RELEASE VERSION

Risk Prioritization Tool for Dams

Users Manual

U.S. DEPARTMENT OF HOMELAND SECURITY

FEMA

Prepared for

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Mitigation Division
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1.1. BACKGROUND

Non-federal dams in the United States are regulated by Dam Safety Offices in forty nine of the fifty states. These state government agencies generally fall within departments tasked with broad responsibilities such as environmental protection, natural resources or public safety, and as such usually do not enjoy abundant resources of funding or personnel.

For a time, Texas had a relatively inactive dam safety program once the senior engineer retired, even though they had over 7,500 dams under their jurisdiction. Since then their program has been re-invigorated with new staff and funding. Other states like New Jersey have maintained a strong team of over 10 engineers working on dam safety, while states like Wisconsin have a single dam safety engineer.

The State Dam Safety offices are also limited in their effectiveness by the strength of legislation and political mandate. Regulators do have review authority for new dams and major upgrades, but what about those thousands of dams whose ownership is uncertain, that may not have been inspected in decades, and may now have a higher downstream hazard than when they were designed and built?

An uncomfortable status quo is maintained until an unexpected dam failure disaster strikes, and the State Regulator must answer hard questions from the same politicians who cut their funding just a few months before. Why did you let this happen? Weren’t you doing your job? Didn’t you know this dam would fail in the next flood?

If lucky, the besieged State Regulator can produce a paper trail of letters sent every year pointing out the deficiencies, requesting action from the owner, which is typically met with silence or the challenge of: “who’s going to pay for this?” Some states have developed innovative funding programs including loans and outright grants, but the money is never enough for the problem dams they know about.

Various states have approached this problem in different ways. States like Washington with a mature dam safety program, reliable funding and capable engineering staff have established semi-quantitative scoring systems to rank their dam safety risks. Doug Johnson of Washington Department of Ecology, Dam Safety Office, maintains an evolving “top ten” list where the highest scoring dams are tackled first, removed from the list when upgrades have been completed, and then others take their place.

The Washington system and similar tools used by the Natural Resource and Conservation Service (NRCS) and Colorado are patterned after the United States Bureau of Reclamation (2001) Dam Safety Risk Based Profile System[1]. These systems follow prescriptive scoring sheets that provide a helpful, but not overly illuminating indication of potential dam safety deficiencies. These profiling tools are consistent and rapidly implemented but may rank a dam with two minor deficiencies the same as a dam with one major deficiency.

Unfortunately, most states have no dam safety profiling system at all. Regulators are aware of the major dams and their problems, but what about the problems they don’t know about?

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[1] *US Bureau of Reclamation (2001) Dam Safety Risk Based Profile System*

The States need a simple tool that allows them to identify and prioritize their dam safety risks so that the limited resources available to them can be used most diligently and effectively.

1.1.1. Regulations and Dam Hazard Classification

Dam safety regulations vary dramatically from state to state. Some states have the authority to restrict operation of any dam or reservoir if they have dam safety concerns. However, most states do not have true enforcement power. They can write letters but without the ability to fund and with the ever changing political priorities, there is only so much they can do to influence the majority of unsophisticated dam owners to take action.

Dam safety regulations are grounded in state law and are fully deterministic and prescriptive. Risk-based thinking is a new concept to most state regulators[2]. Dam safety requirements are tied to dam hazard classifications.

Dam hazard classifications vary between states but generally include three classes based on estimated loss of life and downstream damage from a dam failure:

- High Hazard – Probable loss of life;
- Significant Hazard – Possible loss of life, major damage; and
- Low Hazard – No loss of life, minor damage.

High hazard dams attract the most stringent design requirements such as being able to safely pass the probable maximum flood (PMF), must meet modern stability and filter requirements, have limitations on conduit design, and must be able to sustain maximum credible earthquake (MCE) loading, among other requirements. Significant hazard dams have less specific and less difficult requirements such as the typical requirements to safely pass 50% of the PMF, and lesser requirements on zoning and stability. Low hazard dams may only be required to safely pass the 100 year storm and may not require specific geotechnical investigations and analysis, so long as designs with precedent are cited.

So this deterministic regulatory environment has produced a huge inventory of dams, which do not satisfy design criteria for their hazard class. What is the regulator to do?

1.2. OVERVIEW OF NEW PROCESS

1.2.1. Goals and Objectives

URS Group was under contract with the Federal Emergency Management Agency (FEMA) to develop a new tool for Risk-Based Dam Safety Prioritization to be used by State Dam Safety Regulators.

The objectives for development of a “Risk Tool” are outlined below:

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[2] *The NSW Dam Safety Committee in Australia (State Regulator) recently enacted risk-based dam safety legislation and procedures. The FEMA Risk Tool process is fully consistent with these regulations.*

- Essentially a decision-making tool to identify those dams within a large inventory that most urgently need attention and then allocate resources accordingly
- Provide enhanced understanding of key contributors to risk at each dam
- Systematic and reasoned framework for prioritizing and committing resources among many dam safety issues
- Provide a quantifiable measure of risk from which the urgency of actions can be judged
- Means to effectively communicate dam safety risk situation to decision makers and politicians to impact funding priorities
- Provide a consistent methodology throughout the country for regulators to evaluate dam safety.
- Consistent with standards-based regulatory programs in each state.

To achieve these objectives, consideration must be given to the variety of State agencies, policies, regulations and available resources. The dam risk categorization process and Risk Tool must:

- Be simple, quick and easy to implement
- Be applicable to any type or number of dams
- Acknowledge the limited resources available
- Be flexible to accommodate the broad differences between owners and information known about each dam
- Avoid subjectivity and unnecessary bias
- Be transparent, defensible and reproducible

What the dam risk prioritization tool is **not** is a means to judge dam safety tolerability. Once priorities are judged, then risk acceptance or tolerability is a matter of policy that will vary from state to state. As a minimum, each dam would need to be evaluated individually using compliance with deterministic standards or a detailed risk assessment.

1.2.2. Dam Safety Risk Prioritization Tool Development Process

The work described in this report is part of a four year development and implementation process comprised of the following:

- FY 2004 - 2005 – Development of tool;
- FY 2005 - 2006 – State trials and guidance manual preparation; and
- FY 2007 – Roll out to ASDSO member states.

The guidelines and procedures for the Risk Categorization System were developed utilizing the NDSRB Steering Committee for direction, oversight, and review.

The first step was to review a previous ASDSO Committee report and then develop ideas with the new Steering Committee through meetings held in Washington DC, Las Vegas and Annapolis. The original Steering Committee struggled to reach consensus on any issue, but produced a useful framework for the following work.

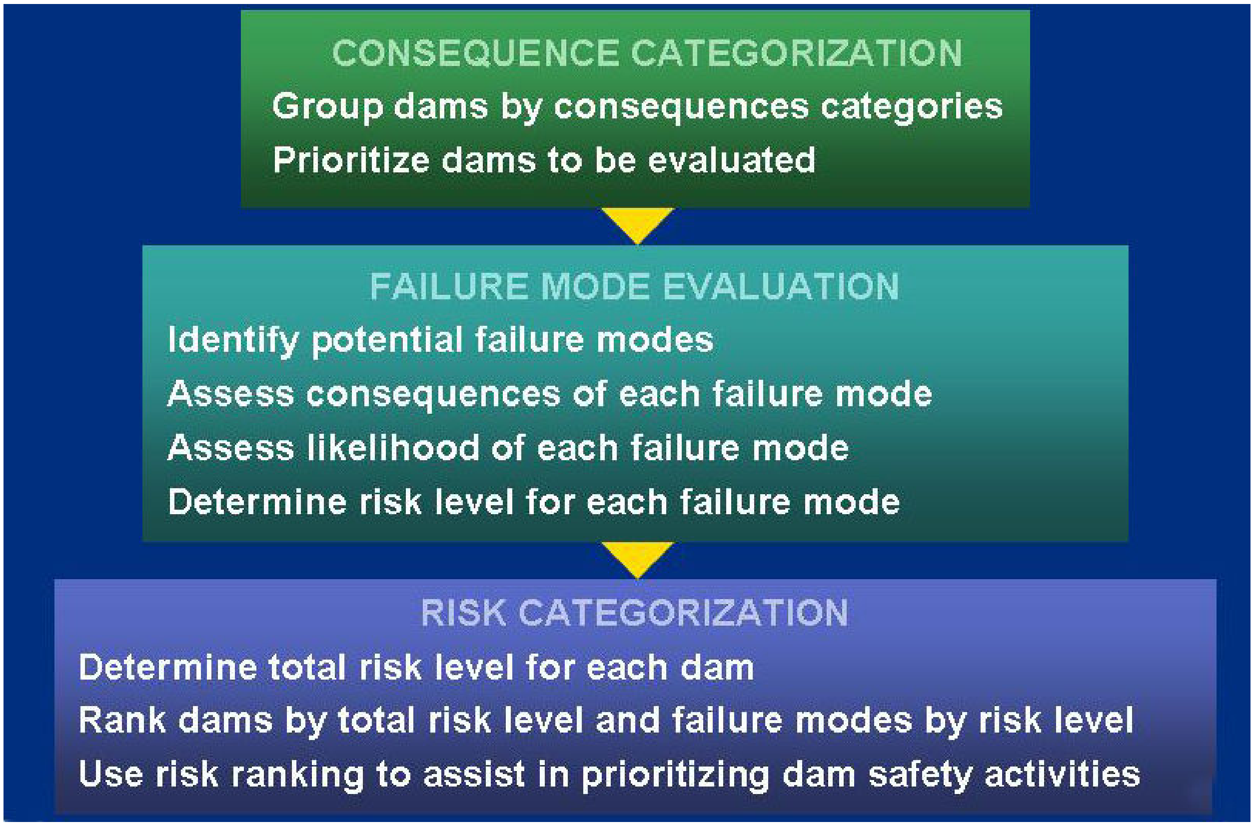
A Consequence Categorization System was established for partitioning an inventory of dams into groupings with similar consequences resulting from dam failure. Dam failure consequence was tied to state dam hazard classification and then expanded to recognize society's aversion to incidents that cause large loss of life. To aid in the prioritization process, Wayne Graham of the United States Bureau of Reclamation (USBR) was commissioned to develop a new simplified loss of life consequence assessment methodology based on the more limited dam failure hydrologic information typically available to state regulators. This process was found to be easy to use and was verified against a number of case histories with dam break / inundation modeling.

Instead of using a generalized, qualitative Risk Matrix of "High, Medium and Low" in the Risk Categorization System, an entirely different system was developed. The revised process builds on the successful elements of various ranking systems currently in use, simplifies potential failure modes analysis and dam risk assessment processes, is based on international guidelines from ANCOLD, International Committee on Large Dams (ICOLD) and others, and is more flexible, quantitative and generally further advanced than the system envisioned in the 2003 ASDSO report. The team relied heavily on the positive experience from Australia and the USBR.

1.2.3. Process Outline

The new process covers the most important failure modes for a wide variety of dam types and dam features, and it explicitly quantifies risks posed by different failure modes. This allows each failure mode likelihood and its consequences to be computed and graphed, and then the failure mode risk and overall dam risk is quantified and compared against risk tolerability criteria.

The Risk Categorization of each dam is then established by the quantitative risk level and its position relative to risk criteria. Each dam can be ranked by total risk and by failure mode risk. Risk Categories parallel those used by the USBR, and reflect different levels of urgency and priority.



CONSEQUENCE CATEGORIZATION

Group dams by consequences categories

Prioritize dams to be evaluated

FAILURE MODE EVALUATION

Identify potential failure modes

Assess consequences of each failure mode

Assess likelihood of each failure mode

Determine risk level for each failure mode

RISK CATEGORIZATION

Determine total risk level for each dam

Rank dams by total risk level and failure modes by risk level

Use risk ranking to assist in prioritizing dam safety activities

The above figure summarizes the three step dam safety risk categorization process. Consequence categorization starts with the existing hazard classification and the National Inventory of Dams (NID) database information. The Failure Mode Evaluation is greatly simplified using a bin process in the worksheet for each type of dam and failure mode to guide the evaluator to failure probabilities based on whatever information is available. The lives consequences are computed in a separate Life Loss Potential (LLP) worksheet. Risk is then quantified by multiplying failure probability by LLP. Risk can then be prioritized based on total dam risk or by failure mode risk.

1.3. DEFINITIONS

Abutment Outflanking – During a flood, flows pass over the reservoir perimeter beyond the limits of the dam structure, probably over the abutments.

As Low As Reasonably Practical (ALARP) –The risk has been reduced as low as reasonably practicable. This reasonableness test reflects society’s aversion to incidents that can potentially cause large loss of life but recognizes that there is a point of diminished returns. ALARP is defined as the point where additional risk reduction is not possible without a disproportionate investment for the benefit gained.

Concrete Core Wall – Early 20th century dam building design when a concrete wall serves as the core with surrounding shells of embankment soils.

Dam Element – a feature of the subject dam which could potentially fail for one of the reasons indicated by the element’s failure modes (i.e. earth dam, unlined spillway, outlet works, etc).

Dam Risk Profile – an individual dam's collection of Elements and LLP worksheets. The Dam Risk Profile is an Excel workbook.

Failure Mode – a method (i.e. piping for an earth dam, earthquake for a concrete dam, etc.) by which a Dam Element could fail resulting in an uncontrolled release of the reservoir.

Failure Probability (F) – a User judged value representing the probability that a particular failure mode will cause failure of the Dam Element. The F value is illustrated as 1 in 100, 1×10^{-2} or 0.01, for example.

Life Loss Potential (LLP) – the number of lives potentially lost given failure of a Dam Element. The LLP value is equal to the estimated population at risk multiplied by a depending upon distance from the dam. Sometimes referred to as "Loss of Life Potential."

Maximum Design Earthquake (MDE) – An extreme design earthquake for which the dam could sustain damage but not catastrophic release of the reservoir. The return period may range from 1 in 5,000 to 1 in 100,000, or may be taken as the deterministic maximum credible earthquake (MCE).

Operating Basis Earthquake (OBE) – An unusual design earthquake expected during the life of the structure with a return period of about 1 in 500 years that does not disrupt the operation of the reservoir.

Population at Risk (PAR) – the estimated number of people within the inundation zone from a dam failure. The value is based on assumed people within dwellings, cars, factories, camping areas, etc that are inside the inundation zone that will get their feet wet.

Risk Portfolio – a collection of User created Dam Risk Profiles. The Risk Portfolio is a Microsoft Excel Workbook which manages the Dam Risk Profile workbooks.

Risk Tool – The combination of Excel spreadsheets (riskportfolio.xls and template.xls) that together comprise the dam risk prioritization program.

Threshold Failure Flood (TFF) – The flood where there is just enough overtopping of the dam to cause breach failure by erosion overturning, sliding, or collapse.

Workbook – A workbook is an excel file that contains one or more worksheets, user forms and macro code. The Risk Portfolio application is an Excel workbook as is each Dam Risk Profile.

Worksheet – A worksheet is a single page within a workbook that contains data arranged in rows and columns.

1.4. LIMITATIONS

The work on this project has been carried out in accordance with reasonable and accepted engineering practices. No warranty or guarantee, either written or implied, is applicable to this work. Additional failure modes and dam elements will likely be added to the tool in future revisions, such as fuse plug spillways, penstocks and slab and buttress concrete dams.

2.1. HARDWARE AND SYSTEM REQUIREMENTS

This application has been developed with Microsoft Excel and will run on any computer that is currently running Microsoft Excel 2002 or newer. Some features of the application will not work with Excel 2000. Screen resolution should be 1024 x 768 or higher. The application requires very little disk space – less than 3 Mb for the application plus 1 Mb for each Dam Profile.

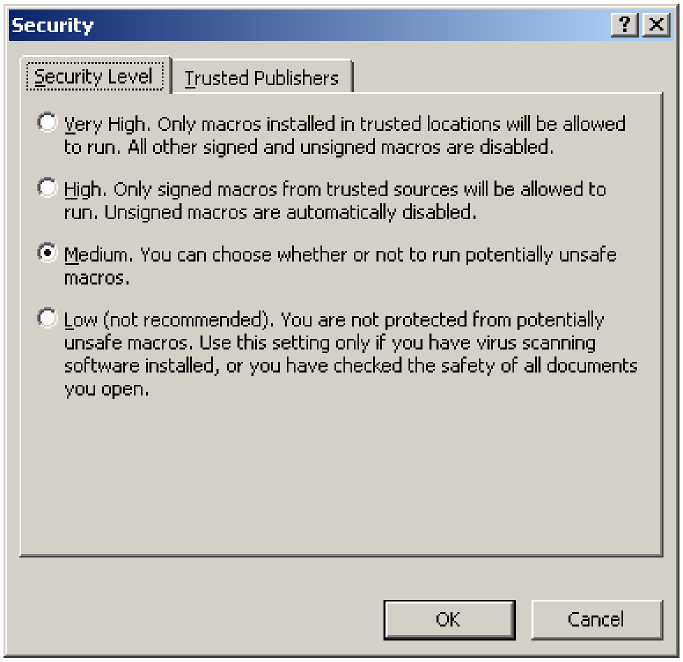
2.2. SOFTWARE INSTALLATION AND SETUP

2.2.1. Installation of the Risk Portfolio Application

The Risk Portfolio application consists of two Microsoft Excel workbooks which must be placed within the same directory on the user's computer.

Copy the two files, RiskPortfolio.xls and Template.xls to the same directory. These file names **CAN NOT** be changed by the User. To create a shortcut to the Risk Tool application on your desktop right-click on the RiskProfile.xls workbook and select the menu item for "Send To", then select "Desktop (Create Shortcut)". It is not necessary to create a shortcut to the Template.xls file as this is a library file only used by the program.

Prior to starting the Risk Tool, the User is required to make modifications to the basic setup of Excel. First, macros must be enabled from the security menu. Furthermore it is necessary to trust the Visual Basic Project. Set these options from the Security dialog box which is available when you click the Tools menu, then select Macros, then Security. On the Security Level tab set the macro level to Medium (or Low). On the Trusted Publishers tab select the checkbox to Trust Access to Visual Basic Project.



