# SAFETY LEVEL EVALUATION SYSTEM FOR DAMS

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## Introduction

The primary function of a dam safety program is to keep people and property downstream of dams safe from dam failures. A dam failure disaster in simple terms consists of a chain of three events: dam failure, inundation of the river valley, and negative impact to people and property. A dam safety program can work in any of these areas to interrupt the chain and avoid some or all of the negative impacts. The focus of most programs has been to keep dams from failing. A brief review of Association of State Dam Safety Officials 2004 State-by-State Statistics on Dams and State Safety Regulation shows that most states have several deficient high-hazard dams. For a program to be effective, it must routinely be able to measure the safety levels of its dams. Knowing the safety levels of dams is critical for making administrative and technical decisions.

Measuring the safety levels of dams might not seem to be as complicated as it actually is. For years programs have pursued, and often measured, compliance with safety standards based on engineering codes and principles, state laws, and administrative rules. But compliance is a black and white system; it does not readily translate into shades of gray, which are needed for effective comparisons. Consider two similar dams (in all respects) that lack adequate flood capacity. Both are considered noncompliant based on flood capacity. The first dam has 10% of its required flood capacity and the second has 95% of its required flood capacity. The first is less safe than the second, and focusing efforts to improve the safety of this dam would provide more public safety than focusing efforts on the second. But how much less safe is it? Now consider Ohio's inventory of more than 400 high-hazard dams with over 100 dams not being compliant with all safety standards. The conditions of the dams are constantly changing – dams are being repaired and periodic and emergency inspections are revealing new deficiencies. Measuring the fluctuating safety levels of dams can be overwhelming.

Many measurement systems have been used over the history of dam safety, each with unique advantages and disadvantages. A simple measurement system has the benefit of wide applicability but lacks the insight of a more complicated, in-depth system. An in-depth measurement system, although excellent in quality, can be cost prohibitive and beyond the resources of a state program. Furthermore, systems usually are static; they are fixed in time. For Ohio's dam safety program, it was determined that a specialized measurement system needed to be developed and tailored to fit into the resources and work processes of Ohio's program, and the system must be dynamic to keep the system results current.

Safety Level Evaluation System for Dams (SLESD) incorporates aspects of risk assessment, risk indexing, a knowledge-based expert system (KBES), and database application to provide an efficient, accurate tool for measuring safety. The system utilizes the logic and thoroughness of risk assessment, the ranking aspect of risk indexing, the power of a KBES, and the accessibility and flexibility of a database. The system is designed to be integrated into the program's work processes and database to ensure that the information is up-to-date. The system is designed for evaluating the safety levels of high-hazard embankment dams in Ohio and is intended to be used by an experienced engineer. In addition, it provides the framework for collecting important program data.

## Ohio's Dam Safety Engineering Program

Ohio Department of Natural Resources, Division of Water, Dam Safety Engineering Program has the responsibility to ensure that human life, health, and property are protected from dam failures. The Ohio Revised Code provides the authority for the program to regulate dam safety and dictates the responsibilities of the program and dam owners. The program regulates more than 1700 dams in Ohio, more than 400 of which are high-hazard. Failure of a high-hazard dam would likely result in loss of life. The program has one central office in Columbus, Ohio, and the staff consists of an administrator, an administrative assistant, three managers, seven engineers, and a construction specialist. Staff levels and budget have changed throughout the program's existence. Since 1999, budgets have diminished, and the program has gradually lost one third of its staff.

