% 13% 4% 4% 4%
1 2 3 4 5 6 7 8 9 10
3 5 3 1 4 2 3 1 1 1
Mean: 4.4
Total: 24
Slide: 33

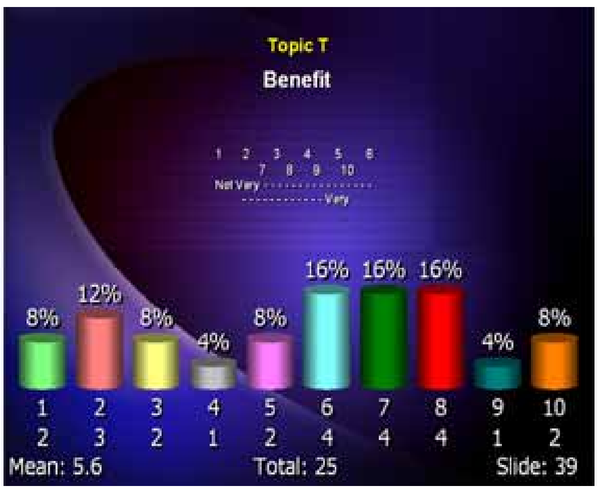

Topic Q
Difficulty
4% 0% 4% 4% 8% 16% 28% 16% 16% 4%
1 2 3 4 5 6 7 8 9 10
1 0 1 1 2 4 7 4 4 1
Mean: 6.8
Total: 25
Slide: 34

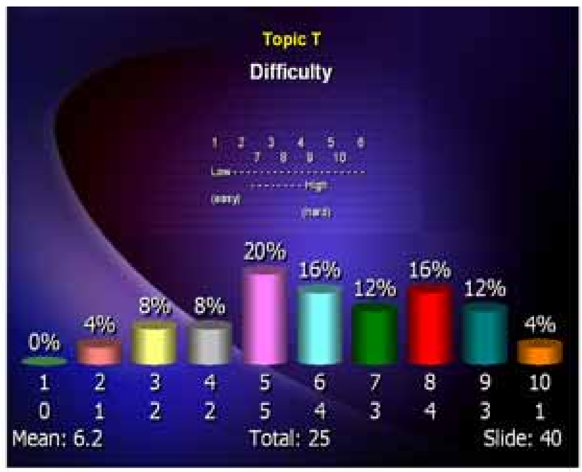

Topic R
Benefit
0% 0% 4% 0% 12% 4% 20% 16% 24% 20%
1 2 3 4 5 6 7 8 9 10
0 0 1 0 3 1 5 4 6 5
Mean: 7.8
Total: 25
Slide: 35

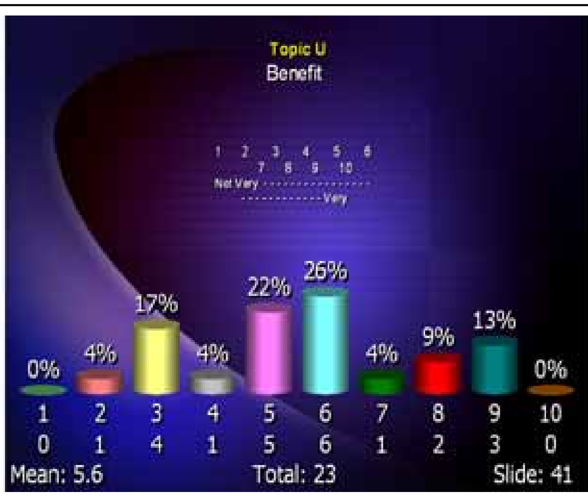

Topic R
Difficulty
0% 0% 0% 8% 24% 12% 24% 4% 28% 0%
1 2 3 4 5 6 7 8 9 10
0 0 0 2 6 3 6 1 7 0
Mean: 6.8
Total: 25
Slide: 36

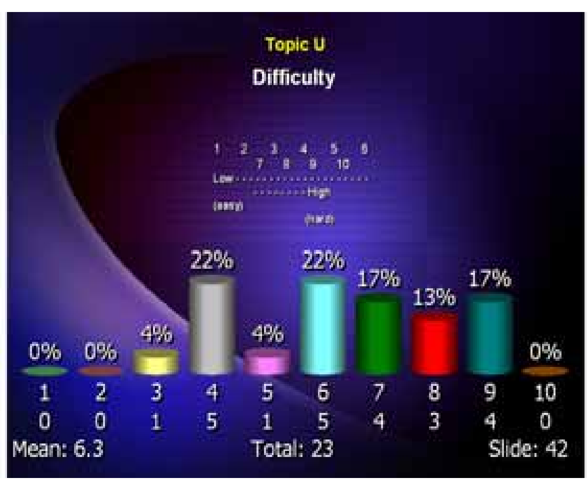

Topic S
Benefit
9% 18% 5% 14% 0% 14% 9% 14% 14% 5%
1 2 3 4 5 6 7 8 9 10
2 4 1 3 0 3 2 3 3 1
Mean: 5.4
Total: 22
Slide: 37