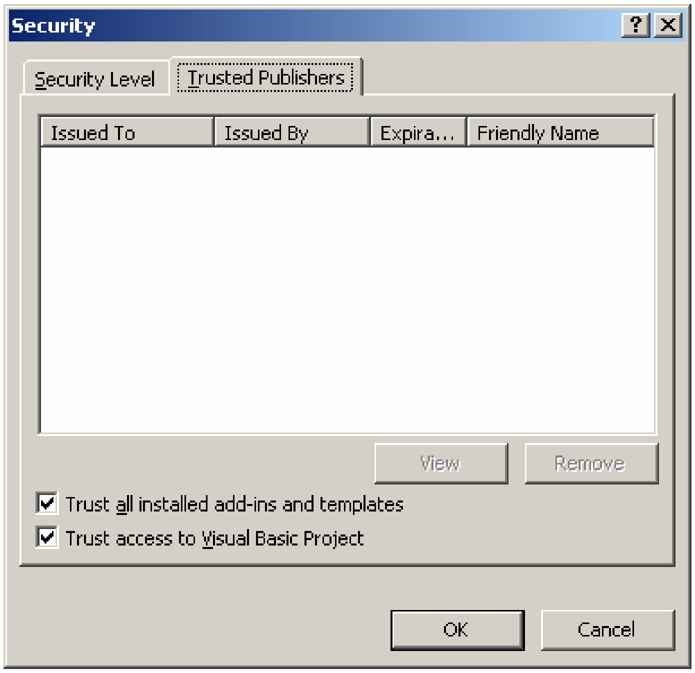
○ Very High. Only macros installed in trusted locations will be allowed to run. All other signed and unsigned macros are disabled.

○ High. Only signed macros from trusted sources will be allowed to run. Unsigned macros are automatically disabled.

● Medium. You can choose whether or not to run potentially unsafe macros.

○ Low (not recommended). You are not protected from potentially unsafe macros. Use this setting only if you have virus scanning software installed, or you have checked the safety of all documents you open.

Security Dialog Box Showing Security Level

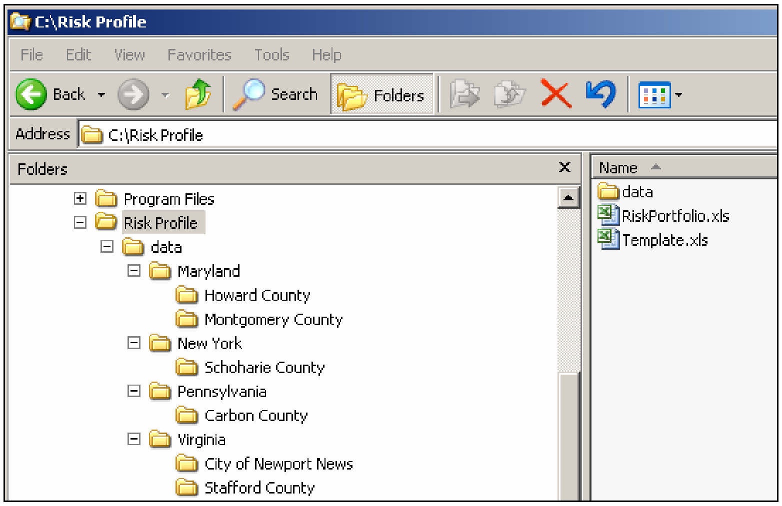


☑ Trust all installed add-ins and templates
☑ Trust access to Visual Basic Project

Security Dialog Box Showing Trusted Publishers Tab

2.2.2. Directory Structure of the Application

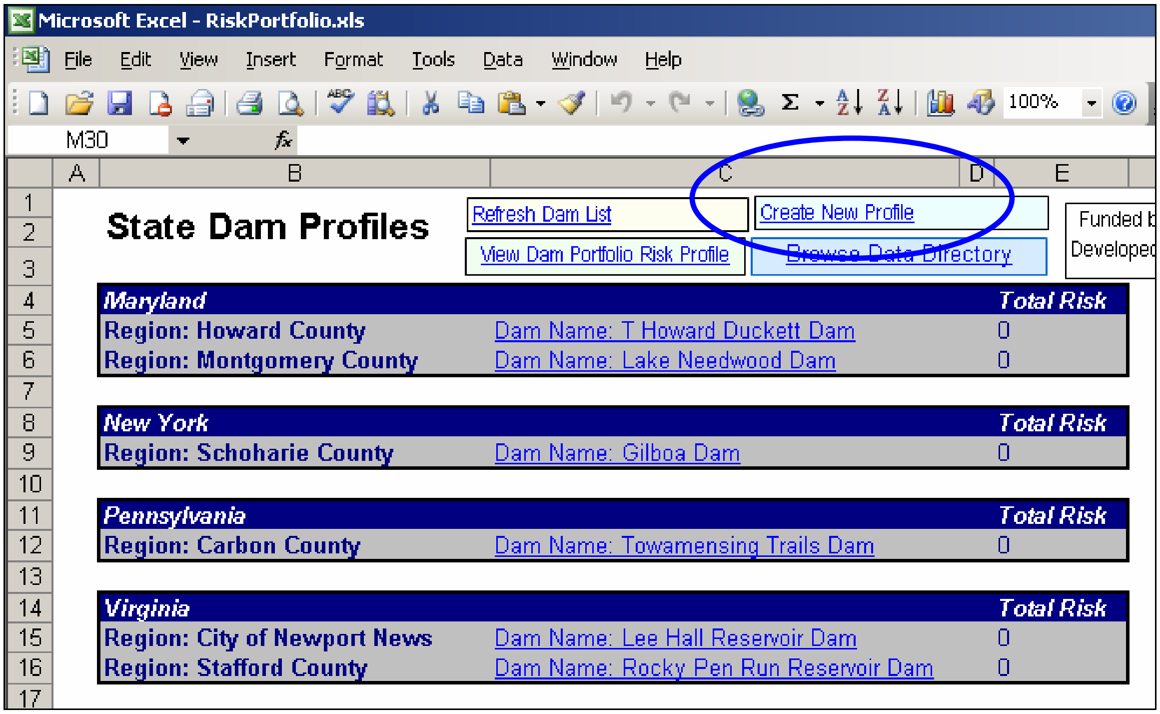
In the screenshot below, note that the RiskPortfolio.xls and Template.xls workbooks are in the same directory. As individual dam risk profiles are created they are placed in the data folder by State and Region. It is not necessary to access the workbooks from the directories because the Risk Portfolio workbook contains a list of all the dam profiles on the Risk Portfolio Main Page (shown below). Please **DO NOT** move the workbooks to different directories or the charts that track the risk will not be able to include them in the totals.



Directory Showing Data Directory

2.2.3. The RiskPortfolio.xls Workbook

From this workbook you can create Dam Risk Profiles, view a listing of the profiles organized by state and region, or view a chart of existing Dam Risk Profiles.



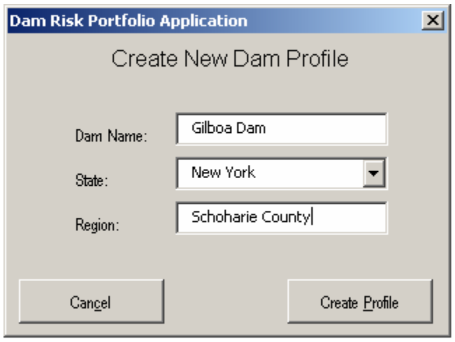
State Dam Profiles

		Total Risk
Maryland		***Total Risk***
Region: Howard County	Dam Name: T Howard Duckett Dam	0
Region: Montgomery County	Dam Name: Lake Needwood Dam	0
New York		***Total Risk***
Region: Schoharie County	Dam Name: Gilboa Dam	0
Pennsylvania		***Total Risk***
Region: Carbon County	Dam Name: Towamensing Trails Dam	0
Virginia		***Total Risk***
Region: City of Newport News	Dam Name: Lee Hall Reservoir Dam	0
Region: Stafford County	Dam Name: Rocky Pen Run Reservoir Dam	0

RiskPortfolio.xls Main Page

How to Create a Dam Risk Profile

From the RiskPortfolio.xls workbook, click on the link called "Create New Profile" (shown in the above screenshot). This will bring up a window (shown below) into which you must enter the Dam Name, State, and Region. Once you click the Create Profile button the new Dam Risk Profile is created, then opened and the total risk is added to the main page of the RiskPortfolio.xls workbook.

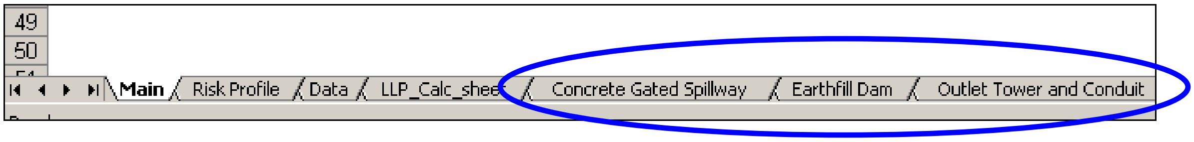


Dam Name: Gilboa Dam
State: New York
Region: Schoharie County

Create New Profile Window

How to view or edit a Dam Risk Profile

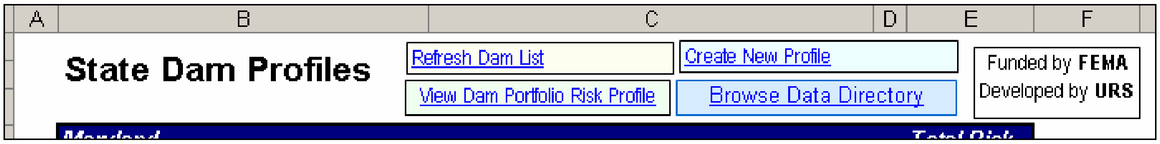
Click on the link for the Dam Risk Profile's name from the RiskPortfolio.xls main page (shown above). This will open the respective dam's risk profile and from there you can fill in data about the dam and add or remove dam elements. You can browse the dam elements by clicking on their worksheet tabs.



Worksheet Tabs Showing Dam Elements

How to Delete a Dam Risk Profile

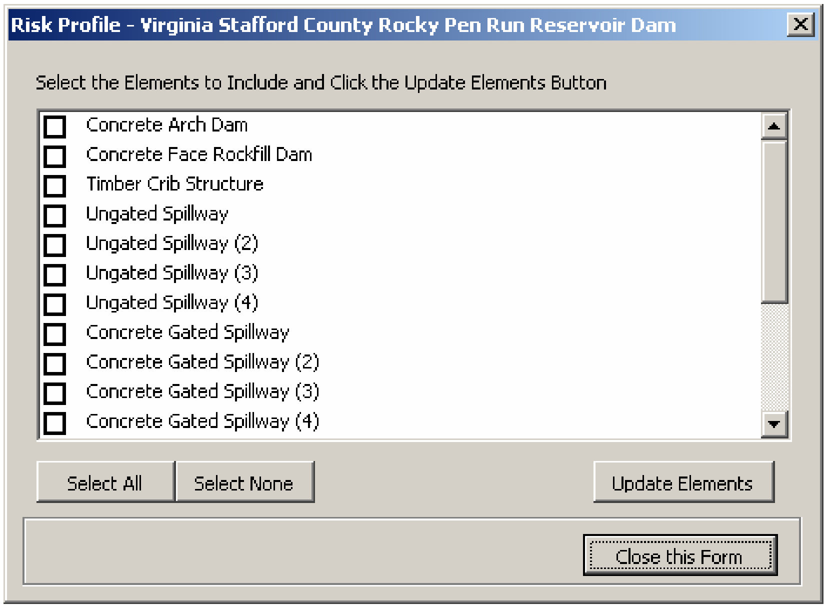
Simply remove the Dam Risk Profile from the data directory. You can do this by clicking on the link called "Browse Data Directory". This will open the windows file Explorer from which you can select and delete the appropriate workbooks and directories. Changes made to the directory will be reflected when you click the "Refresh Dam List" link or reopen the Risk Portfolio application.



Links for Managing Dam Risk Profiles

How to add or remove Dam Elements from a Dam Risk Profile

While in the Dam Risk Profile you can click the button to Add or Remove Elements. This will open a form listing all possible elements. Existing elements will be checked. You can check or uncheck the elements as required for the particular dam.



Risk Profile - Virginia Stafford County Rocky Pen Run Reservoir Dam

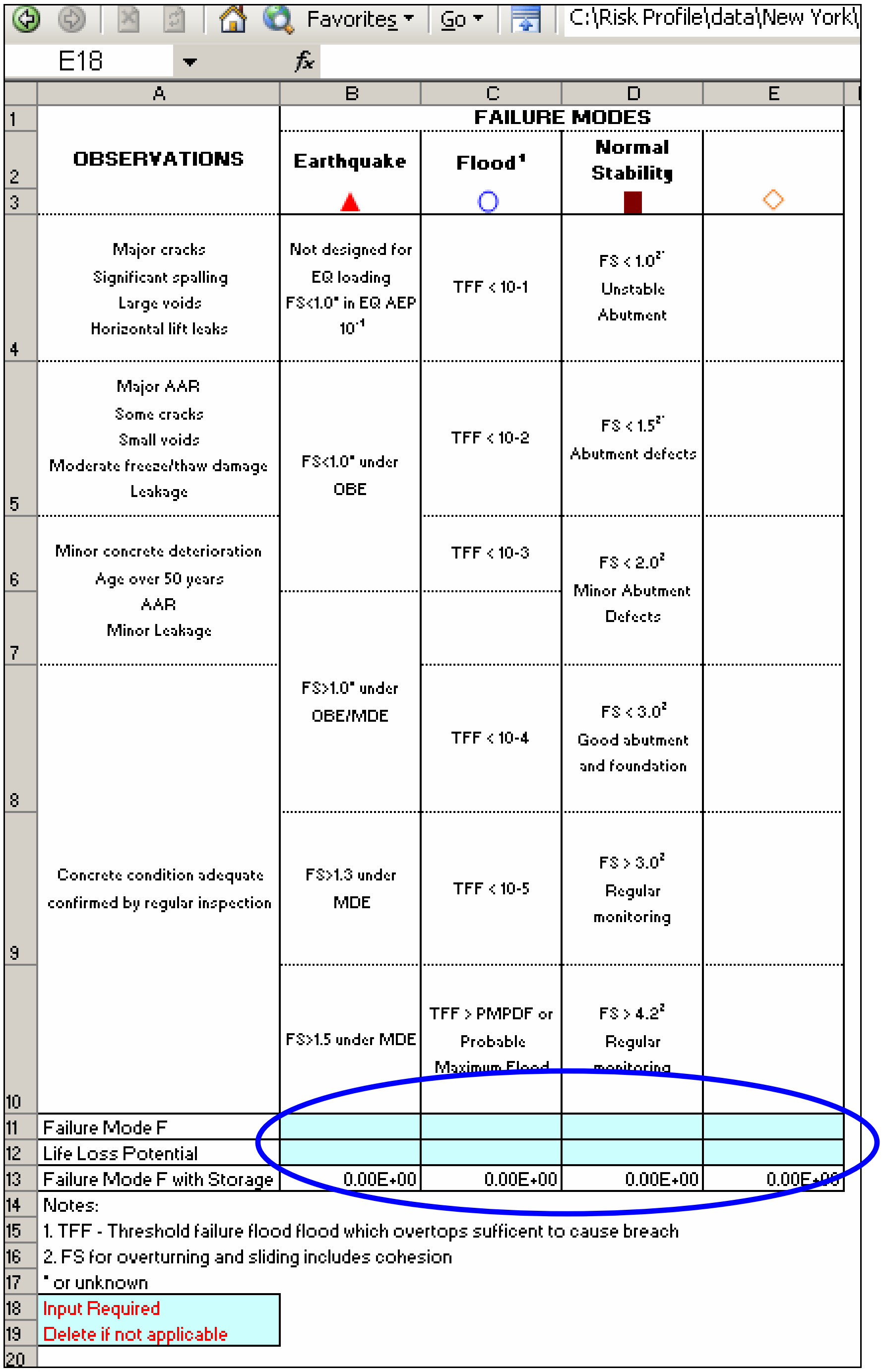
Select the Elements to Include and Click the Update Elements Button

☐ Concrete Arch Dam
☐ Concrete Face Rockfill Dam
☐ Timber Crib Structure
☐ Ungated Spillway
☐ Ungated Spillway (2)
☐ Ungated Spillway (3)
☐ Ungated Spillway (4)
☐ Concrete Gated Spillway
☐ Concrete Gated Spillway (2)
☐ Concrete Gated Spillway (3)
☐ Concrete Gated Spillway (4)

Form Used to Include or Exclude Dam Elements

Editing Failure Probabilities (F) for Dam Elements

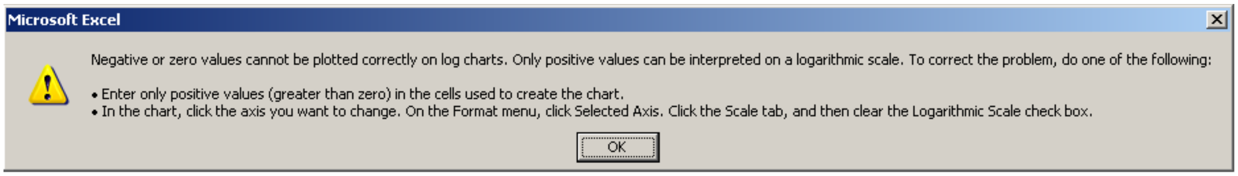
Each Dam Element contains three or four failure modes that are tailored to the Dam Element. In the screenshot below the failure modes are Earthquake, Flood and Normal Stability. The values for these failure modes should be entered in the blue boxes in rows 11 and 12. Selection of the appropriate F values depends upon review of available design and construction data as well as visual observations. Guidance is provided in Section 3.3.