The program's responsibilities are divided into four general areas: periodic safety inspections, repairs and modifications, construction permits, and emergency response. The program performs periodic safety inspections of the high-hazard dams once every five years. Program staff review calculations and other documentation and visually inspect the dam to determine whether the dam complies with current laws, administrative rules, and safety standards. The inspection concludes with providing to the owner with an inspection report that lists the required remedial measures for the dam. When a dam is repaired or modified, often in response to the requirements of an inspection report, the program is responsible for reviewing design reports and construction plans. Staff monitor construction to ensure proper implementation of construction plans. The program is responsible for issuing construction permits for proposed dams. The permit process includes reviewing design reports and monitoring construction. And finally, the program is responsible for responding to emergencies such as uncontrolled seepage from an embankment or a record high pool level during a flood. The program has the authority to take immediate action to correct unsafe dams during emergencies. Considering the number of jurisdictional dams, wide range of responsibilities, and limited budget and resources, the program must prioritize activities and work effectively. The program must have an accurate, efficient system for measuring the safety levels of dams to ensure resources are allocated appropriately.

Understanding how dams fail is key to keeping them safe. Dams are complicated structures, and it can be difficult to predict how they will respond to distress. "… The modes and causes of failure are varied, multiple, and often complex and interrelated, i.e., often the triggering cause may not truly have resulted in failure had the dam not had a secondary weakness. These causes illustrate the need for careful, critical review of all facets of a dam." (Safety of Existing Dams, 1983). The condition of a component of a dam must be evaluated in context, not by itself. Von Thun makes this point in his discussion of the importance of failure mode evaluation for dam safety inspections in "Dam Safety Inspections and Failure Mode Evaluations – They're Made For Each Other" (ASDSO newsletter, May/June 2002, Volume 18, No. 3) A failure mode evaluation analyzes the full chain of events that could lead to a dam failure, or an uncontrolled release of the impoundment. But review of failure modes is not only important for a dam safety inspections; it also has applications to the rest of the program, such as design review and emergency response. Lessons learned from one part of the program need to be shared with the others. Inspections provide data that is valuable during emergencies, repairs provide information for future inspections, and emergency response provides experience to help evaluate the severity of deficiencies during inspections and the appropriateness of repair and permit designs. Understanding of failure modes is the common thread that connects technical decision-making in all parts of the program.

## Approaches for Measuring Safety Level

The concept of safety itself requires discussion. Haimes states "safety manifests itself in the level of risk that is acceptable to those in charge of the system." (Risk of Extreme Events, Reliability, and the Fallacy of the Expected Value, 2004) Safety is, therefore, subjective. It becomes more subjective when risk information, which is directly dependent on probabilities, has a significant amount of uncertainty. Dam safety engineering probabilities such as the probability of the Probable Maximum Precipitation and the probability of a drain system failing fit into this category. Evaluation of the safety level of a dam is subjective venture.

Many approaches have been used to measure safety. The most basic measurement is analysis of compliance. It could be argued that dams that are compliant are safe. Engineers can analyze the features of a dam with respect to their compliance with current laws, administrative rules, and safety standards. For example, a stability analysis shows that an embankment has a factor of safety of 1.35; the design standard is a factor of safety of 1.5. The dam would be noncompliant and would, therefore, be unsafe. Is this dam very unsafe, moderately unsafe, or slightly unsafe? Review of compliance does not answer this question. Consideration of several compliance issues for comparison of several dams makes compliance even less useful as a measurement tool. It might appear that a comparison of the degree of noncompliance would provide insight, but this is not necessarily the case. Consider two dams that overtop during their design floods, the first passes 50% of its design flood while the second passes 75% of its design flood. The dams are noncompliant. One might suspect that the first is less safe because it passes less of its design flood. A closer look shows that the first overtops by 1 foot during its design flood and has a wide crest and mild downstream slope. The second overtops by 3 feet during its design flood and has a narrow crest and steep downstream slope. The second dam would likely be less safe. It is clear that simply reviewing compliance provides limited information for measuring safety levels of dams, especially when comparisons are needed.

Ohio's dam safety program has used informal discussion along with compliance to prioritize dams for repair and emergency inspection. Discussion allows engineers familiar with a particular dams to offer insight regarding the severity of noncompliance and the resulting impact to the overall safety of the dam. While this is an improvement, it has limitations. Each engineer has a different educational background, set of experiences, and way of evaluating the safety of a dam. This makes the evaluations inconsistent and difficult to compare. Furthermore, this approach requires considerable time and personnel resources.