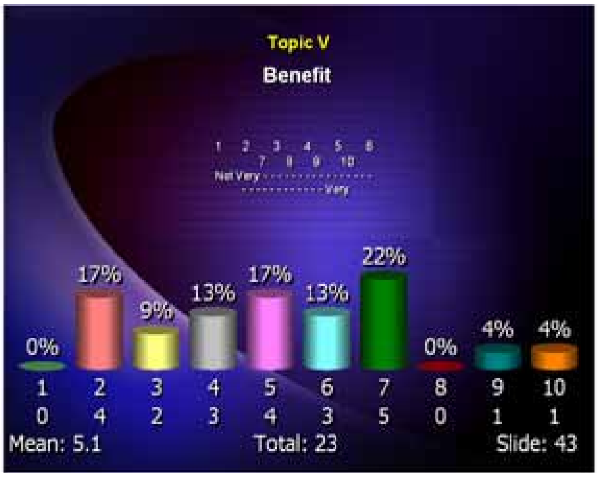

Topic S
Difficulty
0% 5% 0% 23% 14% 27% 14% 14% 5% 0%
1 2 3 4 5 6 7 8 9 10
0 1 0 5 3 6 3 3 1 0
Mean: 5.8
Total: 22
Slide: 38

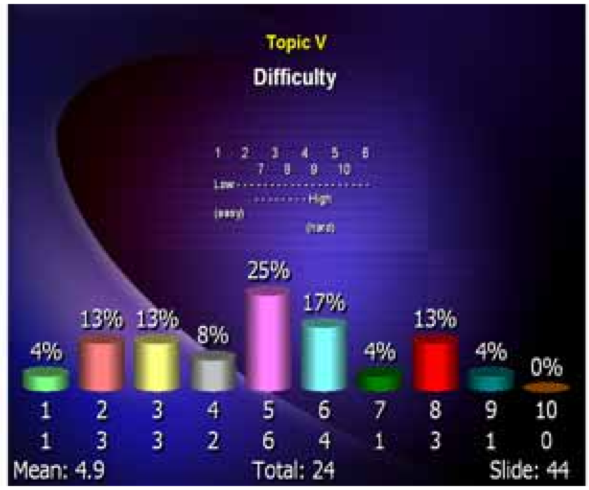

Topic T
Benefit
8% 12% 8% 4% 8% 16% 16% 16% 4% 8%
1 2 3 4 5 6 7 8 9 10
2 3 2 1 2 4 4 4 1 2
Mean: 5.6
Total: 25
Slide: 39

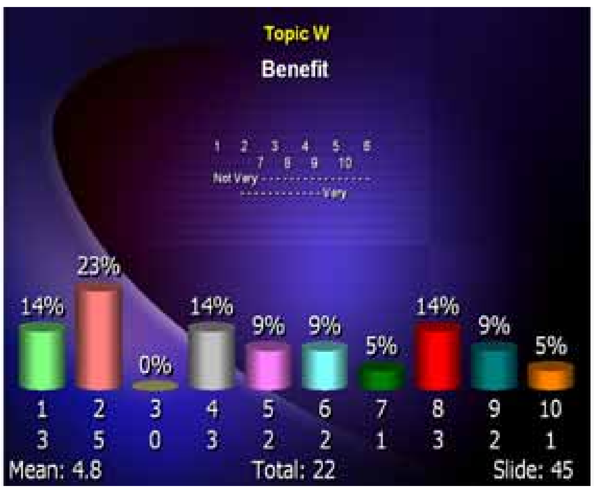

Topic T
Difficulty
0% 4% 8% 8% 20% 16% 12% 16% 12% 4%
1 2 3 4 5 6 7 8 9 10
0 1 2 2 5 4 3 4 3 1
Mean: 6.2
Total: 25
Slide: 40