	A	B	C	D	E
1		FAILURE MODES			
2	OBSERVATIONS	Earthquake	Flood^{1}	Normal Stability	
3		▲	○	■	◇
4	Major cracks Significant spalling Large voids Horizontal lift leaks	Not designed for EQ loading FS<1.0* in EQ AEP 10^{-1}	TFF < 10-1	FS < 1.0^{2*} Unstable Abutment	
5	Major AAR Some cracks Small voids Moderate freeze/thaw damage Leakage	FS<1.0* under OBE	TFF < 10-2	FS < 1.5^{2*} Abutment defects	
6	Minor concrete deterioration Age over 50 years AAR Minor Leakage		TFF < 10-3	FS < 2.0^{2} Minor Abutment Defects	
7		FS>1.0* under OBE/MDE			
8			TFF < 10-4	FS < 3.0^{2} Good abutment and foundation	
9	Concrete condition adequate confirmed by regular inspection	FS>1.3 under MDE	TFF < 10-5	FS > 3.0^{2} Regular monitoring	
10		FS>1.5 under MDE	TFF > PMPDF or Probable Maximum Flood	FS > 4.2^{2} Regular monitoring	
11	Failure Mode F				
12	Life Loss Potential				
13	Failure Mode F with Storage	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	Notes:				
15	1. TFF - Threshold failure flood flood which overtops sufficent to cause breach				
16	2. FS for overturning and sliding includes cohesion				
17	* or unknown				
18	Input Required				
19	Delete if not applicable				
20					

Failure Modes Exist For Each Element

As you enter the data for the failure modes, Excel will try to create the appropriate points on the chart. Until all the data is entered you will see a warning from Excel indicating that the chart data is not completely valid. This does not indicate that there is an error with your data, it occurs because Excel is trying to calculate points with incomplete data. You may safely ignore this message.



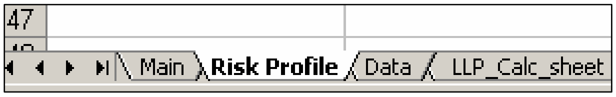
Negative or zero values cannot be plotted correctly on log charts. Only positive values can be interpreted on a logarithmic scale. To correct the problem, do one of the following:

- Enter only positive values (greater than zero) in the cells used to create the chart.
- In the chart, click the axis you want to change. On the Format menu, click Selected Axis. Click the Scale tab, and then clear the Logarithmic Scale check box.

Excel Warning That Data Is Not Yet Complete
****YOU MAY SAFELY IGNORE THIS MESSAGE****

Charts

The RiskPortfolio.xls workbook's Entire Dam Portfolio tab displays a chart of the total risk for each dam in the portfolio. You can access this tab by clicking on it or selecting the "View Dam Portfolio Risk Profile" link on the Main page of the Risk Portfolio.



Each Dam Risk Profile contains a tab which displays a chart of the risk of each failure mode of each element.

2.3. TRANSFERRING AND MOVING DATA

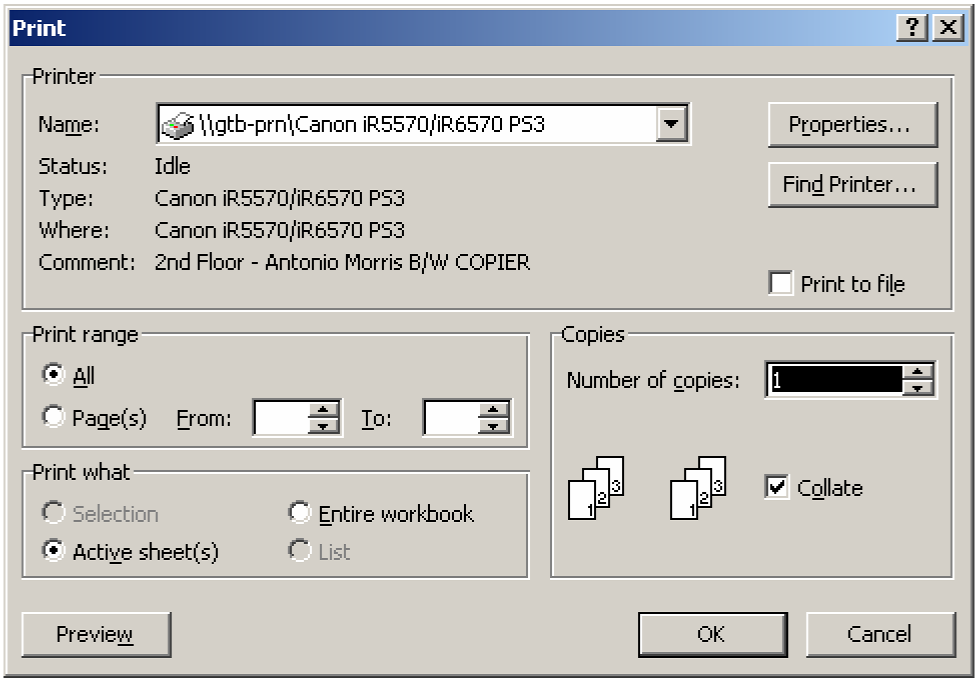
Each Dam Risk Profile is contained within an individual Microsoft Excel workbook. You can move these workbooks to another computer provided you also move the State and Region directories and store them in the directory called Data. The Data directory is automatically created the first time you open the RiskPortfolio.xls application. This directory structure, illustrated in Section 2.2.2, is used by the RiskPortfolio.xls application to create the list of Dams on the Main page and to calculate the risk of the Entire Dam Portfolio. If the Dam Profiles are moved outside this directory structure then they will not be included in the application. Use the Windows Explorer to copy and move Dam Profiles between computers.

2.4. PRINTING OUTPUT

You may wish to print the Dam Elements to take on site with you. As the application has been developed within Microsoft Excel, printing can be done through Excel as well. Each Dam Element is one worksheet. To activate the worksheet click its tab.

To print one copy of the active worksheet to the default printer, click the Printer icon found on the Standard toolbar. To print multiple copies or select a different printer, click on the File menu and select Print to open the print dialog box from which you can change the number of copies or set other printer options.

Click the printer icon to print a single copy of the active worksheet.



Printer

Name: \\gtb-prn\Canon iR5570/iR6570 PS3

Status: Idle

Type: Canon iR5570/iR6570 PS3

Where: Canon iR5570/iR6570 PS3

Comment: 2nd Floor - Antonio Morris B/W COPIER

☐ Print to file

Print range

● All

○ Page(s) From: To:

Copies

Number of copies: 1

☑ Collate

Print what

○ Selection ○ Entire workbook

● Active sheet(s) ○ List

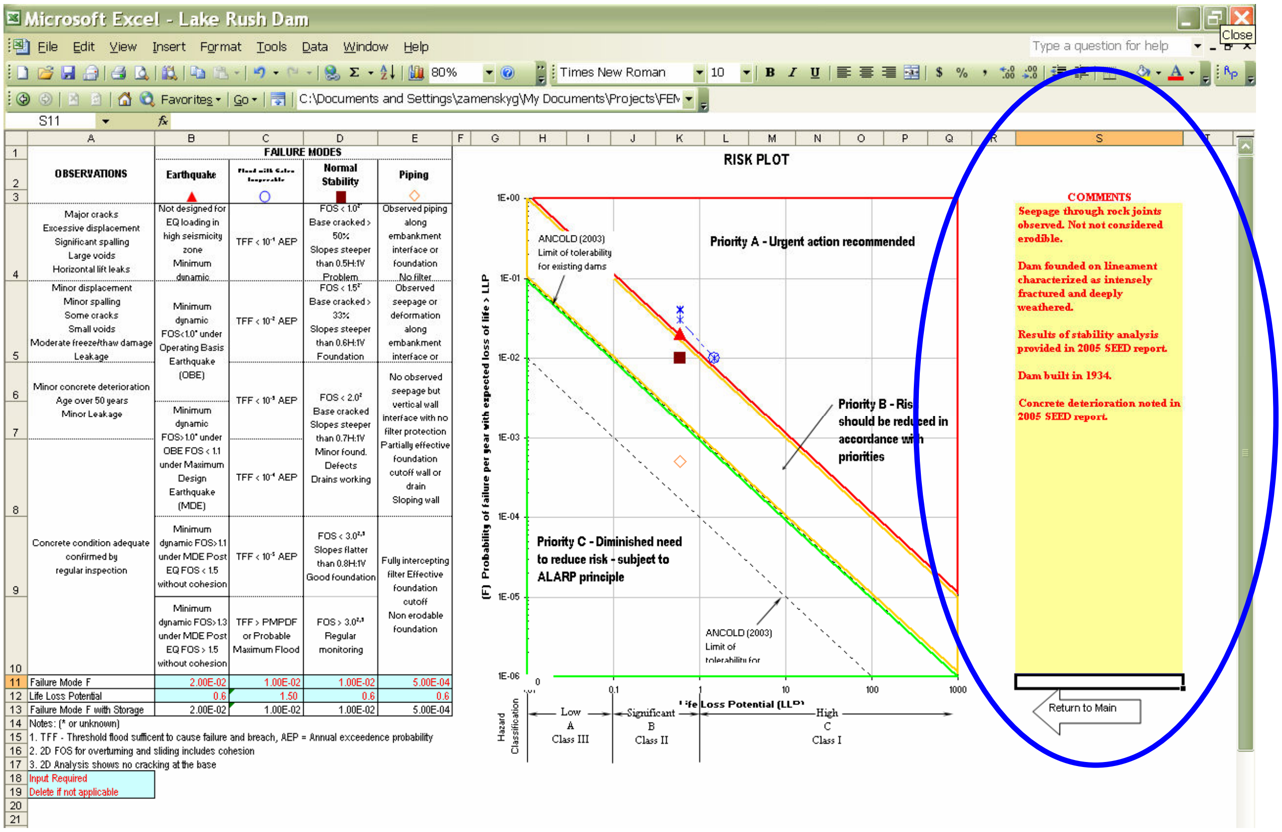
The print dialog box allows you to select multiple copies or change printers.

3.1. START-UP

3.1.1. Document Review

After installation, you are ready to proceed building a dam inventory. The engineering assessment of each dam is conducted by first collecting whatever information was available in the files. In some cases this includes periodic inspection reports, design and construction documentation, U.S. Corps of Engineers Phase I dam safety reports completed in the late 1970's and early 1980's, and perhaps instrumentation data. For other dams, there may be no information except a site inspection report 20 years ago. Fortunately, in most states the dams included in the NID have a Phase I report which includes dam section details, flood hydrology, geology and perhaps a geotechnical study. The Risk Tool is designed for use given any amount of available information. In general, with less information comes a more conservative risk profile.

Referenced documents should be identified and noted within the risk profile file. These notations can be included at the user's discretion in the comment block provided as shown below.



	OBSERVATIONS	FAILURE MODES			
		Earthquake ▲	[illegible] ○	Normal Stability ■	Piping ◇
4	Major cracks Excessive displacement Significant spalling Large voids Horizontal lift leaks	Not designed for EQ loading in high seismicity zone Minimum dynamic	TFF < 10^{-1} AEP	FOS < 1.0^{2} Base cracked > 50% Slopes steeper than 0.5H:1V Problem	Observed piping along embankment interface or foundation No filter
5	Minor displacement Minor spalling Some cracks Small voids Moderate freeze/thaw damage Leakage	Minimum dynamic FOS<1.0* under Operating Basis Earthquake (OBE)	TFF < 10^{-2} AEP	FOS < 1.5^{2} Base cracked > 33% Slopes steeper than 0.6H:1V Foundation	Observed seepage or deformation along embankment interface or
6	Minor concrete deterioration Age over 50 years Minor Leakage		TFF < 10^{-3} AEP	FOS < 2.0^{2} Base cracked Slopes steeper than 0.7H:1V Minor found. Defects Drains working	No observed seepage but vertical wall interface with no filter protection Partially effective foundation cutoff wall or drain Sloping wall
7		Minimum dynamic FOS>1.0* under OBE FOS < 1.1 under Maximum Design Earthquake (MDE)			
8			TFF < 10^{-4} AEP		
9	Concrete condition adequate confirmed by regular inspection	Minimum dynamic FOS>1.1 under MDE Post EQ FOS < 1.5 without cohesion	TFF < 10^{-5} AEP	FOS < $3.0^{2,3}$ Slopes flatter than 0.8H:1V Good foundation	Fully intercepting filter Effective foundation cutoff Non erodable foundation
10		Minimum dynamic FOS>1.3 under MDE Post EQ FOS > 1.5 without cohesion	TFF > PMPDF or Probable Maximum Flood	FOS > $3.0^{2,3}$ Regular monitoring	
11	Failure Mode F	2.00E-02	1.00E-02	1.00E-02	5.00E-04
12	Life Loss Potential	0.6	1.50	0.6	0.6
13	Failure Mode F with Storage	2.00E-02	1.00E-02	1.00E-02	5.00E-04

14 Notes: (* or unknown)
15 1. TFF - Threshold flood sufficent to cause failure and breach, AEP = Annual exceedence probability
16 2. 2D FOS for overturning and sliding includes cohesion
17 3. 2D Analysis shows no cracking at the base
18 Input Required
19 Delete if not applicable

COMMENTS

Seepage through rock joints observed. Not not considered erodible.

Dam founded on lineament characterized as intensely fractured and deeply weathered.

Results of stability analysis provided in 2005 SEED report.

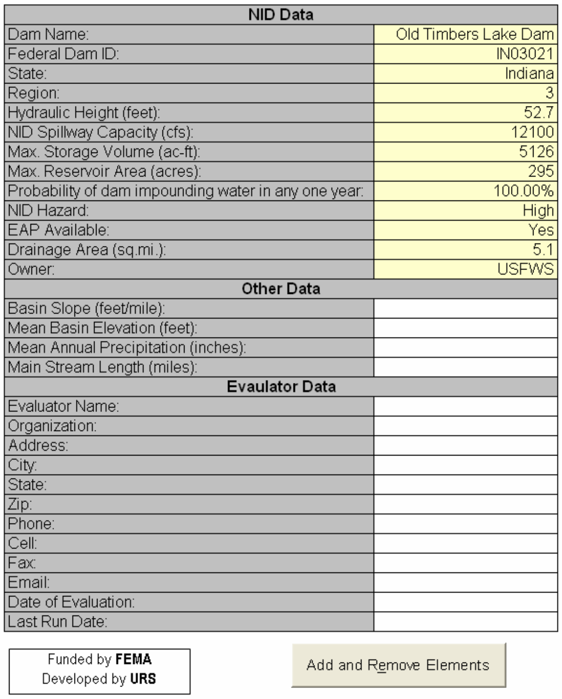
Dam built in 1934.

Concrete deterioration noted in 2005 SEED report.

Dam Element illustrating Comments Section of Worksheet

3.1.2. Initial Data Input

The initial data input screen prompts the user for basic information regarding the dam and the evaluator. The dam information consists mostly of data available from the NID as shown below.



NID Data	
Dam Name:	Old Timbers Lake Dam
Federal Dam ID:	IN03021
State:	Indiana
Region:	3
Hydraulic Height (feet):	52.7
NID Spillway Capacity (cfs):	12100
Max. Storage Volume (ac-ft):	5126
Max. Reservoir Area (acres):	295
Probability of dam impounding water in any one year:	100.00%
NID Hazard:	High
EAP Available:	Yes
Drainage Area (sq.mi.):	5.1
Owner:	USFWS
Other Data	
Basin Slope (feet/mile):	
Mean Basin Elevation (feet):	
Mean Annual Precipitation (inches):	
Main Stream Length (miles):	
Evaulator Data	
Evaluator Name:	
Organization:	
Address:	
City:	
State:	
Zip:	
Phone:	
Cell:	
Fax:	
Email:	
Date of Evaluation:	
Last Run Date:	

This table also prompts the user to establish the *probability of the dam impounding water in any one year*. For most dams, the probability is 100%. This field is intended to accommodate flood control facilities that are usually dry or normally impound a small percentage of the total flood capacity. Without a storage pool, the probability of these flood control dams failing through piping or stability is reduced, although the risk of desiccation cracking maybe higher leading to increased piping risk once the reservoir fills. Therefore, if a significant storage pool is likely once every 10 years, then the *probability of the dam impounding water in any one year* is 10%. The reduced probability is then factored into the failure modes requiring a storage pool.

Use of this factor can be subjective for dams with small normal storage capacities but very large flood capacities. Therefore, unless the impoundment is dry, the User should input a value of 100%.

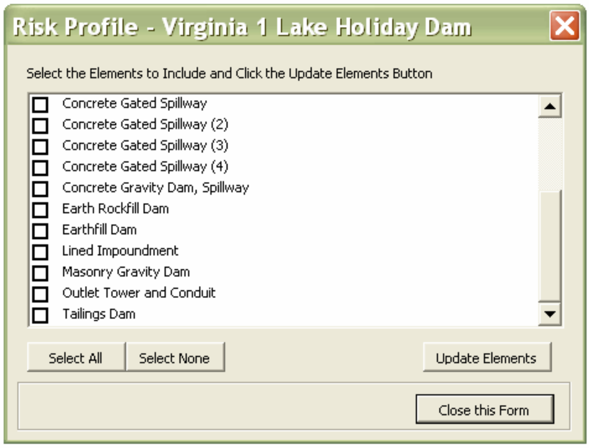
3.2. BUILDING A DAM THROUGH DAM ELEMENTS

The front end visual basic routine has been developed to allow the user to select a suite of worksheets (dam elements) which best describe the primary features of the dam being evaluated. For example, a dam may include an earthfill section, concrete ungated spillway and outlet tower, so those three features are selected. Similarly, a dam may be best characterized by an earthfill section and two ungated spillways.

Selection of the most appropriate dam elements is based on review of the available information. If too few or too many dam elements were initially selected, the Risk Tool allows the user to add or delete dam elements at any time.

Dam elements were prepared for the following types of dam features

- Concrete Gravity Dam
- Concrete Arch Dam
- Masonry Dam (being updated)
- Earthfill Dam
- Earth – Rockfill Dam
- Concrete Face Rockfill Dam
- Timber Crib Dam



Risk Profile - Virginia 1 Lake Holiday Dam

Select the Elements to Include and Click the Update Elements Button

☐ Concrete Gated Spillway
☐ Concrete Gated Spillway (2)
☐ Concrete Gated Spillway (3)
☐ Concrete Gated Spillway (4)
☐ Concrete Gravity Dam, Spillway
☐ Earth Rockfill Dam
☐ Earthfill Dam
☐ Lined Impoundment
☐ Masonry Gravity Dam
☐ Outlet Tower and Conduit
☐ Tailings Dam

- Tailings Dam
- Lined Impoundment
- Outlet Tower and Conduit
- Concrete Gated Spillway (being updated)
- Ungated Spillway (multiple selections permitted)

Additional dam elements (e.g. fuse plug spillways, slab and buttress concrete dam, penstock) are planned for future development for inclusion in later versions of the Risk Tool.