Risk assessment is a tool that offers a systematic, thorough way to measure the safety level of a dam. Risk assessment for a dam includes analysis of the potential failure modes, the inundation due to failure, and the consequences of inundation. A risk assessment would require several engineers to review all available data for a dam, to perform safety inspections, and to perform calculations and analyses. The engineers would need to have a high level of expertise to be able to accurately estimate probabilities. The assessment is specialized for the particular dam. The engineers would relate probability of failure with consequences to determine the risk of dam failure along with a description of uncertainty. The results of the assessment are quantitative and allow for comparison. Risk assessment undoubtedly provides excellent insight into the safety level of a dam.

Although a valuable tool, it is not feasible to perform a risk assessment for Ohio's inventory of over 400 high-hazard dams. The cost to hire consultants to perform the assessments would be excessive for the program's budget. Use of program staff could be more cost effective, but staff does not have sufficient expertise, experience, or time. Regardless of feasibility, it should be noted that risk assessment has several shortcomings. First, it has a limited timeframe of applicability. After a few years, some dams have been repaired and others have deteriorated. Typical risk assessments do not have an efficient method for updating the data. Second, the results are usually contained in a hard-copy report. A report is stored in a file cabinet where it is less accessible to staff as compared to a digital report, which can be easily retrieved. Third, the report does not capture the knowledge of the experts. The experts use their knowledge to perform analyses, review data, and draw conclusions. The report contains the results of the experts' knowledge, but does not document the knowledge. It would be useful to the program to capture the knowledge for use in other parts of the program. And finally, risk assessment is highly dependent on probability. Precise probability data is typically unavailable; therefore, results of the assessment can have limited use.

Risk indexing is an approach that utilizes some concepts of a risk assessment, but uses a more concise, standardized method to make it more feasible than a risk assessment. Risk indexing assigns scores to dams using formulas based on quantified data. The scores allow the dams to be compared to one another, which is important for prioritization. The State of Washington and the Natural Resources Conservation Service have developed and used risk indexing systems. It is faster, less dependant on probability data, more consistent, and less expensive than a full risk assessment. But risk indexing also has several shortcomings. The logic of the evaluation is not explicit; it is contained in the formulas. Therefore, it is difficult to accommodate unique situations or data that is incomplete or inexact. The score of a dam does not indicate a meaningful level of safety. For example, a risk indexing system might score dams between 0 and 100, with 0 being least safe and 100 being most safe. If dam "A" scores a 40 and dam "B" scores a 60, it is clear that dam "A" is less safe than dam "B." But what does 40 mean?  Is 40 very unsafe or slightly unsafe? Although risk indexing has several benefits, it is not the best approach for measuring the safety levels of dams because its shortcomings limit its usefulness.

## Safety Level Evaluation System for Dams

SLESD incorporates aspects of risk assessment, risk indexing, KBES, and database application to provide an efficient tool for measuring safety. It provides the benefits of the approaches described previously while limiting the shortcomings. The system utilizes the logic and thoroughness of risk assessment, the scoring of risk indexing, the power of a KBES, and the accessibility and flexibility of a database. The system was designed for high-hazard embankment dams in Ohio and was intended to be used by an experienced engineer. The goals for this stage of development were accurate determination of overall safety level of a dam and proper framework to allow Ohio's dam safety program to implement the system. The system was designed to assess the safety level of a dam itself; the safety level does not include consideration of downstream hazard.

The overall safety level of a dam is a sum of the safety levels during various loadings and failure modes. SLESD guides the user through safety level evaluations for standardized combinations of loadings and failure modes (Figure 1). Loading conditions include normal pool, 12% PMF[1], 25% PMF, 50% PMF, 75% PMF, and 100% PMF. Failure modes include overtopping, seepage, and structural collapse of spillway. The evaluation is combines qualitative and quantitative data. The system provides structure and guidance to improve consistency.