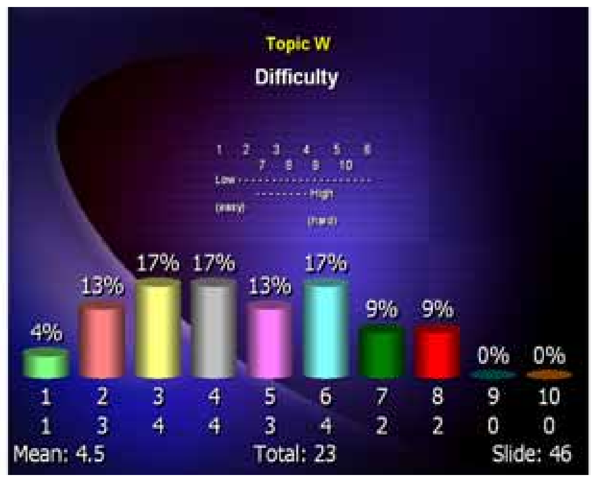

Topic U
Benefit
0% 4% 17% 4% 22% 26% 4% 9% 13% 0%
1 2 3 4 5 6 7 8 9 10
0 1 4 1 5 6 1 2 3 0
Mean: 5.6
Total: 23
Slide: 41

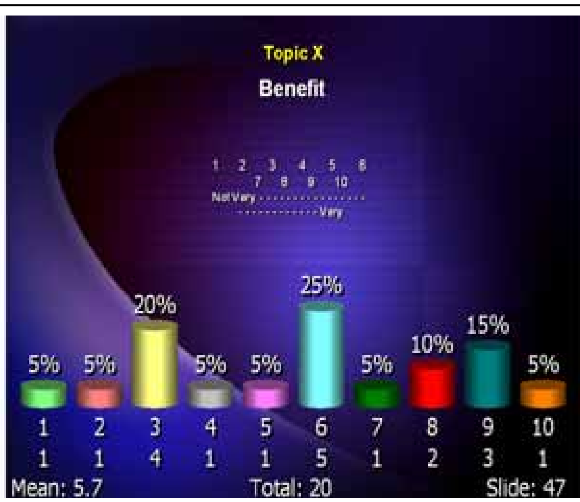

Topic U
Difficulty
0% 0% 4% 22% 4% 22% 17% 13% 17% 0%
1 2 3 4 5 6 7 8 9 10
0 0 1 5 1 5 4 3 4 0
Mean: 6.3
Total: 23
Slide: 42

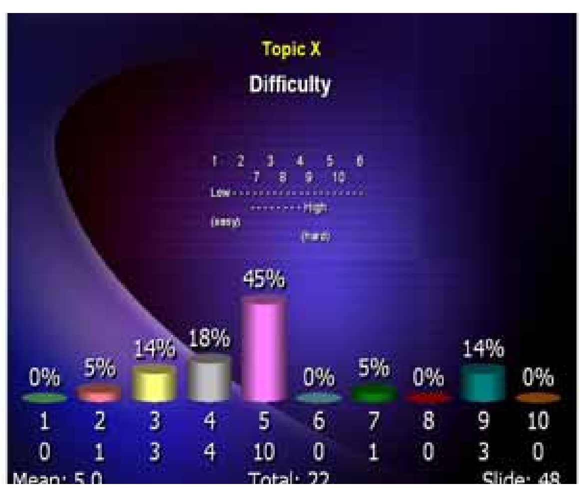

Topic V
Benefit
1 2 3 4 5 6
7 8 9 10
Not Very
Very
0% 17% 9% 13% 17% 13% 22% 0% 4% 4%
1 2 3 4 5 6 7 8 9 10
0 4 2 3 4 3 5 0 1 1
Mean: 5.1
Total: 23
Slide: 43

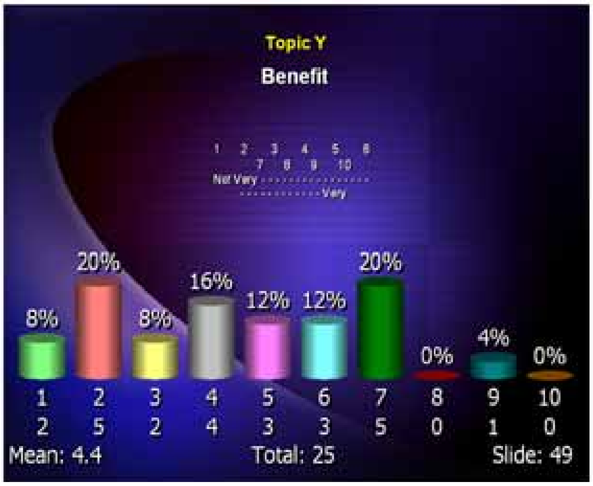

Topic V
Difficulty
1 2 3 4 5 6
7 8 9 10
Low
High
(easy)
(hard)
4% 13% 13% 8% 25% 17% 4% 13% 4% 0%
1 2 3 4 5 6 7 8 9 10
1 3 3 2 6 4 1 3 1 0
Mean: 4.9
Total: 24
Slide: 44