3.3. FAILURE MODE EVALUATION

Each dam element contains a series of three or four likely failure modes. These failure modes represent physical mechanisms that could result in failure of the dam and an uncontrolled release of the impounded reservoir. The **Failure Modes Table** is typically comprised of four vertical columns of failure mode bins such as Earthquake, Flood, Piping and Normal Stability. In each column are bins of descriptors which aid in selecting the order of magnitude of failure probability F ranging from 1 to 1 x 10^{-6}. In addition there is a column of specific observations which provide clues about which bin might be appropriate. General descriptions in making subjective judgements of failure probability are provided below.

Guidelines to Evaluate the Reasonableness of Subjective Probabilities, Barneich et Al. (1996)[3]

Description of Condition or Event	Order of Magnitude of Probability Assigned
Occurrences of the condition or event are observed in the available database.	10^{-1}
The occurrence of the condition or event is not observed, or is observed in one isolated instance, in the available database; however, several potential failure scenarios can be identified.	10^{-2}
The occurrence of the condition or event is not observed in the available database. It is difficult to think about any plausible failure scenario; however, a single scenario could be identified after considerable effort.	10^{-3}
The condition or event has not been observed, and no plausible scenario could be identified, even after considerable effort.	10^{-4}

Probability estimates should be input in scientific notation such as “1 E –3” for 1 in 1,000 years. Other notations such as 5% in 100 years should be converted to “2 E-3.”

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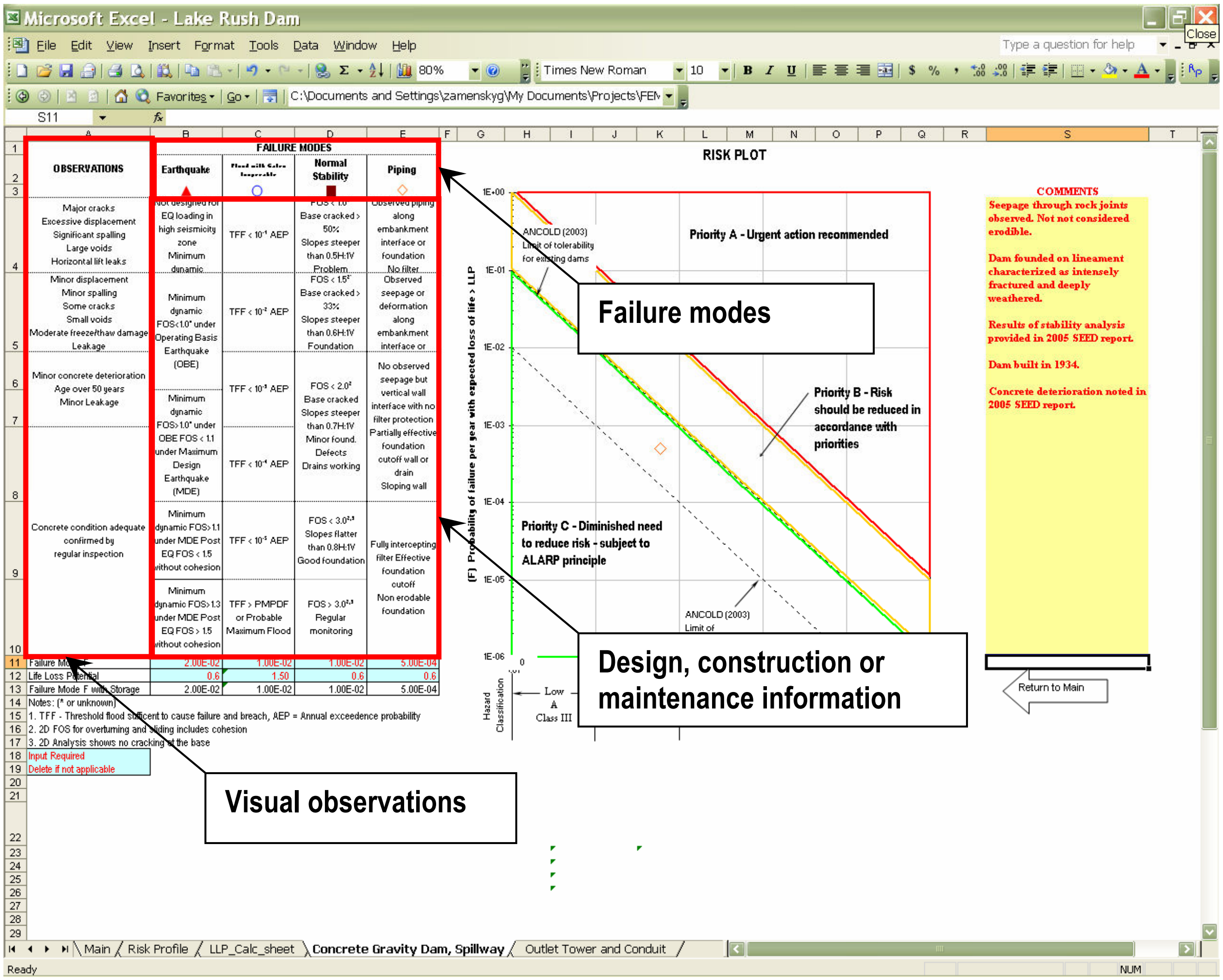
[3] *Barneich et Al. (1996) “The Reliability Analysis of a Major Dam Project” Uncertainty in Geologic Environment From Theory to Practice, Geotechnical Special Publication No. 58., Volume 2.*



	OBSERVATIONS	FAILURE MODES			
		Earthquake	[illegible]	Normal Stability	Piping
3		▲	○	■	◇
4	Major cracks Excessive displacement Significant spalling Large voids Horizontal lift leaks	Not designed for EQ loading in high seismicity zone Minimum dynamic	TFF < 10^{-1} AEP	FOS < 1.0 Base cracked > 50% Slopes steeper than 0.5H:1V Problem	Observed piping along embankment interface or foundation No filter
5	Minor displacement Minor spalling Some cracks Small voids Moderate freeze/thaw damage Leakage	Minimum dynamic FOS<1.0* under Operating Basis Earthquake (OBE)	TFF < 10^{-2} AEP	FOS < 1.5^2 Base cracked > 33% Slopes steeper than 0.6H:1V Foundation	Observed seepage or deformation along embankment interface or
6	Minor concrete deterioration Age over 50 years Minor Leakage		TFF < 10^{-3} AEP	FOS < 2.0^2 Base cracked Slopes steeper than 0.7H:1V Minor found. Defects Drains working	No observed seepage but vertical wall interface with no filter protection Partially effective foundation cutoff wall or drain Sloping wall
7		Minimum dynamic FOS>1.0* under OBE FOS < 1.1 under Maximum Design Earthquake (MDE)			
8			TFF < 10^{-4} AEP		
9	Concrete condition adequate confirmed by regular inspection	Minimum dynamic FOS>1.1 under MDE Post EQ FOS < 1.5 without cohesion	TFF < 10^{-5} AEP	FOS < $3.0^{2,3}$ Slopes flatter than 0.8H:1V Good foundation	Fully intercepting filter Effective foundation cutoff Non erodable foundation
10		Minimum dynamic FOS>1.3 under MDE Post EQ FOS > 1.5 without cohesion	TFF > PMPDF or Probable Maximum Flood	FOS > $3.0^{2,3}$ Regular monitoring	
11	Failure Mode F	2.00E-02	1.00E-02	1.00E-02	5.00E-04
12	Life Loss Potential	0.6	1.50	0.6	0.6
13	Failure Mode F with Storage	2.00E-02	1.00E-02	1.00E-02	5.00E-04

Notes: (* or unknown)
1. TFF - Threshold flood sufficent to cause failure and breach, AEP = Annual exceedence probability
2. 2D FOS for overturning and sliding includes cohesion
3. 2D Analysis shows no cracking at the base

Input Required
Delete if not applicable

COMMENTS

Seepage through rock joints observed. Not not considered erodible.

Dam founded on lineament characterized as intensely fractured and deeply weathered.

Results of stability analysis provided in 2005 SEED report.

Dam built in 1934.

Concrete deterioration noted in 2005 SEED report.

Failure Mode Descriptors and Guidance

The following failure modes were included in the dam element worksheets where appropriate for each dam type: Normal Stability, Piping, Normal Flood, Extreme Flood, Earthquake, Gates, Valves, and Outlet Tower Stability.

Each failure mode is characterized by a column of physical observations, geometric details, analysis results and other pertinent information. The columns are made up of bins with ranges of failure probability corresponding to the noted information about the dam in each bin. If possible, average dam conditions and failure probabilities are described to provide a means to benchmark the user's frame of reference. This allows the evaluation to judge whether this dam is better or worse than the defined average. Since each bin covers 1 to 2 orders of magnitude, estimation precision is not critical. More important is relative consistency between dams and failure modes.

3.3.1. Piping

Piping is perhaps the most difficult failure mode, so the **Historical Performance Method** developed by Dr. Mark Foster while he was at the University of New South Wales (UNSW) has been used to guide the binning process. The Foster et al (1998)[4] paper has been appended to assist the User in selecting the appropriate order of magnitude. The UNSW method provides guidance on the adjustments to the failure probabilities based on whether various conditions are better or worse then the average. A new piping toolbox is currently being developed for the Corps of Engineers and Bureau of Reclamation that will update these guidelines.

The column bins provide descriptors which are based on the average historical precedent for each set of conditions. The first bin covers the range of annual failure probability of $1x10^{-2}$ to 1. Obviously, if there is active piping going on with turbid seepage, no filter, erodible soils and an unprotected seepage exit, this represents the most dangerous situation for an earthfill dam to experience piping failure. The probability of failure may be as high 0.5, or 1 if failure is imminent.

According to Foster et al (1998)[4], an average homogeneous earthfill dam with no filters has an annualized probability of piping failure of 2×10^{-4}. However, if there are known defects, the presence of dispersive clay, observed piping, etc. then the risk levels should be higher. On the other hand with well compacted clay and a filter toe drain, then the risk would be lower. Suggested adjustment factors are provided in the paper. Piping through the embankment, foundation and from the embankment into the foundation should also be considered.

3.3.2. Flood

It would seem that the flood probabilities would be the easiest to estimate. However, flood estimation in the United States is still rooted in deterministic hydrology, and estimation of flood recurrence interval is not straightforward when all that is available is the percentage of the PMF passed through the spillway. Perhaps one day a more progressive probabilistic approach to flood hydrology, similar to that used in Australia, will address this problem as more states view dam safety from a risk perspective. The flood recurrence probability for extreme events is always a matter of some debate and should be handled consistently for each climatological area of the State. For example, in arid areas where the probable maximum precipitation (PMP) is controlled by freak storms, the PMF may be projected to occur only once in a million years (1×10^{-6}). Whereas in more temperate climates subject to frequent tropical storms, the PMF might have a return period of 1 in 10,000 or 1×10^{-4}. Each State should provide guidelines for PMF estimation.

3.3.3. Earthquake

For Earthquake, some judgment of whether liquefaction might be a problem and the recurrence interval of the threshold earthquake for liquefaction and flow failure is required. So clues such as loose sands in the foundation, or hydraulic fill construction would be important to identify. However, if the region is quiet seismically, this failure mode can be skipped. Critical information or assumptions should be noted directly in the yellow **Comments column** so there is no doubt about what was assumed by the Evaluator.

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[4] *Foster, M, R Fell, M Spannagle (1998) "Risk Assessment – Estimating the Probability of Failure of Embankment Dams By Piping," ANCOLD Annual Conference, Sydney, November*

3.3.4. Stability

With stability, slope angles, or telltale signs of cracking, slumps or deformation may be helpful indicators if stability analyses are not available. However, if factors of safety have been computed in design or dam safety reports, than these figures should be used to select the appropriate order of magnitude of failure probability.

3.3.5. General considerations

The age of the dam has an important impact in its historic performance. Dams can have a one to two order of magnitude higher probability of failure during initial filling and their first five years of operation then after five years. Dams with design flaws that have performed well for fifty years may also provide an indication of lower risk, although after this period like humans they start to show their age and should have a thorough checkup. Several dams in Australia started to show interesting problems with deformation and cracking at 45-60 years of age, whereas some century old puddle clay core dams have never shown any indications of problems. Furthermore, there were major changes in dam design technology after some significant failures such as the St Francis concrete gravity dam in California (post 1930) and the Teton zoned earthfill dam in Idaho (post 1975). Each state may have similar eras of dam building where technological changes were introduced to advance the state of practice. An example is the shift away from seepage collars in 1990's after several failures of NRCS dams with these details.

Without proper documentation of design and construction, the User should consider a conservative approach to selecting failure probabilities. In essence, the User is identifying a lack of supporting data for a given failure mode. If there is a lack of a recent inspection, the tables suggest that the probabilities of failure should be increased by 10.

3.4. CONSEQUENCE ASSESSMENT

The main focus of state dam safety regulators is protecting public safety. Therefore, the type of consequence of primary interest in the prioritization tool is human lives. However, the method typically used for life loss estimation from dam failure (Graham, 1999)[5] requires extensive dam break modeling, which is typically not available to the regulator.

To overcome this limitation, Wayne Graham developed a simplified procedure dated June 18, 2004 entitled *"A Method for Easily Estimating the Loss of Life from Dam Failures"*, appended to this report. A spreadsheet was developed to assist in determining the potential for loss of life based on the methodology outlined by Graham using primarily information from the NID database.

The simplified approach requires several estimates of hydrologic and geographic parameters:

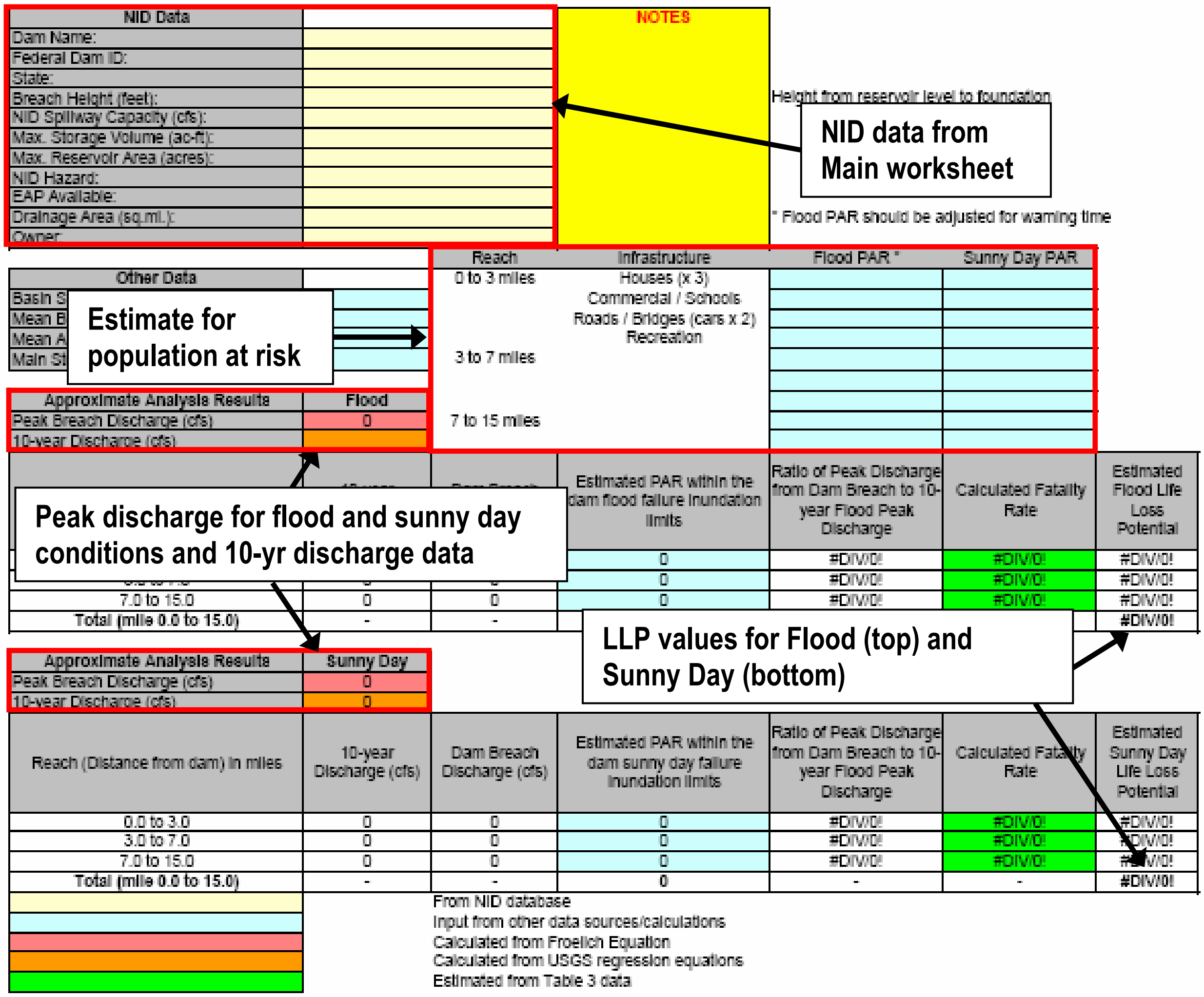
- Estimation of the peak dam breach discharge;
- Estimation of the peak 10-year frequency discharge;
- Estimation of the Population at Risk (PAR) in a given reach; and

---

[5] *Graham, Wayne J., 1999. A Procedure for Estimating Loss of Life Caused by Dam Failure. September; and USBR, 1999. Policy and Procedures for Dam Safety Modification Decision Making. April*

- Estimation of the fatality rate in a given reach.

An illustration of the worksheet used to estimate the life loss potential is provided below. The practical application of assessing the major inputs to the worksheet is discussed below.



NID Data	
Dam Name:	
Federal Dam ID:	
State:	
Breach Height (feet):	
NID Spillway Capacity (cfs):	
Max. Storage Volume (ac-ft):	
Max. Reservoir Area (acres):	
NID Hazard:	
EAP Available:	
Drainage Area (sq.mi.):	
Owner:	

NOTES

Height from reservoir level to foundation

NID data from Main worksheet

* Flood PAR should be adjusted for warning time

Other Data	
Basin S	
Mean B	
Mean A	
Main St	

Estimate for population at risk

Reach	Infrastructure	Flood PAR *	Sunny Day PAR
0 to 3 miles	Houses (x 3)		
	Commercial / Schools		
	Roads / Bridges (cars x 2)		
	Recreation		
3 to 7 miles			
7 to 15 miles			

Approximate Analysis Results	Flood
Peak Breach Discharge (cfs)	0
10-year Discharge (cfs)	

Peak discharge for flood and sunny day conditions and 10-yr discharge data

	10-year	Dam Breach	Estimated PAR within the dam flood failure inundation limits	Ratio of Peak Discharge from Dam Breach to 10-year Flood Peak Discharge	Calculated Fatality Rate	Estimated Flood Life Loss Potential
			0	#DIV/0!	#DIV/0!	#DIV/0!
			0	#DIV/0!	#DIV/0!	#DIV/0!
7.0 to 15.0	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Total (mile 0.0 to 15.0)	-	-				#DIV/0!