Each combination of failure mode and loading constitutes one scenario. The system requires the evaluation of twenty-one scenarios. For each scenario, the system provides one branch of a fault tree and specialized information from the database and knowledge base. The fault tree shows the general logic of how the dam would fail during a specific the failure mode. Figure 2 provides examples of fault trees and their interpretation, and Figure 3 shows the user interface. The user follows the direction from the fault tree, reviews the specialized information, makes intermediate assessments, and finally evaluates the safety level of the dam for that scenario. The system converts the safety level to a score by multiplying the pre-assigned weight for each scenario and a percentage that corresponds to the safety level. Descriptions of safety levels and their corresponding percentages are shown in Table 1. The weights and percentages that correspond to a particular safety level were established during development of the system. For example, consider that a safety level for the scenario of overtopping failure during 100% PMF is "poor." The pre-assigned weight for this scenario is 5, and the percentage for a safety level of "poor" is 85%. Thus, the score for the scenario is 5 x 0.85 = 4.25. After the user has evaluated the safety levels for all of the scenarios (Figure 4), the system calculates the scores and determines the overall safety level of the dam. An example demonstrating all the steps in evaluating a safety level for a scenario is provided later.

The system follows the general logic of a risk assessment by evaluating failure modes. Failure modes have been grouped into three general categories: overtopping, seepage, and structural collapse of a spillway. An overtopping failure occurs when floodwater flows over the embankment crest and causes the dam to fail. This process is discussed in detail in Prediction of Embankment Dam Breach Parameters. It generally consists of eroding the grass ground cover, eroding the downstream slope and crest until the erosion connects to the reservoir, and then forming the breach. Seepage failures occur when seepage under or through the embankment progressively erodes embankment soil to form a breach. Structural collapse of the spillway occurs when spillway discharge is not properly contained in the spillway. Discharge overtopping sidewalls or flowing through open joints can erode a spillway's foundation or embankment fill, leading to the formation of a breach. For all of these modes, the formation of the breach and subsequent uncontrolled release of the reservoir depends upon there being a sufficient amount of water in the reservoir.

SLESD uses several concepts that are incorporated in risk indexing. First, the system uses standardized data. The team determined what data (in addition to the data that is normally collected to support the National Inventory of Dams) the user would need to make intermediate and final safety level evaluations. It is more efficient to forecast data needs and then gather the data than to gather data and try to design a system at a later time. Erodibility of embankment fill and potential for spillway clogging are examples of additional data that needs to be collected and entered into the database. Use of standardized data also improves consistency. Second, the system uses a scoring system to allow for the results to be compared. However, the system goes a step further and provides interpretation of the score.

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[1] [The Probable Maximum Flood (PMF) "means the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the drainage basin under study." (Ohio Administrative Code) The PMF is the design flood for high-hazard dams.]

Finally, the system is faster than a full risk assessment, which makes it more feasible for the program to use.

KBES is a tool that has not been used widely in dam safety. KBES is “a concept used to develop a computer program that attempts to embody the knowledge, reasoning, and decision making process of an expert(s).” (Hadipriono, CE688 Class Notes, Ohio State University) The knowledge is represented in rules (Figure 5) and pseudo-rules. Rules are used to interpret data and draw conclusions. Rules are represented as “if-then” statements that interpret data based on expert opinion. For example, the depth of overtopping of an embankment can be quantified. A rule used in the system states that if the depth of overtopping is between 3 and 6 inches, then the depth of overtopping is described as shallow. These rules take the form of look-up tables and are easily captured in a database. The rules have two main benefits. First, they convey knowledge that has been incorporated into the system, and second, they help prevent information overload. Programs can gather so much data that it becomes overwhelming for an engineer to sort through all the numbers to make sense of them. The rules filter the data and then change it into information and knowledge. Some situations are too complex to be readily represented with rules. In these cases, the system uses pseudo-rules and guidance. Pseudo-rules and guidance provide the user with an explanation of how the information should be interpreted. It is the user’s responsibility to review the pseudo-rules and guidance and draw a conclusion. For example, the damage to an earthen embankment due to floodwater overtopping, given that depth and duration are known, is dependant upon several factors including downstream slope gradient, ground cover, erodibility of the soil, and anomalies on the slope that could initiate erosion. Rather than develop complicated if-then statements to process data, the program describes the process of embankment erosion, lists important factors, and provides examples to assist the user in making the determination. The pseudo-rules and guidance allow for unique situations to be considered. Use of a database for storing rules and pseudo-rules allows the system to grow as rules are refined and added in response to additional studies and new experiences.