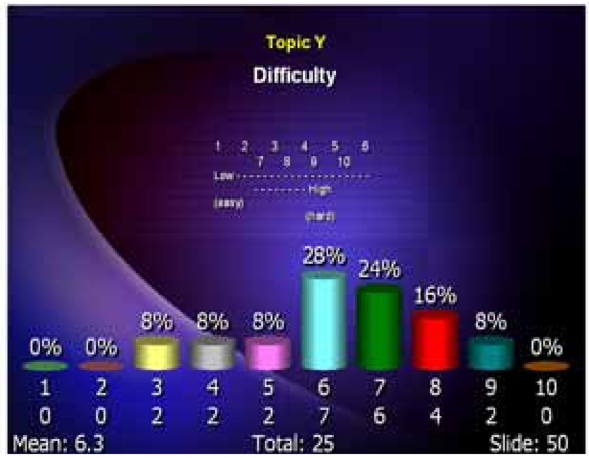

Topic W
Benefit
1 2 3 4 5 6
7 8 9 10
Not Very
Very
14% 23% 0% 14% 9% 9% 5% 14% 9% 5%
1 2 3 4 5 6 7 8 9 10
3 5 0 3 2 2 1 3 2 1
Mean: 4.8
Total: 22
Slide: 45

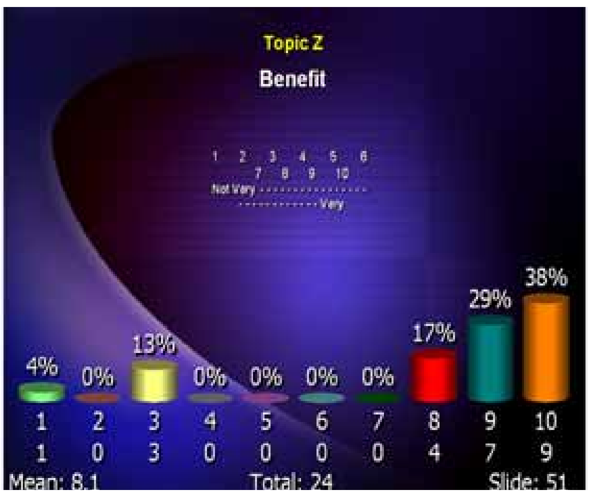

Topic W
Difficulty
1 2 3 4 5 6
7 8 9 10
Low
High
(easy)
(hard)
4% 13% 17% 17% 13% 17% 9% 9% 0% 0%
1 2 3 4 5 6 7 8 9 10
1 3 4 4 3 4 2 2 0 0
Mean: 4.5
Total: 23
Slide: 46

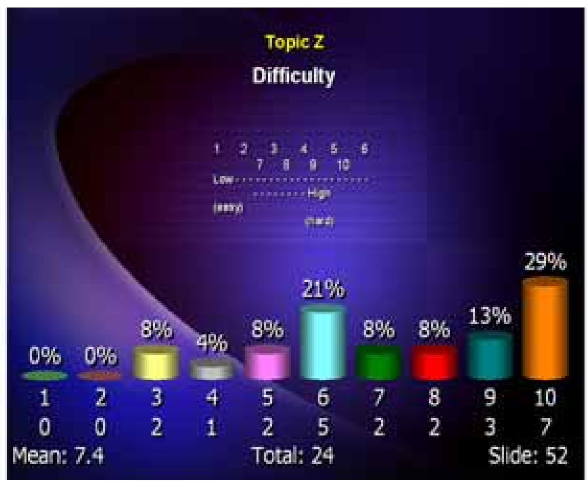

Topic X
Benefit
1 2 3 4 5 6
7 8 9 10
Not Very
Very
5% 5% 20% 5% 5% 25% 5% 10% 15% 5%
1 2 3 4 5 6 7 8 9 10
1 1 4 1 1 5 1 2 3 1
Mean: 5.7
Total: 20
Slide: 47

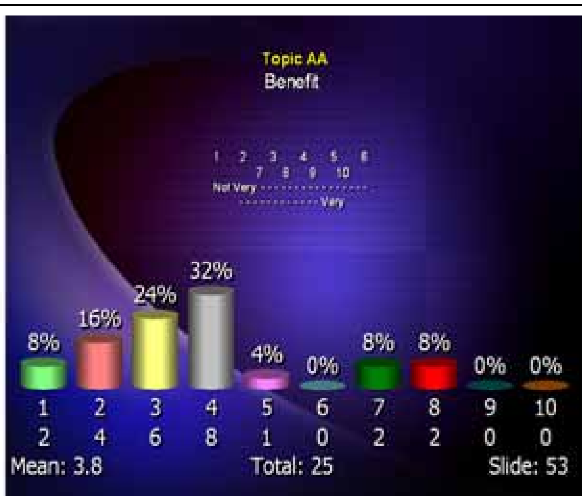

Topic X
Difficulty
1 2 3 4 5 6
7 8 9 10
Low
High
(easy)
(hard)
0% 5% 14% 18% 45% 0% 5% 0% 14% 0%
1 2 3 4 5 6 7 8 9 10
0 1 3 4 10 0 1 0 3 0