LLP values for Flood (top) and Sunny Day (bottom)

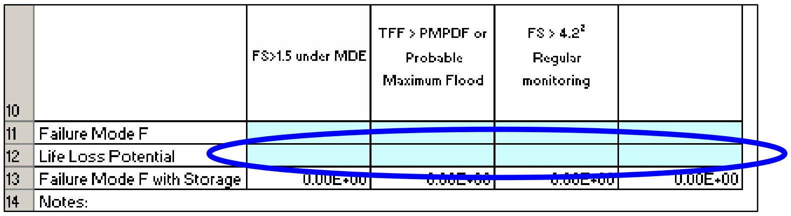
Approximate Analysis Results	Sunny Day
Peak Breach Discharge (cfs)	0
10-year Discharge (cfs)	0

Reach (Distance from dam) in miles	10-year Discharge (cfs)	Dam Breach Discharge (cfs)	Estimated PAR within the dam sunny day failure inundation limits	Ratio of Peak Discharge from Dam Breach to 10-year Flood Peak Discharge	Calculated Fatality Rate	Estimated Sunny Day Life Loss Potential
0.0 to 3.0	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
3.0 to 7.0	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
7.0 to 15.0	0	0	0	#DIV/0!	#DIV/0!	#DIV/0!
Total (mile 0.0 to 15.0)	-	-	0	-	-	#DIV/0!

🟨	From NID database
🟦	Input from other data sources/calculations
🟥	Calculated from Froelich Equation
🟧	Calculated from USGS regression equations
🟩	Estimated from Table 3 data

Life Loss Potential Worksheet

The resulting LLP values for the Flood and Sunny Day conditions are then applied to each failure mode for every Dam Element. The User must manually input the values into each failure mode at the locations shown below.



10		FS>1.5 under MDE	TFF > PMPDF or Probable Maximum Flood	FS > 4.2² Regular monitoring	
11	Failure Mode F				
12	Life Loss Potential				
13	Failure Mode F with Storage	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	Notes:				

Entering LLP Estimate

Selection of the appropriate LLP for each failure mode should thoughtfully consider the operation of the particular dam and spillway. For instance, it is possible that failure of a valve on an outlet works facility would not result in an uncontrolled release of the reservoir. However, the resulting discharge may or may not be a hazard. Guidance for application of the LLP value is provided in the following table.

Failure Mode	LLP Consideration
Earthquake	Sunny Day
Flood	Flood
Normal Stability	Sunny Day
Piping	Sunny Day
Seepage	Sunny Day
Training Walls	Flood – can failure of training walls lead to catastrophic breach and release of reservoir?
Abutment Outflanking	Flood
Lined Chute and Dissipator	Flood – can spillway channel erosion lead to catastrophic breach and release of the reservoir?
Unlined Channel	Flood – can spillway channel erosion lead to catastrophic breach and release of the reservoir?
Conduits	Sunny Day
Gates	Flood – can gate failure lead to catastrophic breach and release of the reservoir?
Valves	Sunny Day – can valve failure lead to catastrophic breach and release of the reservoir?

If failure of a gate, valve or spillway chute does not cause a catastrophic breach of the dam, then a much smaller PAR and LLP should be utilized for these failure modes.

3.4.1. Estimating the Peak Dam Breach Discharge

Key to the practical application of the methodology is in the estimate of the peak dam breach discharge. Ideally, the user will have access to dam break analyses that include discharge values for a sunny day failure as well as failure during the inflow design flood. If no detailed dam breach analyses are available, the most simplistic approach to estimating the peak dam breach discharge is to utilize the Froelich equation.

$$Q_p = 40.1V^{.295}H^{1.24}$$

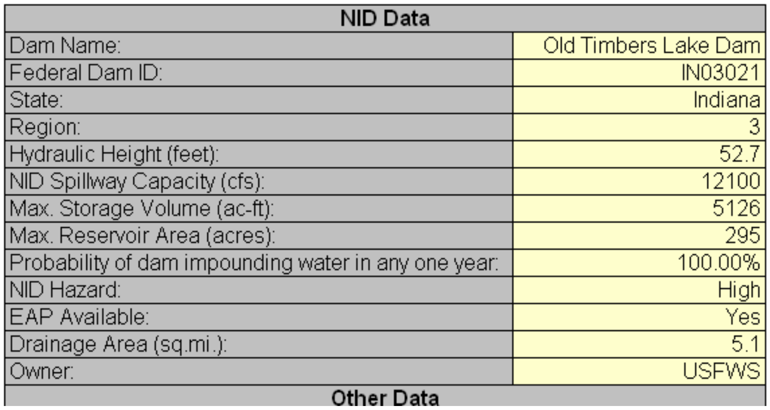
where:

Q_p = the peak outflow in cubic feet per second from the breached embankment dam

V = the reservoir storage volume in acre-feet at the time of failure

H = the height of the embankment in feet from the bottom of the final breach to the top of embankment

The parameters utilized in this equation are readily ascertained from the NID database. With the information provided in the Main worksheet (shown below), the Risk Tool automatically computes peak discharge using the Froelich equation. The calculated value can easily be overwritten by the user if alternate data is available, such as computed breach flows from dambreak analyses.



NID Data	
Dam Name:	Old Timbers Lake Dam
Federal Dam ID:	IN03021
State:	Indiana
Region:	3
Hydraulic Height (feet):	52.7
NID Spillway Capacity (cfs):	12100
Max. Storage Volume (ac-ft):	5126
Max. Reservoir Area (acres):	295
Probability of dam impounding water in any one year:	100.00%
NID Hazard:	High
EAP Available:	Yes
Drainage Area (sq.mi.):	5.1
Owner:	USFWS
Other Data	

NID Data Input to Risk Tool

3.4.2. Estimating the 10-year Frequency Peak Discharge

The 10-year flood flow or flood with an annual exceedance probability of 1×10^{-1} represents in simplistic terms the bank full condition where no loss of life would be expected. Estimates for the 10-year frequency flood event may or may not be available and could be difficult to simplistically estimate. There are several methods for estimating the 10-year frequency peak discharge and these include:

- Statistical analysis of stream gauge data
- Regional regression equations

- Rainfall-runoff modeling

Of the methods outlined above and assuming no detailed estimates of the 10-year discharge are readily available, the regional regression equations offer the most simplistic method for estimating the 10-year discharge. The USGS has published nationwide summaries for estimating flood discharges for ungaged sites in the publication entitled *Nationwide Summary of U.S. Geological Survey Regional Regression Equations for Estimating Magnitude and Frequency of Floods for Ungaged Sites, 1993, Water-Resources Investigations report 94-4002*. The USGS link: http://onlinepubs.er.usgs.gov/djvu/WRI/wrir_94_4002.djvu

Regression equations have been developed for all 50 states based on properties of the watersheds within specific definable regions. These parameters (among others) typically include:

- Drainage area,
- Basin or stream slope,
- Basin mean elevation, and
- Mean annual precipitation.

The drainage area is typically published in the NID database and the other parameters can generally be obtained from available USGS or other available topographic mapping.

It is important to note that the USGS regional regression equations are based on data from gauged sites in the region, and as more data becomes available, these equations are continually being adjusted and updated.

In addition, the USGS has also developed a software package for estimating floods at ungauged sites. The program is termed *The National Flood Frequency (NFF)* program and offers a simplistic tool for determining the 10-year frequency discharge lacking any detailed or other estimates.

3.4.3. Estimating the Population at Risk (PAR)

Ideally, flood and sunny day dam break inundation maps are available from dam safety reports or the Emergency Action Plan (EAP), from which the count of dwellings, roads, bridges, schools, parks and industrial facilities can be made. However, if this information is unavailable, then the flood rise could be assumed at say 20% of the dam height in the first 3 mile reach, 10% of the dam height from 3 to 7 miles downstream, and 5 % of the dam height from 7 to 15 miles downstream. Typically, the potential for loss of life diminishes significantly beyond a distance of 15 miles due to increased warning time for these areas. However, the ultimate decision to include potential loss of life beyond 15 miles is the User's. If desired, in order to work within the context of the Risk Tool, the user should include potential loss of life beyond 15 miles in the 7 to 15 miles category on the LLP worksheet.

Three people are assumed as PAR for each dwelling within the inundation footprint. Cars on bridges and roads are assumed to have 2 occupants, and trailer parks, schools, recreation facilities including fishing areas, and commercial properties are characterized based on their size and temporal (seasonal) use. If the User has specific information then other occupancy rates can be used.

Lacking any other data, the approach offers a sound basis for approximating the dam inundation extents. Unsteady flow dam breach models are the best way to estimate the inundation extents and the PAR. However, these models are very time consuming and require detailed data. New GIS tools are available that can greatly assist with the plotting of dam breach inundation extents and estimation of the PAR. The simplistic methods of estimating the peak breach discharges and ratios of peak dam breach discharge to 10-year discharge (and hence the potential hazard) do not account for any attenuation of the dam breach flood wave or the effect of large contributing drainage areas below the dam.

3.4.4. Estimate of the Fatality Rate

The simplistic approach presented in Graham (2004) and provided in the table below does not account for attenuation of the dam breach flood wave or the effect of large contributing drainage areas below the dam. As such, the estimates of the fatality rates that are based on distance downstream from the dam and the ratio of the peak dam breach discharge to the 10-year peak discharge could be skewed. At any rate, lacking any detailed dam breach and inundation analysis, the approach and fatality rate estimates are reasonable and based on data from real dam breach events.

Fatality Rates in Dam Failures, Graham (2004)[6]

	Fatality Rate based on distance from dam		
Q_b/Q_{10}	0 to 3 miles	3 to 7 miles	7 to 15 miles
> 100	0.75	0.5	0.37
50 to 100	0.5	0.33	0.25
30 to 50	0.25	0.2	0.13
20 to 30	0.2	0.15	0.1
10 to 20	0.1	0.08	0.05
5 to 10	0.02	0.015	0.01
3 to 5	0.01	0.007	0.005
1 to 3	0.005	0.003	0.002
< 1	0.001	0.0001	0

In the LLP worksheet, "Flood" numbers are appropriate for the full or percentages of the Probable Maximum Flood (PMF) and Threshold Failure Flood (TFF) scenarios where some warning of the impending flood is likely. The Threshold Failure Flood is defined as the flood where there is just enough overtopping of the dam to cause failure by erosion or collapse. This may range from 6 inches to 3 feet above the dam crest flood depending on the crest details and downstream slope conditions. "Sunny Day" conditions refer to a piping or earthquake failure where there is no warning. The inundation footprint may be larger for the flood case because the flood is being passed as well, but the warning time may significantly reduce the population at risk. Recent work by Wayne Graham reveals that even with warning, some portion of the PAR does not evacuate.

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[6] *Graham, Wayne (2004) "Risk-Base Dam Safety Prioritization" Draft.*

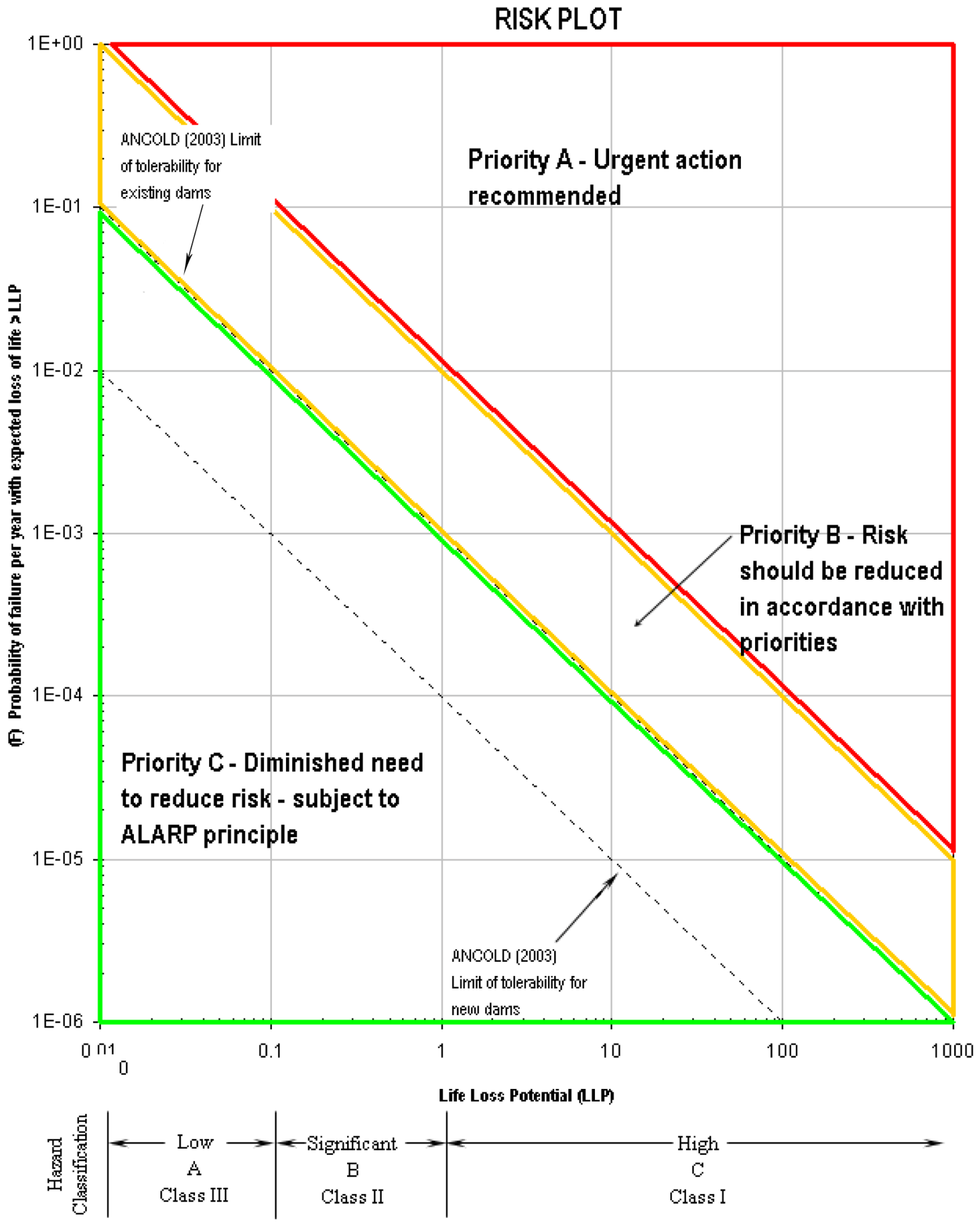
The simplified method was checked for several dams with detailed dam breach modeling results. Both Graham (1999, 2004) methods provided consistent results within 10 % which is quite good for such a simplified process.

If the estimated LLP for either the "Flood" or "Sunny Day" condition is greater than 1,000, the User must override the estimate to 1,000. Currently, the workbook only supports an LLP of up to 1,000.

3.5. RISK CATEGORIZATION

Once each failure mode probability F has been entered, then the appropriate LLP should be transferred from the LLP worksheet. With these two values, the loss of life risk is computed by multiplying the failure probability by the consequences. In many of the arid western states, dams may fill only rarely. This factor is multiplied times the non-flood failure probability, based on the probability of filling in any year (see Section 3.1.2).

The computed failure probability F – LLP pairs are plotted automatically on the Risk Plot (shown below).



Risk Plot from any Dam Element worksheet

The diagonal lines on this plot are lines of equal risk. Guidance on risk priority is provided from the Bureau of Reclamation[7] and ANCOLD[8] which have led to three regions of risk priority and urgency:

Priority A – Urgent Action Recommended

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[7] *US Bureau of Reclamation (2003)* "Guidelines For Achieving Public Protection in Dam Safety Decisionmaking," *June 15*

[8] *Australian National Committee on Large Dams (2003)* "Guidelines in Risk Assessment," *ISBN 0 731 027 620*

Priority B – Risk Should be Reduced in Accordance with Priorities

Priority C – Diminished Need to Reduce Risk Subject to ALARP Principle.

Urgent Action means that the dam safety risk as it is currently understood by the State Engineer is very high and that urgent action is required by the dam owner. These actions might range from contacting the owner expressing concern to requesting additional investigations of the failure mode in question to requiring reservoir restriction in extreme cases. Further investigations may be all that are necessary to clarify the situation and reveal that the assumptions made in this first assessment are excessively conservative. The lower limit of risk urgency corresponds to an annualized lives risk of 1 in 100 or 1×10^{-2}.

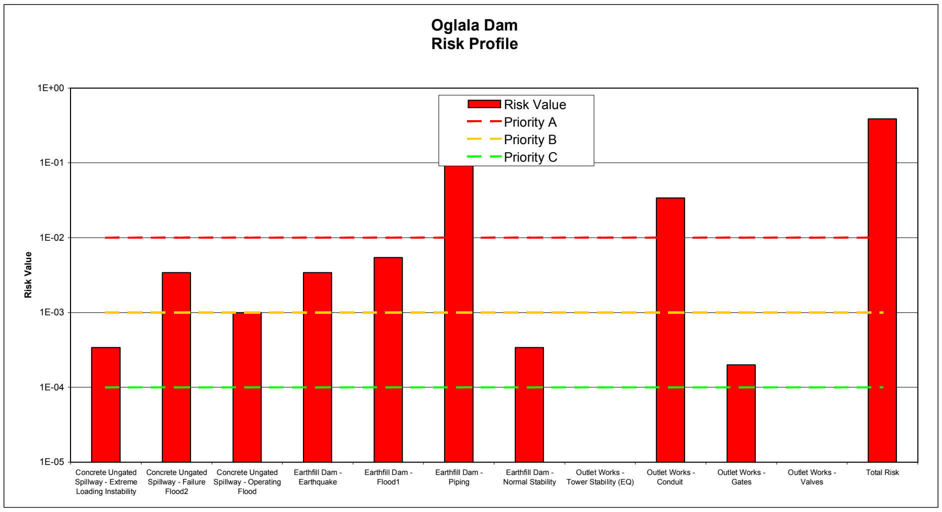
Risk Should be Reduced in Accordance with Priorities indicates that risk level still falls above the level of 1 in 1000 or 1×10^{-3}, but that the risk can be addressed in an appropriate and deliberate sequence of dams or failure modes based on their relative risk. This category recognizes that funds and resources available to address these dam risk issues are finite and that it takes time to resolve these issues. Other factors such as social and political issues may also be considered. However, the risk is still considered by international guidelines to require some action to lower risk.

Diminished Need to Reduce Risk Subject to the ALARP Principle covers the region where the dam safety risk falls below the 1×10^{-3} limit. Satisfying the ALARP test means that the risk has been reduced as low as reasonably practicable. This reasonableness test reflects society's aversion to incidents that can potentially cause large loss of life but recognizes that there is a point of diminished returns. ALARP is defined as the point where additional risk reduction is not possible without a disproportionate investment for the benefit gained.

Each State may wish to adjust these dam safety risk thresholds and definitions to best suit their specific circumstances. These are suggested limits based on established Bureau of Reclamation and international practice. The results from this risk tool should not be used to judge risk tolerability since these imprecise quantities are meant **only** to establish priorities.

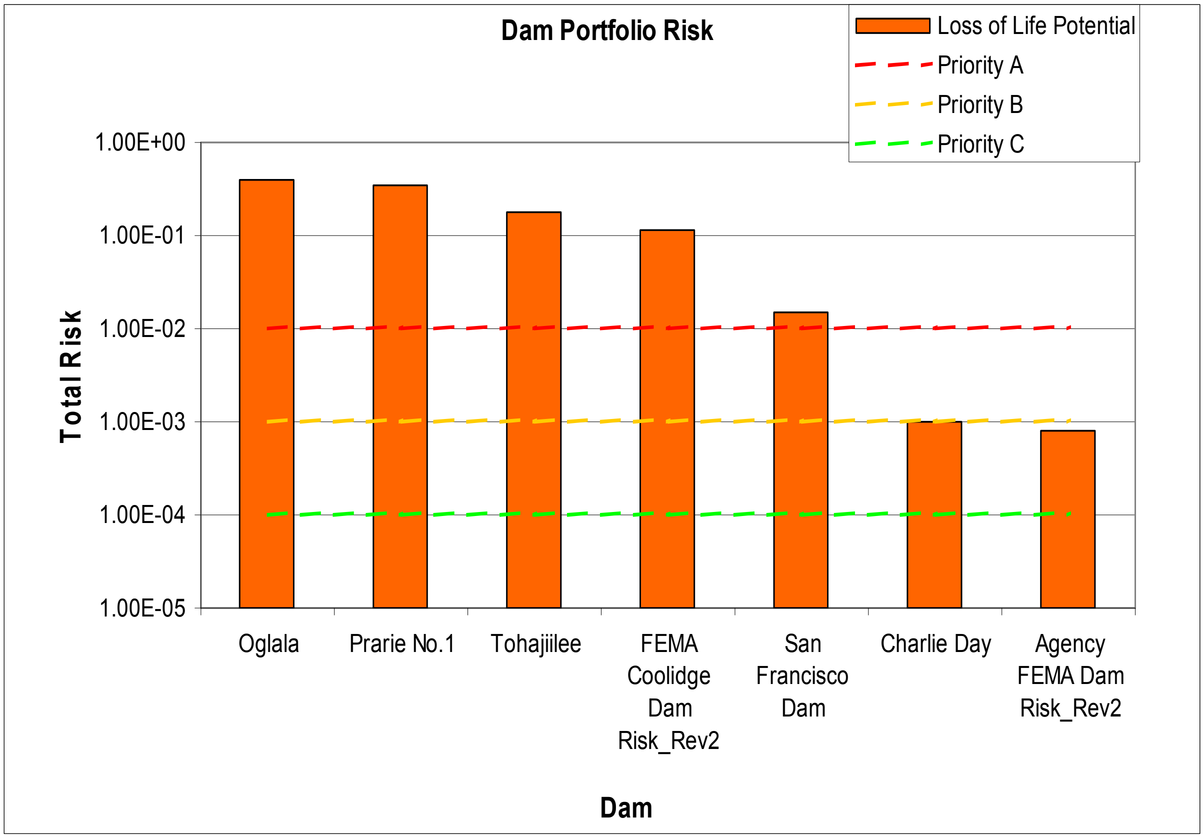
3.6. RISK PRIORITIZATION

The final step in the process is the ranking of the failure modes and dams in each grouping by dam safety risk. Each failure mode is ranked by risk in the bar chart histogram navigated to by clicking the **Risk Profile** tab at the base of the worksheet. This illustrates the relative risk level for each failure mode for each dam separately. If the User then wants to see what failure mode is predominating the risk for a particular dam, then they can look back at the Risk Profile. If this does not seem right, then the specific failure mode worksheet selections can be reviewed for reasonableness and adjustment.



Risk Ranking By Failure Modes for a Given Dam (within each Dam Element)

To view other dams in the portfolio, click on the **RiskProfile.xls** tab, which will bring up the state dam profiles by region or other preset grouping. To view the entire dam portfolio risk profile by total risk, then click on the **View Dam Portfolio Risk Profile** box. This provides a clear graphical presentation of the relative dam safety risk of each dam in the grouping.



Risk Portfolio

4.1. GENERAL

Because risk methods are relatively new to state regulators, two mini-trials were conducted to confirm the viability and acceptability of the process. The trials were implemented in August and September 2004 with a three day session with the New Jersey DEP and a one day workshop with ten Bureau of Reclamation risk specialists examining Bureau of Indian Affairs dams. These sessions were immensely valuable in demonstrating that the process provided a quick, efficient and reasonable quantification of risk for a wide variety of dams, some with almost no information. Based on these trials a number of enhancements were implemented to improve the process.

The next step was an extended beta trial with the State of Texas. This process included training of new dam safety staff and several multi-day workshops. This trial demonstrated the need for a more user-friendly front end setup routine, as well as guidelines for selecting average dam benchmark failure probabilities. These enhancements were developed and trialed. Texas' unique situation with over 7,500 dams also stimulated the need for a more rapid consequence analysis process to identify which groups of dams should be tackled in what priority.

The second beta trial was conducted in the State of Washington which has implemented one of the most advanced risk-based dam safety priority systems. This short trial confirmed the direction being followed in development and that the process was equally viable for more advanced states as for states with less developed dam safety programs

4.2. TRIALS PERFORMED

Each of the trials provided the development team valuable guidance and insight about how the prioritization tools would be utilized.

New Jersey DEP, August 2004. The first trial was conducted with the New Jersey DEP. The three person DEP team included a mid and two junior level staff. The team collected files for 7 dams and after a half day training exercise were able to complete 7 dams in 1.5 days. The team struggled with flood recurrence and preferred their normal percentage of PMF. However, the LLP calculation was completed easily with a useful CD-based state topographic map. The Corps Phase I inspection reports were very useful. However, we found that some of the risks were probably over-predicted. The team was able to calibrate ourselves on a series of cascade flood failures that had occurred several weeks before, so there was a timely impetus for the risk prioritization work.

Failure of Upper Aetna Dam in NJ

Bureau of Indian Affairs Dam Trial, September 2004. A Workshop was conducted at the Bureau of Reclamation with ten experienced dam safety specialists. After working the first dam together soliciting feedback on the process, the group split up into two-person teams, completing six more dams in less then 2 hours. The dams had a wide range of information including one case not in the NID database. The group suggested revised failure mode definitions to match experience. Much discussion ensued about the addition of warning time to LLP computation. We found that it was important to use a facilitator in each state.

Texas Beta Trial, 2005 – 2006. The first beta trial of the full development package was conducted with Texas Commission on Environmental Quality (TCEQ) dam safety team. The first step was a three day training exercise at the TCEQ office in Austin in October 2005. The team worked through a number of dams and recognized some unique situations in Texas:

- Since the dam safety program had been inactive there was a huge effort required to bring the team up to speed with the 7,500 dam inventory. In fact a prescreening tool was needed;.
- ▪ Training of new staff with limited dam safety experience;
- ▪ Useful calibration of Livingston Dam near failure;
- ▪ Focus on flood control dams; and
- Focus on dams with little or no information.

Livingston Dam during Hurricane Rita

TCEQ was then provided with a trial period between October 2005 – March 2006. In the midst of this a Flood Estimation Training was provided in December 2005. Furthermore, TCEQ developed new Draft Statewide Flood Guidelines in March 2006. There was a follow-up workshop in April 2006 in which a new Visual Basic front end routine was introduced to simplify assembly of dam features. To address the problem of subjectivity in some assessments, the tool provides guidance on “average dam” conditions from the UNSW dam failure database. The team focused on aging NRCS dams, many with corrugated metal pipe (CMP) outlets. The trial revealed that many of the NID hazard classifications were inaccurate because of the significant development in the last 20 years. Another issue was infrequent inspections, so the team increased the risk by a factor of 10.

Washington Beta Trial, April 2006. Washington State was selected as the second beta test site because of their advanced dam safety prioritization program in place for five years. The Washington team was cautious at first, but after working several dams realized that the process helps to correct hazard classifications and checks a broader range of failure modes. They became very supportive and liked “average dam” risk guidelines. Washington plans to use the tool as part of the yearly cycle of dam inspections.

Other mini-trials have been conducted with US Fish and Wildlife Service, US Park Service, and other state regulators who have shown interest. This has demonstrated time and again the value of providing a tool that is transparent and easily adaptable to the unique situations in any state. A prescriptive “black box” would just not work with such a diverse and independent group of state regulators. Hence the prioritization process is truly still evolving.

Appendix A

RISK ASSESSMENT - ESTIMATING THE PROBABILITY OF FAILURE OF EMBANKMENT DAMS BY PIPING

By Mark Foster[1], Robin Fell[2] and Matt Spannagle[1]

ABSTRACT

This paper describes a method for estimating the probability of failure of embankment dams by piping. The so called "UNSW method" is based on the results of an analysis of historic failures and accidents of embankment dams. An estimate of the probability of failure of a dam by piping is made by adjusting the historical rates of failure by piping by applying weighting factors which take into account the dam zoning; filters; age of the dam; core soil types; compaction; foundation geology; dam performance; and monitoring and surveillance. The method is intended for preliminary assessments only and is ideally suited as a risk ranking method for portfolio type risk assessments to identify which dams to prioritise for more detailed studies and as a check on event tree methods.

INTRODUCTION

As part of a research project which is developing methods to assess the probability of failure of dams for use in quantitative risk assessments, the authors have carried out a detailed statistical analysis of failures and accidents of embankment dams and of the world population of existing dams (Foster, Fell and Spannagle, 1998). By comparing the characteristics of the dams which have experienced piping incidents to the characteristics of the dam population, the analysis was able to assess the relative influence particular factors have on the likelihood of piping.

This paper describes the UNSW method for estimating the probability of failure by piping based on the results of that analysis. Discussion of the application of the method and description of how the weighting factors were quantified is presented. Details of the quantification of the weighting factors are not discussed in this paper due to space restrictions, but they are given in Foster, Fell and Spannagle (1998).

OVERVIEW OF THE UNSW METHOD

The method involves the adjustment of the historical average probabilities of failure of the three modes of piping to take account of the characteristics of the dam, such as dam zoning, filters, core properties, compaction, foundation geology, past performance and monitoring and surveillance. These adjustments are made with the use of weighting factors which are multiplied by the average probabilities of failure.

The average probabilities of failure and average annual probabilities of failure were determined for the three modes of piping failure from the incident and population statistics taken up to 1986 described in Foster et al (1998) and are summarised in Table 1.

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To assess the annual probability of failure of an embankment dam by piping:

1. Determine the average annual probabilities of failure from Table 1 for each of the three modes of piping failure:
   - piping through the embankment,
   - piping through the foundation, and
   - piping from the embankment into the foundation,

   allowing for the age of the dam, i.e. whether less than or older than 5 years (about 2/3 of piping failures occur on first filling or in the first 5 years of operation).

2. Apply numerical weightings from Tables 2, 3 and 4 to take account of the characteristics of the dam, such as core properties, compaction and foundation geology, and to take account of the past performance of the dam. The weighting factors are multiplied together to the average annual probability of failure.

3. Add the probabilities to obtain the overall annual probability of failure by piping, P_p:

   so $P_p = P_e + P_f + P_{ef}$

Table 1. Average probability of failure of embankment dams by mode of piping and dam zoning

ZONING CATEGORY	EMBANKMENT			FOUNDATION			EMBANKMENT INTO FOUNDATION		
	AVER-AGE. P_{Te} ($x10^{-3}$)	AVERAGE ANNUAL P_e ($x\ 10^{-6}$)		AVER-AGE. P_{Tf} ($x10^{-3}$)	AVERAGE ANNUAL P_f ($x\ 10^{-6}$)		AVER-AGE. P_{Tef} ($x10^{-3}$)	AVERAGE ANNUAL P_{ef} ($x\ 10^{-6}$)	
		First 5 Years Operation	After 5 Years Operation		First 5 Years Operation	After 5 Years Operation		First 5 Years Operation	After 5 Years Operation
Homogeneous earthfill	16	2080	190	↑	↑	↑	↑	↑	↑
Earthfill with filter	1.5	190	37						
Earthfill with rock toe	8.9	1160	160						
Zoned earthfill	1.2	160	25						
Zoned earth and rockfill	1.2	150	24						
Central core earth and rockfill	(<1.1)	(<140)	(<34)	1.7	255	19	0.18	19	4
Concrete face earthfill	5.3	690	75						
Concrete face rockfill	(<1)	(<130)	(<17)						
Puddle core earthfill	9.3	1200	38						
Earthfill with corewall	(<1)	(<130)	(<8)						
Rockfill with corewall	(<1)	(<130)	(<13)						
Hydraulic fill	(<1)	(<130)	(<5)	↓	↓	↓	↓	↓	↓
ALL DAMS	**3.5**	**450**	**56**	**1.7**	**255**	**19**	**0.18**	**19**	**4**

Notes: (1) P_{Te}, P_{Tf} and P_{Tef} are the average probabilities of failure over the life of the dam.
(2) P_e, P_f and P_{ef} are the average annual probabilities of failure.

The bracketed values shown in Table 1 are for dam zoning categories where there have been no recorded failures by piping through the embankment. For these categories, the average probability of failure over the life of the dam was assumed to be less than 1 x 10^{-3}. Figure 1 shows the dam zoning categories used.

If a factor has two or more possible weighting factors that can be selected for a particular dam characteristic, such as different zoning types or different foundation geology types, then the weighting factor with the greatest value should be used. This is consistent with the method of analysis that was used to determine the weighting factors, as only the characteristics relevant to the piping incident were included in the analysis.

Table 2. Summary of the weighting factors for piping through the embankment mode of failure.

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF FAILURE				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
ZONING	Refer to Table 1 for the average annual probabilities of failure by piping through the embankment depending on zoning type				
EMBANKMENT FILTERS $w_{E(filt)}$		No embankment filter (for dams which usually have filters (refer to text) [2]	Other dam types [1]	Embankment filter present - poor quality [0.2]	Embankment filter present - well designed and constructed [0.02]
CORE GEOLOGICAL ORIGIN $w_{E(cgo)}$	Alluvial [1.5]	Aeolian, Colluvial [1.25]	Residual, Lacustrine, Marine, Volcanic [1.0]		Glacial [0.5]
CORE SOIL TYPE $w_{E(cst)}$	Dispersive clays [5] Low plasticity silts (ML) [2.5] Poorly and well graded sands (SP, SW) [2]	Clayey and silty sands (SC, SM) [1.2]	Well graded and poorly graded gravels (GW, GP) [1.0] High plasticity silts (MH) [1.0]	Clayey and silty gravels (GC, GM) [0.8] Low plasticity clays (CL) [0.8]	High plasticity clays (CH) [0.3]
COMPACTION $w_{E(cc)}$	No formal compaction [5]	Rolled, modest control [1.2]	Puddle, Hydraulic fill [1.0]		Rolled, good control [0.5]
CONDUITS $w_{E(con)}$	Conduit through the embankment - many poor details [5]	Conduit through the embankment - some poor details [2]	Conduit through embankment - typical USBR practice [1.0]	Conduit through embankment - including downstream filters [0.8]	No conduit through the embankment [0.5]
FOUNDATION TREATMENT $w_{F(ft)}$	Untreated vertical faces or overhangs in core foundation [2]	Irregularities in foundation or abutment, Steep abutments [1.2]		Careful slope modification by cutting, filling with concrete [0.9]	
OBSERVATIONS OF SEEPAGE $w_{E(obs)}$	Muddy leakage Sudden increases in leakage [up to 10]	Leakage gradually increasing, clear, Sinkholes, Seepage emerging on downstream slope [2]	Leakage steady, clear or not observed [1.0]	Minor leakage [0.7]	Leakage measured none or very small [0.5]
MONITORING AND SURVEILLANCE $w_{E(mon)}$	Inspections annually [2]	Inspections monthly [1.2]	Irregular seepage observations, inspections weekly [1.0]	Weekly - monthly seepage monitoring, weekly inspections [0.8]	Daily monitoring of seepage, daily inspections [0.5]

Table 3. Summary of the weighting factors for piping through the foundation mode of failure.