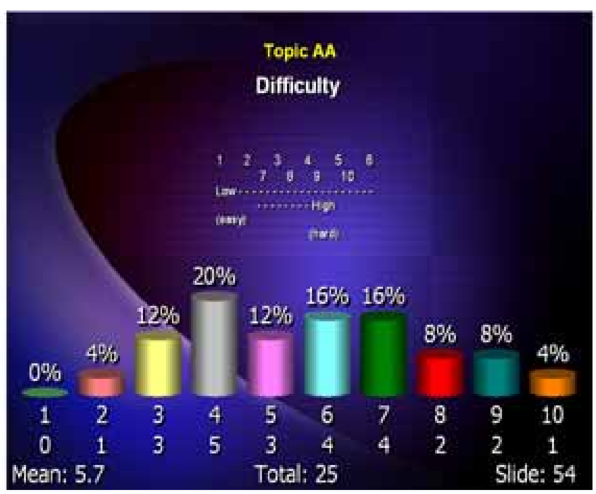

Topic Y
Benefit
8% 20% 8% 16% 12% 12% 20% 0% 4% 0%
1 2 3 4 5 6 7 8 9 10
2 5 2 4 3 3 5 0 1 0
Mean: 4.4
Total: 25
Slide: 49

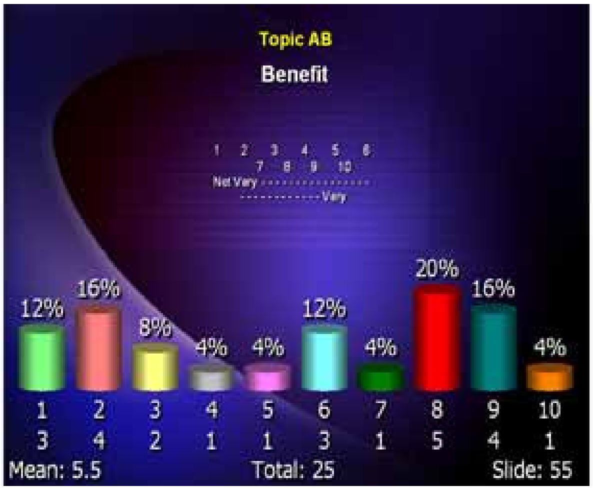

Topic Y
Difficulty
0% 0% 8% 8% 8% 28% 24% 16% 8% 0%
1 2 3 4 5 6 7 8 9 10
0 0 2 2 2 7 6 4 2 0
Mean: 6.3
Total: 25
Slide: 50

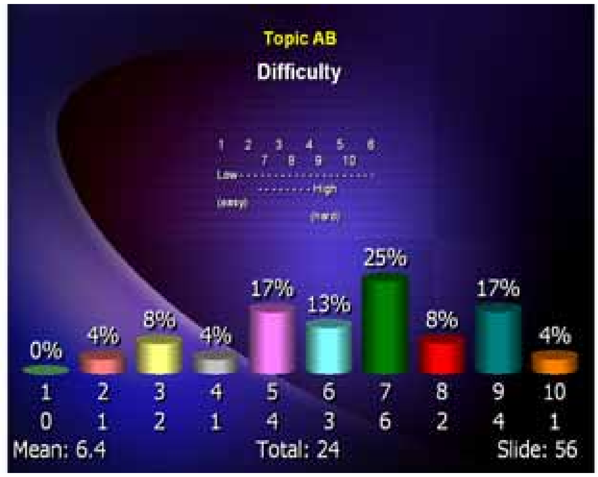

Topic Z
Benefit
4% 0% 13% 0% 0% 0% 0% 17% 29% 38%
1 2 3 4 5 6 7 8 9 10
1 0 3 0 0 0 0 4 7 9
Mean: 8.1
Total: 24
Slide: 51