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF FAILURE				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
ZONING	Refer to Table 1 for the average annual probability of failure by piping through the foundation				
FILTERS $w_{F(filt)}$		No foundation filter present when required [1.2]	No foundation filter [1.0]	Foundation filter(s) present [0.8]	
FOUNDATION TYPE (below cutoff) $w_{F(fnd)}$	Soil foundation [5]		Rock – clay infilled or open fractures and/or erodible rock substance [1.0]	Better rock quality →	Rock – closed fractures and non-erodible substance [0.05]
CUTOFF TYPE (Soil foundation) $w_{F(cts)}$ OR		Shallow or no cutoff trench [1.2]	Partially penetrating sheetpile wall or poorly constructed slurry trench wall [1.0]	Upstream blanket, Partially penetrating well constructed slurry trench wall [0.8]	Partially penetrating deep cutoff trench [0.7]
CUTOFF TYPE (Rock foundation) $w_{F(ctr)}$	Sheetpile wall Poorly constructed diaphragm wall [3]	Well constructed diaphragm wall [1.5]	Average cutoff trench [1.0]	Well constructed cutoff trench [0.9]	
SOIL GEOLOGY TYPES (below cutoff) $w_{F(sg)}$, OR	Dispersive soils [5] Volcanic ash [5]	Residual [1.2]	Aeolian, Colluvial, Lacustrine, Marine [1.0]	Alluvial [0.9]	Glacial [0.5]
ROCK GEOLOGY TYPES (below cutoff) $w_{F(rg)}$	Limestone [5] Dolomite [3] Saline (gypsum) [5] Basalt [3]	Tuff [1.5] Rhyolite [2] Marble [2] Quartzite [2]		Sandstone, Shale, Siltstone, Claystone, Mudstone, Hornfels [0.7] Agglomerate, Volc. Breccia [0.8]	Conglomerate [0.5] Andesite, Gabbro [0.5] Granite, Gneiss [0.2] Schist, Phyllite, Slate [0.5]
OBSERVATIONS OF SEEPAGE $w_{F(obs)}$ OR	Muddy leakage Sudden increases in leakage [up to 10]	Leakage gradually increasing, clear, Sinkholes, Sandboils [2]	Leakage steady, clear or not observed [1.0]	Minor leakage [0.7]	Leakage measured none or very small [0.5]
OBSERVATIONS OF PORE PRESSURES $w_{F(obp)}$	Sudden increases in pressures [up to 10]	Gradually increasing pressures in foundation [2]	High pressures measured in foundation [1.0]		Low pore pressures in foundation [0.8]
MONITORING AND SURVEILLANCE $w_{F(mon)}$	Inspections annually [2]	Inspections monthly [1.2]	Irregular seepage observations, inspections weekly [1.0]	Weekly - monthly seepage monitoring, weekly inspections [0.8]	Daily monitoring of seepage, daily inspections [0.5]

Table 4. Summary of the weighting factors for piping from the embankment into the foundation - accidents and failures

FACTOR	GENERAL FACTORS INFLUENCING LIKELIHOOD OF INITIATION OF PIPING - ACCIDENTS AND FAILURES				
	MUCH MORE LIKELY	MORE LIKELY	NEUTRAL	LESS LIKELY	MUCH LESS LIKELY
ZONING	Refer to Table 1 for the average annual probability of failure by piping from embankment into foundation				
FILTERS $w_{EF(filt)}$	Appears to be independent of presence/absence of embankment or foundation filters [1.0]				
FOUNDATION CUTOFF TRENCH $w_{EF(cot)}$	Deep and narrow cutoff trench [1.5]		Average cutoff trench width and depth [1.0]	Shallow or no cutoff trench [0.8]	
FOUNDATION TYPE $w_{EF(fnd)}$		Founding on or partly on rock foundations [1.5]			Founding on or partly on soil foundations [0.5]
EROSION CONTROL MEASURES OF CORE FOUNDATION $w_{EF(ecm)}$	No erosion control measures, open jointed bedrock or open work gravels [up to 5]	No erosion control measures, average foundation conditions [1.2]	No erosion control measures, good foundation conditions [1.0]	Erosion control measures present, poor foundations [0.5]	Good to very good erosion control measures present and good foundation [0.3 – 0.1]
GROUTING OF FOUNDATIONS $w_{EF(gr)}$		No grouting on rock foundations [1.3]	Soil foundation only - not applicable [1.0]	Rock foundations grouted [0.8]	
SOIL GEOLOGY TYPES $w_{EF(sg)}$, OR	Colluvial [5]	Glacial [2]		Residual [0.8]	Alluvial, Aeolian, Lacustrine, Marine, Volcanic [0.5]
ROCK GEOLOGY TYPES $w_{EF(rg)}$	Sandstone interbedded with shale or limestone [3] Limestone, gypsum [2.5]	Dolomite, Tuff, Quartzite [1.5] Rhyolite, Basalt, Marble [1.2]	Agglomerate, Volcanic breccia Granite, Andesite, Gabbro, Gneiss [1.0]	Sandstone, Conglomerate [0.8] Schist, Phyllite, Slate, Hornfels [0.6]	Shale, Siltstone, Mudstone, Claystone, [0.2]
CORE GEOLOGICAL ORIGIN $w_{EF(cgo)}$	Alluvial [1.5]	Aeolian, Colluvial [1.25]	Residual, Lacustrine, Marine, Volcanic [1.0]		Glacial [0.5]
CORE SOIL TYPE $w_{EF(cst)}$	Dispersive clays [5] Low plasticity silts (ML) [2.5] Poorly and well graded sands (SP, SW) [2]	Clayey and silty sands (SC, SM) [1.2]	Well graded and poorly graded gravels (GW, GP) [1.0] High plasticity silts (MH) [1.0]	Clayey and silty gravels (GC, GM) [0.8] Low plasticity clays (CL) [0.8]	High plasticity clays (CH) [0.3]
CORE COMPACTION $w_{EF(cc)}$	Appears to be independent of compaction - all compaction types [1.0]				
FOUNDATION TREATMENT $w_{EF(ft)}$	Untreated vertical faces or overhangs in core foundation [1.5]	Irregularities in foundation or abutment, Steep abutments [1.1]		Careful slope modification by cutting, filling with concrete [0.9]	
OBSERVATIONS OF SEEPAGE $w_{EF(obs)}$	Muddy leakage, Sudden increases in leakage [up to 10]	Leakage gradually increasing, clear, Sinkholes [2]	Leakage steady, clear or not monitored [1.0]	Minor leakage [0.7]	Leakage measured none or very small [0.5]
MONITORING AND SURVEILLANCE $w_{EF(mon)}$	Inspections annually [2]	Inspections monthly [1.2]	Irregular seepage observations, inspections weekly [1.0]	Weekly - monthly seepage monitoring, weekly inspections [0.8]	Daily monitoring of seepage, daily inspections [0.5]

The method is intended for preliminary assessments only. It is ideally suited as a risk ranking method for portfolio type risk assessments to identify which dams to prioritise for more detailed studies. Since the method is based on a dam performance database approach, it tends to lump together the factors which influence the initiation and progression of piping and it is not possible to assess what influence each of the factors is having. It is recommended that more rigorous event tree based methods be used for detailed studies so as to gain a greater understanding of how each of the factors influences either the initiation or progression of piping, or the formation of a breach.

The user of the method is cautioned against varying the weighting factors significantly when applying the method to actual dams as they have been calibrated to the population of dams so that the net effect on the population is neutral.

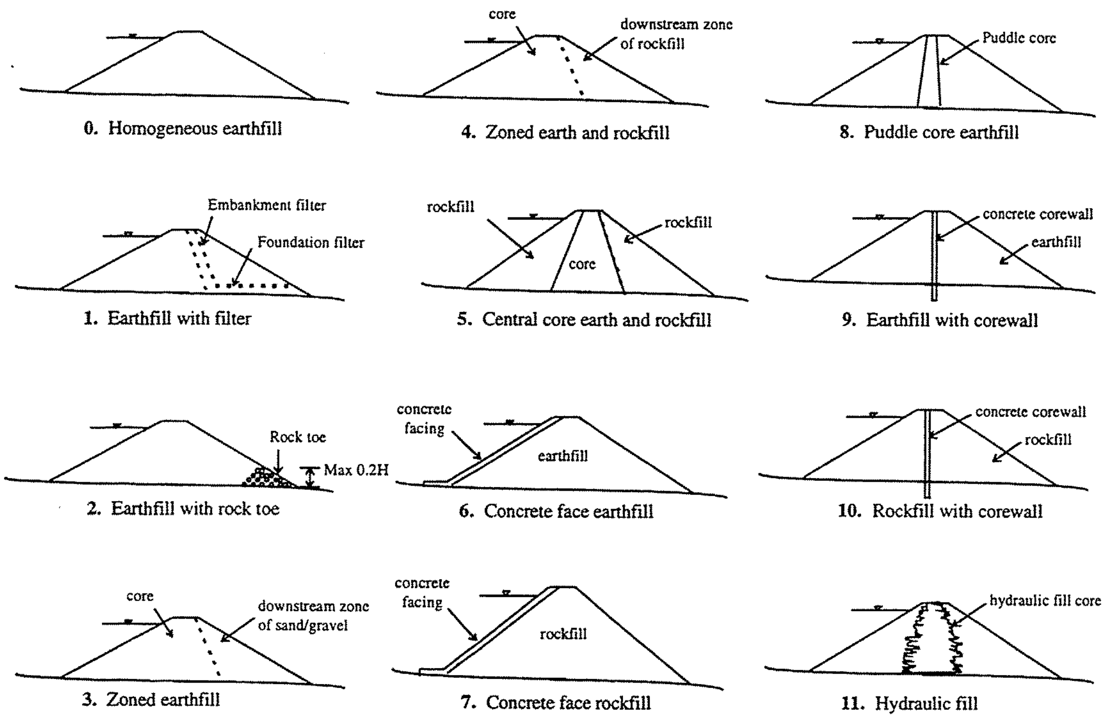

Figure 1. Dam zoning categories

APPLICATION OF THE METHOD

The following are details relating to the application of the weighting factors for each of the three modes of piping.

(a) Piping through the embankment

Embankment Filters $w_{E(filt)}$

The weighting factors for embankment filters, $w_{E(filt)}$, are only applied to the dams with zoning categories that usually have embankment filters present. These are:

- Earthfill with filter dams
- Zoned earthfill dams
- Zoned earth and rockfill dams
- Central core earth and rockfill dams

If an embankment filter is present, an assessment of the quality of the filter is required and this should include an assessment of the filter retention criteria, e.g. by comparison with Sherard and Dunnigan (1989). The likelihood of segregation of the filter materials should also be assessed by considering the construction methods used and the grading curves of the filter materials.

Compaction $w_{E(cc)}$

The methods of compaction are briefly described below to give guidance on the application of the method.

- *No formal compaction* - fill materials in the core were dumped in place and either no compaction, compaction by animal hooves or by travel of construction equipment only.
- *Rolled, modest control* - core materials were rolled but with poor control of moisture content (e.g., varying greater than ± 2% of optimum water content) and/or compacted in relatively thick layers.
- *Rolled, good control* - core materials compacted in thin layers, good control of moisture content within ± 2% of optimum water content and greater than 95% of Standard compaction.

Hydraulic fill and puddle methods of compaction are assigned $w_{E(cc)} = 1.0$ as they are exclusive to hydraulic fill and puddle core dams and these are already taken into account by the average probabilities of failure of the zoning categories.

Conduits $w_{E(con)}$
The categories used to describe the degree of detailing incorporated into the design of conduits located through the embankment are described as follows:

- *Conduit through the embankment - many poor details*: more than 4 of the poor detailing characteristics described below.
- *Conduit through the embankment - some poor details:* 2- 3 poor detailing characteristics
- *Conduit through the embankment - typical USBR practice:* details of conduits typical of USBR practice in the 1950-1970's which are described below.
- *Conduit through the embankment - includes downstream filters:* downstream end of the conduit surrounded by a well designed and constructed filter zone.
- *No conduit through the embankment*: outlet tunnel in the abutment, no outlet conduit e.g. flood control dams, or outlet through a concrete section of the dam.

Conduits through the embankment include both conduits above the level of the general foundation of the dam and conduits located in trenches excavated through the foundation of the dam.

Poor details of outlet conduits are (Fell et al, 1992):

1. No filter provided at the downstream end of the conduit.
2. Outlet conduit located in a deep and narrow trench in soil or erodible rock, particularly with vertical or irregular sides.
3. Corrugated metal formwork used for concrete surround.
4. Poor conduit geometry such as overhangs, circular pipe with no support, poorly designed seepage cutoff collars or other features that make compaction of the backfill around the conduit difficult.
5. No compaction or poorly compacted backfill.
6. Old cast iron or other types of pipes in badly deteriorated condition or of unknown condition.
7. Poor joint details, no or deteriorated rubber stops.
8. Cracks in the outlet conduit, open joints, seepage into conduit.
9. Conduit founded on soil.

Typical USBR practice in the 1950's to 70's for the detailing of conduits includes the following features (USBR 1977);

1. No downstream filter surrounding the outlet conduit.
2. Special compaction around the outlet conduit with special materials and hand tampers.
3. Outlet conduits were typically concrete formed in place with rectangular or horse-shoe shaped sections.
4. Concrete cutoff collars spaced at 15 feet (5 m).
5. Trench slopes excavated at 1 V: 1 H.

Foundation Treatment $w_{E(ft)}$
The presence and treatment of both small scale and large scale irregularities in the foundation need to be considered for the assessment of foundation treatment. See Fell et al (1992) for details of good practice.

Observations of Seepage $w_{E(obs)}$
The observations of seepage should incorporate an assessment of the full performance history of the dam and not just the current condition. Previous piping incidents may give indicators of deficiencies in design and that similar conditions may exist elsewhere in the dam. The following notes give some guidance to the other qualitative descriptions given in the Table 2.

Except for the category of seepage emerging on the downstream slope, all of the other descriptions of leakage are for the seepage flows collected from the drainage systems of the dam. The qualitative description of the neutral category "leakage steady, clear or not observed" is intended to represent the leakage condition that would be expected to be normal (or typical) for the type and size of the dam being considered. The other two descriptions of "minor" leakage and "none or very small" leakage are intended to represent seepage conditions better than the typical dam. A higher category could be selected if pore pressures measured in the dam are shown to have sudden fluctuations in pressure or a steady increase in pressures which may tend to indicate active or impending piping conditions. However, this does not necessarily apply the other way, as satisfactory performance of the pore pressures only indicates piping is not occurring at the location of the piezometers.

Allowance is made in the method to apply a value of $w_{E(obs)}$ within the range of 2 to 10 depending on the nature, severity and location of any past piping episodes. This assessment should include piping events that may have occurred over the full life of the dam.

(b) Piping Through The Foundation

Foundation Filters $w_{F(filt)}$

There are two categories defined for the cases where there are no foundation filters provided. In the worst case, foundation filters are not provided where it would be expected that foundation filters would be required, i.e., for dams constructed on permeable foundations. These cases are given the highest value of $w_{F(filt)}$ as shown in Table 3. Dams with no foundation filters on impermeable and non-erodible foundations would not be expected to require foundation filters and so a lower weighting is suggested.

Foundation Type (below cutoff) $w_{F(fnd)}$

Three categories were used to describe the type of foundation below the 'cutoff' of the dam as follows:

- Soil foundations
- Erodible rock foundations - potential erodible materials present such as clay filled joints or infilled karstic channels
- Non-erodible rock foundations

The 'cutoff' is taken to be either a cutoff trench or a sheetpile or slurry trench/diaphragm wall. Examples are shown in Figure 2.

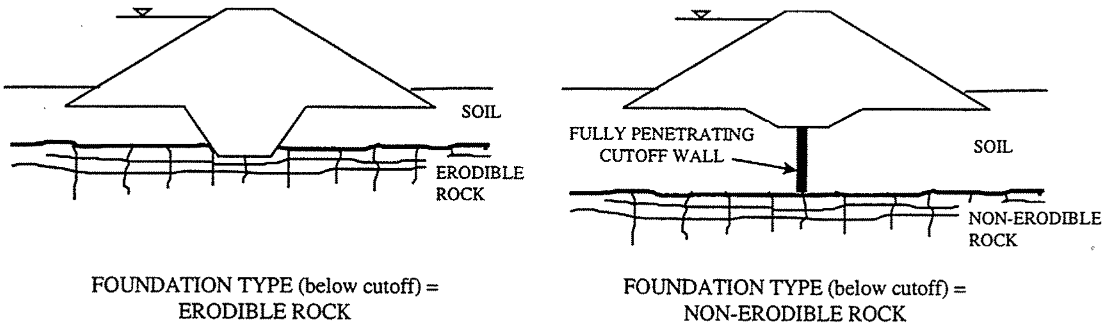

Figure 2. Examples of foundation type below the cutoff.

There should be a good basis for selecting the non-erodible rock category for describing a particular dam foundation given the weighting for non-erodible rock gives a reduction of 20 times compared to erodible rock. Intermediate values may be used.

Foundation cutoff type $w_{F(cts)}$ $w_{F(ctr)}$

There are two separate sets of weightings for the foundation cutoff type depending whether the cutoff is founded on either a soil or rock foundation. For dams with cutoffs founding on soil foundations only, the foundation cutoff factors ($w_{F(cts)}$) for soil foundations should be used, and vice-versa for rock foundations ($w_{F(ctr)}$). For dams where the cutoff is founded partly on soil foundations and partly on rock foundations (along the longitudinal axis of the dam), then the product of weighting factors of:

Foundation Type x Foundation Cutoff x Geology Type

i.e.,

$w_{F(fnd)}$ soil x $w_{F(cts)}$ x $w_{F(sg)}$

and

$w_{F(fnd)}$ rock x $w_{F(ctr)}$ x $w_{F(rg)}$

should be determined for both the soil and rock sections and the highest value obtained used.

Observations of Seepage and Pore Pressures $w_{F(obs)}$ $w_{F(obp)}$

Only one of the weighting factors should be applied out of observations of seepage or pore pressures, selecting the worst case. The assessment of the observations of seepage and pore pressures should consider the full performance history of the dam and not just the current condition of the dam.

All of the descriptions of leakage refer to seepage flows either emerging downstream of the dam or foundation seepage collected in the drainage systems of the dam. Seepage emerging from the drainage system of the dam would tend to indicate a potentially less hazardous seepage condition and therefore the weighting factors can be reduced slightly by a factor of say 0.75.

The qualitative description of the mutual category "leakage steady, clear" can be considered to be the leakage that would be expected to be normal for the type of foundation geology and the size of the dam being considered. The lower categories represent leakage conditions better than the typical conditions.

(c) Piping from the Embankment into the Foundation

Foundation Cutoff

If the cutoff trench penetrates both soil and rock, as illustrated below, then the product of weighting factors for:

Foundation Type x Erosion Control Measures x Grouting of Foundations x Geology Type

should be determined for both the soil and rock characteristics and the highest value used,
i.e., take the maximum of:

$w_{EF(fnd)}$ soil x $w_{EF(ecm)}$ x $w_{F(gr)}$ soil x $w_{F(sg)}$

or

$w_{EF(fnd)}$ rock x $w_{EF(ecm)}$ x $w_{F(gr)}$ rock x $w_{F(rg)}$

The following descriptions are given for guidance in applying the descriptive terms in the foundation cutoff categories.