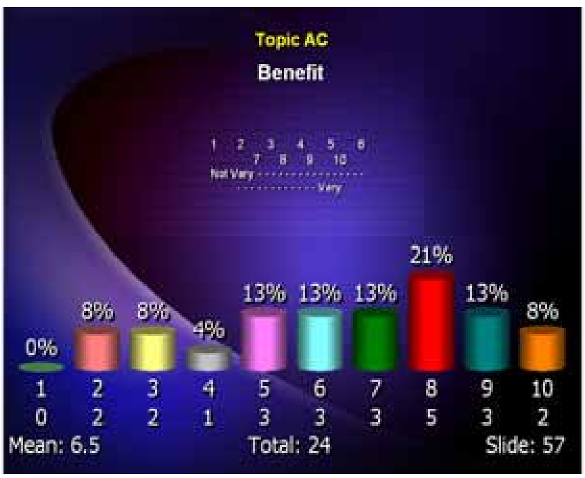

Topic Z
Difficulty
0% 0% 8% 4% 8% 21% 8% 8% 13% 29%
1 2 3 4 5 6 7 8 9 10
0 0 2 1 2 5 2 2 3 7
Mean: 7.4
Total: 24
Slide: 52

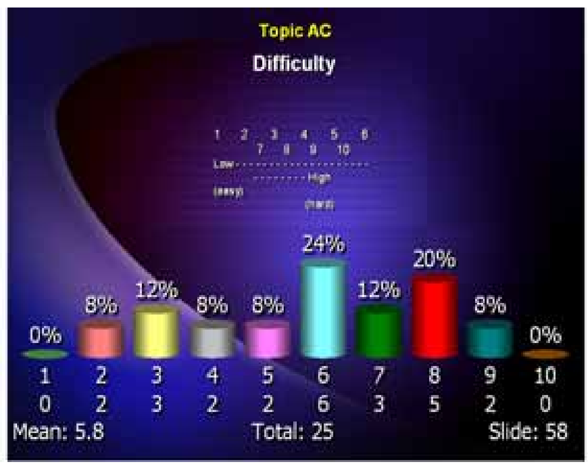

Topic AA
Benefit
8% 16% 24% 32% 4% 0% 8% 8% 0% 0%
1 2 3 4 5 6 7 8 9 10
2 4 6 8 1 0 2 2 0 0
Mean: 3.8
Total: 25
Slide: 53

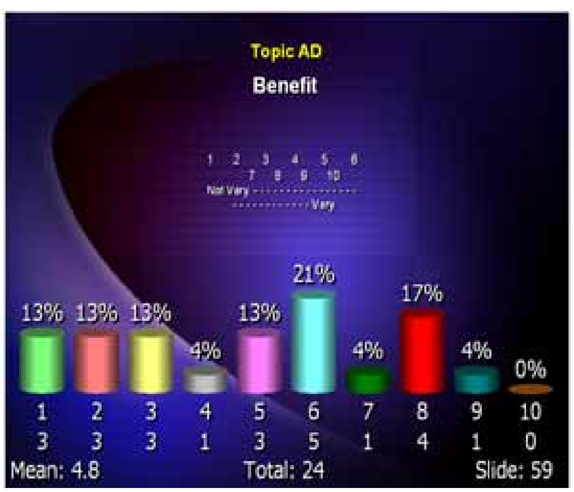

Topic AA
Difficulty
0% 4% 12% 20% 12% 16% 16% 8% 8% 4%
1 2 3 4 5 6 7 8 9 10
0 1 3 5 3 4 4 2 2 1
Mean: 5.7
Total: 25
Slide: 54

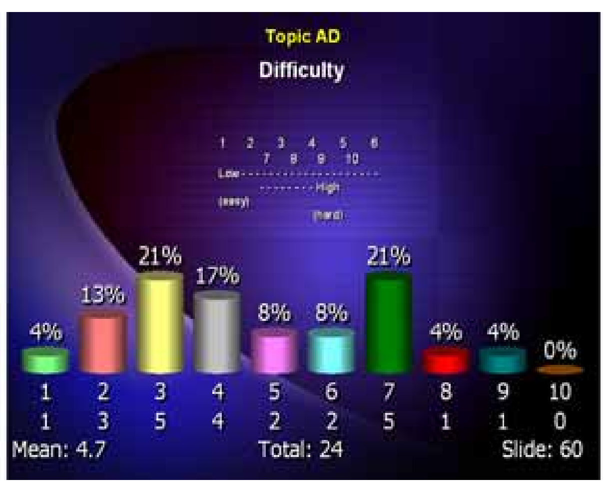

Topic AB
Benefit
1 2 3 4 5 6 7 8 9 10
Not Very ---------- Very
12% 16% 8% 4% 4% 12% 4% 20% 16% 4%
1 2 3 4 5 6 7 8 9 10
3 4 2 1 1 3 1 5 4 1
Mean: 5.5
Total: 25
Slide: 55

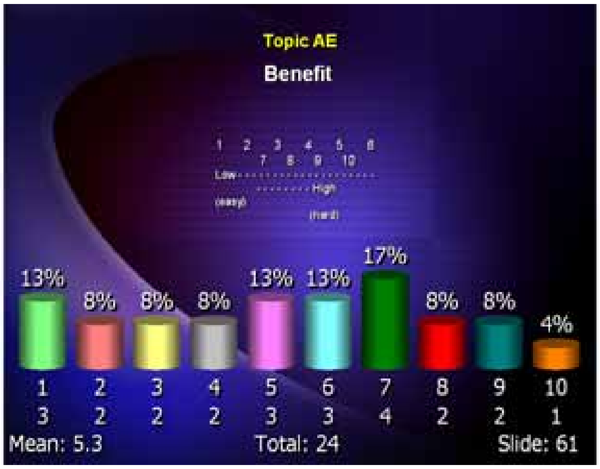

Topic AB
Difficulty
1 2 3 4 5 6 7 8 9 10
Low ---------- High
(easy)
(hard)
0% 4% 8% 4% 17% 13% 25% 8% 17% 4%
1 2 3 4 5 6 7 8 9 10
0 1 2 1 4 3 6 2 4 1
Mean: 6.4
Total: 24
Slide: 56

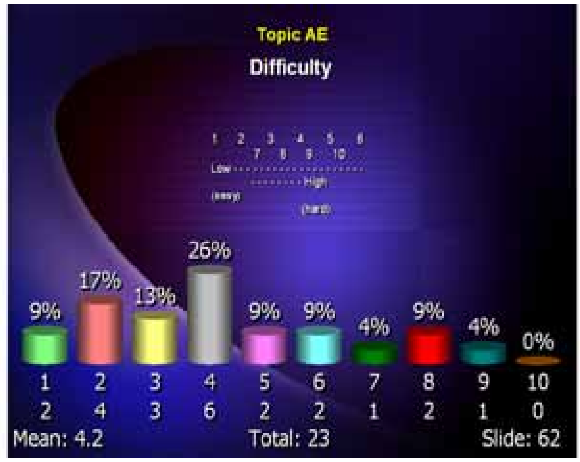

Topic AC
Benefit
1 2 3 4 5 6 7 8 9 10
Not Very ---------- Very
0% 8% 8% 4% 13% 13% 13% 21% 13% 8%
1 2 3 4 5 6 7 8 9 10
0 2 2 1 3 3 3 5 3 2
Mean: 6.5
Total: 24
Slide: 57

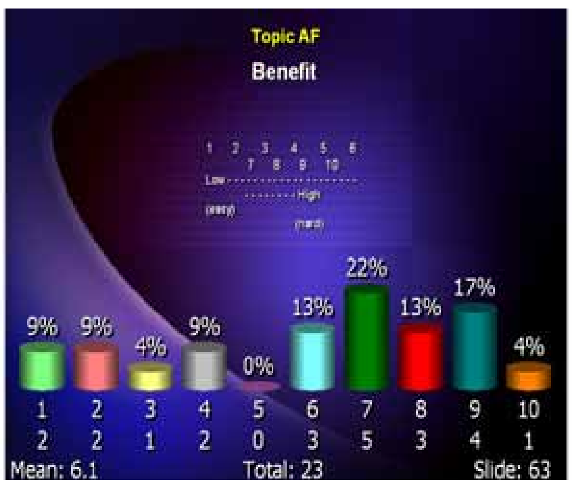

Topic AC
Difficulty
1 2 3 4 5 6 7 8 9 10
Low ---------- High
(easy)
(hard)
0% 8% 12% 8% 8% 24% 12% 20% 8% 0%
1 2 3 4 5 6 7 8 9 10
0 2 3 2 2 6 3 5 2 0
Mean: 5.8
Total: 25
Slide: 58

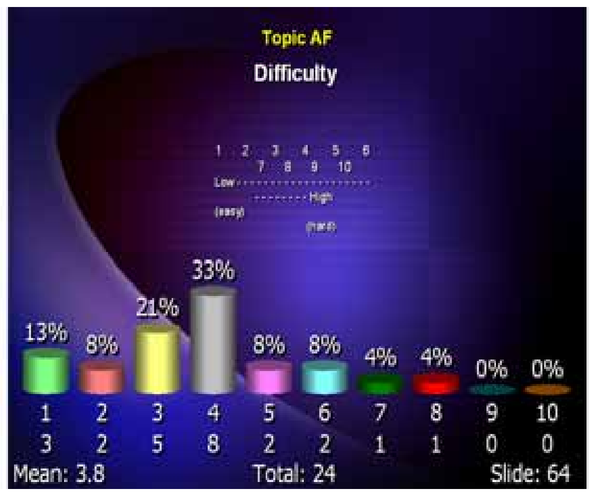

Topic AD
Benefit
1 2 3 4 5 6 7 8 9 10
Not Very ---------- Very
13% 13% 13% 4% 13% 21% 4% 17% 4% 0%
1 2 3 4 5 6 7 8 9 10
3 3 3 1 3 5 1 4 1 0
Mean: 4.8
Total: 24
Slide: 59