- Deep and narrow cutoff trench: the cutoff trench would be considered to be "deep" if the trench is >3-5m deep from the general foundation level and "narrow" if the width to depth ratio (W/D) is < about 1.0, where the width is measured at the top of the cutoff trench.
- Shallow or no cutoff trench: a cutoff trench would be considered to be "shallow" if it is <2-3m.
- Average cutoff trench width and depth: depth 2-5m and W/D >1.0.

The geology types refer to the geology types that are in contact with the core materials, which includes soil or rock types that are in contact with the sides and base of the cutoff trench.

Erosion Control Measures $w_{EF(ecm)}$

The term erosion control measures refers to the design features used to protect the core materials from within the cutoff trench being eroded into the foundation and these can include:

- slush concrete on rock foundations
- filters located on the downstream side of the cutoff trench for soil or rock foundations

The descriptive terms of "poor", "average" or "good" foundation conditions refer to the presence of features in the foundation into which core materials can be eroded into. For rock foundations, poor foundation conditions could include any of the following:

- continuous open joints or bedding, or with clay infill or other erodible material.
- heavily fractured rock.
- karstic limestone features.
- stress relief joints in steep valleys or previously glaciated regions.

Good foundation conditions would be considered to be tight, widely spaced joints with no weathered seams.

For soil foundations, poor foundation conditions would include the presence of open-work gravels or other soils with void like features. Good foundation conditions would be fine grained soils with no structures or soils where the filter retention criteria between the foundation soils and the core materials are met.

Observations Of Seepage $w_{EF(obs)}$

Refer to the comments for piping through the embankment.

LIMITATIONS OF THE METHOD

The following points discuss the limitations of the proposed method.

- As the weighting factors are often based on low numbers of accident and failure cases, some of the factors and the baseline annual probabilities of failure for the zoning categories are sensitive to the occurrence of only one or two piping failures for dams with a particular zoning category or some other characteristic. This may tend to either underestimate or overestimate the influence of these factors. However, attempts were made in the analysis of the weighting factors to highlight these cases and to check the reasonableness of the factors based on the expected susceptibility of the particular conditions for piping failure.

- The probabilities of failure are based on large dams (>15m height) and so the method may tend to underestimate the probability of failure of piping if applied to smaller dams.

- The analysis of the weighting factors assumes the factors to be independent of each other, however it is probable there are interdependencies between some of the factors. Therefore, when the weightings are multiplied together, some 'doubling-up' of the weighting factors may occur and this may tend to over or under emphasise some factors. Any obvious cases of this 'doubling-up' of factors were accounted for in the analysis and any remaining cases are probably not significant.

- Since the method is based on accidents and failures, it is inherently difficult to get low weighting factors using this approach. Dams with favourable characteristics often have no failures on which to base a weighting factor on and so it must be based on some other basis. This was particularly evident for the influence of embankment filters on piping through the embankment where a value judgement was required to assess the weighting factor for well designed and constructed filters. Therefore, care should be taken in applying the probability of failure obtained by this method to acceptable risk guidelines particularly at very low probabilities of failure.

CALIBRATION OF WEIGHTING FACTORS

The weighting factors represent how much more or less likely a dam will fail relative to the 'average' dam. Quantification of the weighting factors were based on the results of the statistical analysis of failures and accidents of dams by piping, as described in Foster et al (1998), and were determined by comparing the characteristics of the dams that have experienced piping incidents to the characteristics of the dam population using the following equation:

$$\text{Weighting Factor} = \frac{\text{Percentage of failure cases with the particular characteristic}}{\text{Percentage of dam population with the particular characteristic}}$$

For the characteristics which have not been involved in any dam failures, the weighting factor determined from the data is zero and so for these cases, judgement was used to assign the weighting factor. As an example, there are no known failures by piping through the embankment for dams with fully intercepting embankment filters, and the factors adopted assume dams with good quality filters are 100 times more likely to fail by piping through the embankment than dams with no filters. This is a value judgement of the generally accepted belief of the reliable performance of well designed and constructed filters in sealing concentrated leaks through the core (Sherard et al 1985; Peck 1990; Ripley 1984).

It was not possible to calibrate the weighting factors related to the past performance and the degree of monitoring and surveillance of the dam due to the lack of data on the population of dams. The weighting factors for these factors were judgementally assigned using as a basis the weightings of other factors which were considered to be related or of similar significance.

The weighting factors were also checked by ensuring that when the factors are applied to the dam population the effect is neutral. This is possible by checking that the sum of the product of the weighting factors and the percentage population for each of the factors is equal to 100%, i.e.,

$$\sum(\text{Weighting Factor} \times \%\text{Population}) = 100\%$$

Descriptions of the analysis and the assumptions used to derive the weighting factors are not given in this paper due to space limitations, however details are given in Foster et al (1998).

CONCLUSIONS

A method for estimating the probability of failure of embankment dams by piping has been presented. The method is intended for preliminary assessments only and is ideally suited as a risk ranking method for portfolio type risk assessments to identify which dams to prioritise for more detailed studies, and for a check on event tree methods for evaluating the probability of failure by piping.

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Appendix B

Risk-Based Dam Safety Prioritization
A Project Sponsored by ASDSO and FEMA
A Method for Easily Estimating the Loss of Life from Dam Failure
Draft, by Wayne Graham, June 18, 2004

Introduction

There is a hazard potential classification system used in the United States to describe the adverse consequences that would result from dam failure. There are a variety of hazard classification systems in use, and most assign a dam either a low, significant or high hazard classification.

The Federal Guidelines for Dam Safety: Hazard Potential Classification Systems for Dams, FEMA 333, was issued in 1998 in an attempt to provide hazard classification definitions that could be used uniformly by all federal and state dam safety agencies. FEMA 333 defines the three hazard potential classifications as follows:

Low Hazard Potential – Dam failure results in no probable life loss and low economic and/or environmental losses.

Significant Hazard Potential – Dam failure results in no probable life loss but can cause economic loss, environmental damage, disruption of lifeline facilities, or can impact other concerns.

High Hazard Potential – Dam failure results in probable life loss.

Purpose and Need

Most dam safety management organizations apply more stringent inspection, design and maintenance criteria to high hazard dams than to significant, and especially, low hazard dams. There is a need to develop a procedure for further dividing high hazard dams into categories based on the adverse consequences that would result from dam failure. The failure of some high hazard dams might cause loss of life whereas the failure of other high hazard would likely cause the death of perhaps hundreds of people. The failure of some high hazard dams can easily cause much more destruction and damage than a high hazard dam that just marginally fit into that category. A simple to use loss of life estimating procedure is needed for dam safety risk based prioritization to help assure that the limited time and financial resources allocated to dam safety are wisely invested.

Historical Dam Failure Data

Many dam failures do not cause any loss of life. During the 9-year period from late 1985 to late 1994, there were more than 400 dam failures in the United States. In more than 98 percent of these dam failures, there were no fatalities. Many of these dams were small and/or were located in sparsely populated areas.

While many dams have failed with no resultant life loss, some of the worst U.S. floods (measured in terms of life loss) have resulted from dam failure. Dam failure can be sudden, causing rapid onset of flooding followed by rapidly rising flood levels. During the last 25 years (1979 to 2003), there have been no U.S. dam failures that have caused more than about 4 fatalities. Prior to this period, however, the U.S. has had the South Fork (Johnstown) Dam failure in 1889 which resulted in 2,209 deaths, and the St. Francis Dam failure in 1928 which resulted in about 420 deaths (the exact number of deaths is subject to some uncertainty).

One of the defining characteristics of dam failures, is that the highest fatality rates and most of the loss of life occur in close proximity to the dam. Data from several dam failures will be presented to demonstrate this characteristic.

There have been 6 or 7 U.S. dam failures that have caused more than 50 fatalities. Table 1 summarizes data from these failures. Note that in several of these cases most of the fatalities occurred in the first few miles downstream from the dam.

Table 1

Dam Failure Data

U.S. Dams that Caused More Than 50 Fatalities

Dam, State and Date of Failure	Height (ft)	Volume Released (acre-feet)	Total Loss of Life	Percentage of Total Loss of Life in Listed Distance Downstream from Dam		
				First 3 miles	First 7 miles	First 15 miles
Williamsburg Dam, (Mill River Dam) MA May 16, 1874	43	307	138	41	100	100
South Fork Dam (Johnstown Dam) PA May 31, 1889	72	11,500	2,209	Unknown	Unknown	About 100
Walnut Grove Dam AZ February 22, 1890	110	60,000	70 to 100	Precise location of people is not available. Many of those that died were at a construction camp, 15 miles from the dam.		
Austin Dam PA September 30, 1911	43 to 50	550 to 850	78	100 (all in first 2 miles)	100	100
St. Francis Dam CA March 12-13, 1928	188	38,000	420	Fatalities occurred throughout the 54 mile reach from the dam to the Pacific Ocean		
Buffalo Creek Coal Waste Dam WV February 26, 1972	46	404	125	28	85	100
Canyon Lake Dam SD June 9, 1972	37	700 (10,100 from entire flood)	33 from dam failure (165 total)	Unknown	Unknown	100

More accurate data is available for the failure of dams that have occurred in recent years. Table 2 summarizes information for U.S. dam failures that occurred from 1960 to 1998 and released up to 2,000 acre-feet during their failure.

Table 2

Dam Failure Data

Dams that released up to 2,000 acre-feet of water during their failure

U.S. data for failures that caused fatalities

Arranged in ascending order of volume released from reservoir, excluding flood inflow

1960 to 1998

Dam	Height (ft)	Volume Released (acre-ft)	Loss of Life	Percentage of total LOL in first 3 mi.	Percentage of total LOL in first 7 mi.	Percentage of total LOL in first 15 mi
Bear Wallow	36	40	4	100	100	100
Lake "O" Hills	15	48	1	Unknown	Unknown	Unknown
Evans, then Lockwood	18 and 14	72 and 32	2	100	100	100
Mohegan Park	20	138	6	100	100	100
Bergeron Pond	36	193	1	100	100	100
Lee Lake	25	300	2	0	100	100
Buffalo Creek Coal Waste	46	404	125	28	85	100
Laurel Run	42	450	40	100	100	100
Kelly Barnes	40	630	39	100	100	100
Kendall Lake	18	690	4	100	100	100
Lawn Lake, then Cascade Lake	26 and 17	674 and 25	3	0	100	100
Baldwin Hills	66	700	5	100	100	100
Canyon Lake	37	700 (10,100 from entire flood)	33 from dam failure (165 total)	Unknown	Unknown	100
Nix Lake	23	837	1	100	100	100
Little Deer Creek	86	1150	1	0	100	100
Timber Lake	33	1449	2	100	100	100

Procedure for Estimating Losses

From the information provided above, it is clear that study efforts should focus on evaluating the flooding that would occur in the first 5 to 15 miles downstream from a dam. It is in these areas where the warning may be deficient, the flooding most severe.

The steps involved in estimating consequences are as follows:

Step 1: Determine dam failure scenario to evaluate

Assume that the dam fails with the reservoir water surface at the crest of the dam. While dams may fail from piping or other causes with the water below the dam crest, this simplifying assumption is reasonable to use for nearly all dams.

Step 2: Determine area flooded from dam failure

In cases where dam failure inundation maps are not available, it will be necessary to develop some approximation of the flooding that would result from dam failure. This necessitates estimating the peak dam failure outflow at the dam and in downstream areas and then determining the extent of flooding that would result from these discharges. Dam failure modeling can be used for this or some simplified procedures, described below, can be used.

The peak dam failure discharge for embankment dams can be estimated using an equation contained in the paper, “Peak Outflow from Breached Embankment Dam,” by David C. Froelich. The equation, in English units, is $Q_p = 40.1V^{.295}H^{1.24}$, where Q_p is the peak outflow in cubic feet per second from the breached embankment dam, V is the reservoir storage volume in acre-feet at the time of failure, and H is the height of the embankment in feet from the bottom of the final breach to the top of embankment.

The peak discharge from a dam failure decreases, sometimes rapidly, as the flood travels downstream from the dam. Plots of peak discharge (as a percentage of the discharge immediately downstream from the dam) versus distance downstream from the dam are available for estimating flows in downstream areas. One such plot appears in “Dam Safety Guidelines, Technical Note 1: Dam Break Inundation Analysis and Downstream Hazard Classification,” issued by the State of Washington in July 1992. Flood depths at various locations along the river can then be determined using Manning’s equation using cross section geometry obtained from the best available topographic maps. Flood boundaries can then be approximated on available mapping. The maps should not extend more than 15 miles downstream from the dam because historical dam failure data indicates that people in these areas have not been seriously threatened by dam failure (in most cases).

Step 3 – Estimate the number of people at risk from dam failure

Using the results from step 2, the number of people at risk can be estimated for various locations downstream from the dam. It is suggested that the number of people at risk be estimated for three different reaches: the dam to mile 3, mile 3 to mile 7, and mile 7 to mile 15. The number of people at risk can be estimated using the population of communities and the percentage of the community that is flooded or by obtaining the number of houses off of maps or a site visit and multiplying the number of houses or residences by 3. Seasonally occupied locations or sites that have significant differences in population between weekday and weekend, such as campgrounds, may need special consideration.

Step 4 – Determine the Loss of Life From Dam Failure

People have located residences and other facilities on the floodplain for hundreds or thousands of years. Many years ago, people had little knowledge of the flooding that could occur from natural (as opposed to dam failure) flooding and would sometimes locate in areas that could be flooded every few years. With the implementation of flood plain zoning regulations as part of the National Flood Insurance Program, there is less new development in the most frequently flooded portions of the floodplain although the existing developments remain and new developments do occur in areas that would be impacted by dam failure. A dam failure can potentially cause large loss of life when the discharge from dam failure is much greater than typical and usual flows on the river that the flood wave passes through. Comparing the discharge from dam failure to commonly occurring flows can provide some measure of the potential danger caused by the dam failure flood. The 10-year flood, i.e., the flood that has a 10% chance of occurring in any given year can be used as a base to compare dam failure discharges to. The 10-year flood is used because it can generally be accurately estimated for a site. Three dam failures from the 1970's show how a comparison of the dam failure discharge to the 10-year flood can help explain why some dam failures are extremely lethal.

Buffalo Creek Coal Waste Dam failed on February 26, 1972. There were 125 fatalities with about 82% of these occurring in the first 6 miles downstream from the dam. The drainage area at the dam was only 1.1 square miles. The peak discharge resulting from dam failure is available for three locations. Less than 1 mile downstream from the dam, at Buffalo Creek below Saunders, the peak discharge resulting from dam failure was 50,000 ft^3/s and the 10-year flood at this site is 805 ft^3/s resulting in a ratio of dam failure discharge to 10-year discharge of about 62. About 7 miles downstream from the dam, at Buffalo Creek below Stowe, the peak discharge from dam failure was 13,000 ft^3/s and the 10-year flood at this site is 2,100 ft^3/s resulting in a ratio of dam failure discharge to 10-year discharge of about 6. About 12 miles downstream from the dam, at Buffalo Creek above Accoville, the peak discharge from dam failure was 8,800 ft^3/s

and the 10-year flood at this site is 2,820 ft^3/s resulting in a ration of dam failure discharge to 10-year discharge of about 3.

Laurel Run Dam failed on July 20, 1977. There were 40 fatalities, with all of these occurring in the first 2.5 miles downstream from the dam. The drainage area at the dam was 7.9 square miles. The peak dam failure discharge was 37,000 ft^3/s. The 10-year flood at this location is 920 ft^3/s. The ratio of the dam failure peak discharge to the 10-year flood peak discharge is about 40.

Kelly Barnes Dam failed on November 6, 1977. There were 39 fatalities, with all of these occurring in the first 1.5 miles downstream from the dam. The drainage area at Toccoa Falls College, 0.8 miles downstream from the dam is 6.2 square miles. The peak discharge at this location resulting from dam failure was 24,000 ft^3/s. The 10-year flood at this location is 1,260 ft^3/s. The ratio of the dam failure peak to the 10-year flood peak discharge is about 19. At a location 4.5 miles downstream from the dam, the drainage area is 12.8 square miles. The peak discharge resulting from dam failure was 6,380 ft^3/s at this location and the 10-year flood is 1,960 ft^3/s, resulting in a ratio of dam failure discharge to 10-year flood peak discharge of about 3.3

The loss of life from dam failure can be estimated using a fatality rate that is appropriate for each area impacted by dam failure. Table 3 supplies fatality rates that can be used to estimate the loss of life caused by dam failure. The table separates the area downstream from a dam into three reaches (measured by distance from the dam) and provides fatality rates based on the ratio of the peak dam failure discharge divided by the 10-year flood for each of the three reaches. Except for very unusual cases (such as very high dams), the contribution of loss of life from areas more than 15 miles downstream from a dam should be minimal and generally would be much less than the losses estimated for the first 15 miles downstream from the dam.

Table 3

Fatality Rates for Estimating Life Loss from Dam Failure

Derived from an Analysis of U.S. Dam Failures

(June 18, 2004 Note: This is draft information, subject to considerable revision. Do not use or quote)

The ratio of the peak discharge resulting from dam failure divided by the 10-year flood discharge (measured at upstream end of reach)	Fatality Rate (Percentage of people [prior to any evacuation] within the dam failure floodplain who would likely die as a result of dam failure)		
	From the dam (mile 0.0) to mile 3.0	From mile 3.0 to mile 7.0	From mile 7.0 to mile 15.0
More than 100	0.75	0.50	0.37
50 to 100	0.50	0.33	0.25
30 to 50	0.25	0.20	0.13
20 to 30	0.20	0.15	0.10

10 to 20	0.10	0.08	0.05
5 to 10	0.02	0.015	0.01
3 to 5	0.01	0.007	0.005
1 to 3	0.005	0.003	0.002
Less than 1	0.001	0.0001	0.0000

Table 4 is an example showing how this data would be used for a hypothetical dam.

Table 4

Example Dam

Loss of Life Resulting from Dam Failure

Reach (Distance from Example Dam) in miles	Number of people located within the dam failure flood boundary	Ratio of Peak Discharge from Dam Failure to 10-Year Flood Peak Discharge	Fatality Rate	Loss of Life
0.0 to 3.0	60	35	0.250	15
3.0 to 7.0	400	6	0.015	6
7.0 to 15.0	500	2	0.002	1
Total (mile 0.0 to 15.0)	960	Not applicable	Not applicable	22

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