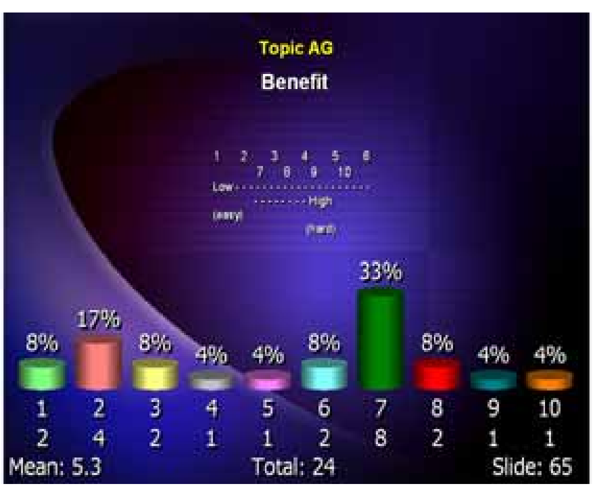

Topic AD
Difficulty
1 2 3 4 5 6 7 8 9 10
Low ---------- High
(easy)
(hard)
4% 13% 21% 17% 8% 8% 21% 4% 4% 0%
1 2 3 4 5 6 7 8 9 10
1 3 5 4 2 2 5 1 1 0
Mean: 4.7
Total: 24
Slide: 60

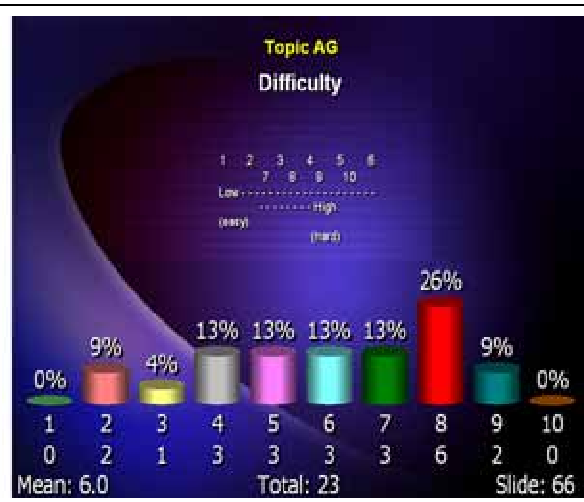

Topic AE
Benefit
1 2 3 4 5 6 7 8 9 10
Low - - - - High
(easy) (hard)
13% 8% 8% 8% 13% 13% 17% 8% 8% 4%
1 2 3 4 5 6 7 8 9 10
3 2 2 2 3 3 4 2 2 1
Mean: 5.3 Total: 24 Slide: 61


Topic AE
Difficulty
1 2 3 4 5 6 7 8 9 10
Low - - - - High
(easy) (hard)
9% 17% 13% 26% 9% 9% 4% 9% 4% 0%
1 2 3 4 5 6 7 8 9 10
2 4 3 6 2 2 1 2 1 0
Mean: 4.2 Total: 23 Slide: 62


Topic AF
Benefit
1 2 3 4 5 6 7 8 9 10
Low - - - - High
(easy) (hard)
9% 9% 4% 9% 0% 13% 22% 13% 17% 4%
1 2 3 4 5 6 7 8 9 10
2 2 1 2 0 3 5 3 4 1
Mean: 6.1 Total: 23 Slide: 63


Topic AF
Difficulty
1 2 3 4 5 6 7 8 9 10
Low - - - - High
(easy) (hard)
13% 8% 21% 33% 8% 8% 4% 4% 0% 0%
1 2 3 4 5 6 7 8 9 10
3 2 5 8 2 2 1 1 0 0
Mean: 3.8 Total: 24 Slide: 64


Topic AG
Benefit
1 2 3 4 5 6 7 8 9 10
Low - - - - High
(easy) (hard)
8% 17% 8% 4% 4% 8% 33% 8% 4% 4%
1 2 3 4 5 6 7 8 9 10
2 4 2 1 1 2 8 2 1 1
Mean: 5.3 Total: 24 Slide: 65


Topic AG
Difficulty
1 2 3 4 5 6 7 8 9 10
Low - - - - High
(easy) (hard)
0% 9% 4% 13% 13% 13% 13% 26% 9% 0%
1 2 3 4 5 6 7 8 9 10
0 2 1 3 3 3 3 6 2 0
Mean: 6.0 Total: 23 Slide: 66