KBES allows for the logic of the system to be displayed. SLESD uses fault trees to show the logic of how the system guides the user. Figure 2 shows fault trees for three scenarios, each a different mode of failure. Showing the logic of the system assists the user with understanding how the system works and allows for the system to be modified in the future. Furthermore, it allows data to be better interpreted. When using a risk indexing system, one can encounter a situation where a certain parameter is required for a formula, and selection of this parameter can significantly influence the final score. A risk indexing system does not clearly show the logic of the formula, and one is left to make a best estimate. A fault tree shows the chain of events from loading to failure. This allows the user to use better judgment when the data does not perfectly fit the situation.

Use of a database in Safety Level Evaluation System for Dams provides several key elements. First, it makes the information “real-time” and accessible. All dam safety staff are connected to the database. As staff perform their day-to-day work in all parts of the program, they supply information to the database. This ensures that current data will be available. This is an improvement over other measurement approaches that require the retrieval of large amounts of data before they can be applied. Second, the database provides the user with the right information at the right time. The program stores large quantities of data about dams. The database can be designed to display pertinent data and filter extraneous information that can overwhelm the user. Third, it can perform calculations and simulate the inference engine of a KBES by employing lookup tables and filtering data. By storing the knowledge base rules in a database, the system becomes flexible because the rules and overall system can be easily updated as new knowledge is gained. And last, a database program such as Microsoft Access has tools that increase the appeal of the user interface, an important facet for successful implementation of any system. For this stage of the project, Microsoft Excel was used to simulate a database. The system will later be transferred to Access.

## System Development and Application

SLESD was developed in two stages. First, the design engineer created the structure and concept of the system. The design engineer reviewed other systems, the program's database, and other available program data, and prepared the framework for developing rules. Second, the design engineer gathered a team of program experts. In this context of the project, an expert is considered a person with considerable knowledge and understanding of dam safety. The team consisted of four registered professional engineers with an average of 9 years of experience in dam safety in Ohio (the design engineer was also a team member). The engineers had a variety of backgrounds including geotechnical, construction, program management, hydraulics, and hydrology. The team reviewed the system's structure and logic and provided input to the knowledge base by creating, reviewing, and adjusting rules. The design engineer met with the team seven times for an average of two hours per meetings.

The team calibrated the system using hypothetical situations and real dams. The team evaluated several scenarios to ensure that the system was guiding the user to the best safety level assessment. Next, weights were assigned to each of the scenarios (Figure 4), and percentages were assigned to safety levels. The team reviewed and compared the scores that were generated based on the weights and percentages, and also investigated the sensitivity of the system. The team adjusted rules, pseudo-rules, guidance, weights and percentages until the system was reliable. The team developed a scale for interpreting the score as a linguistic description (Figures 3 & 4). The team adjusted the scale until the system was describing a proper safety level of the dam with respect to each failure mode and overall safety.

The team used the calibrated system to evaluate the safety levels of Cowan Lake Dam, Rupert Lake Dam, and Forked Run Lake Dam. Table 2 provides general background information about these dams. These dams had not been used in the calibration process. The team reviewed the project files and construction plans for each dam. Data from the dam safety database and additional data that was identified during system development was gathered and entered into the system. The team used the system to evaluate the safety level of each dam for each scenario. A detailed description of the safety level evaluation of Cowan Lake Dam for overtopping mode of failure during PMF is described below. More detailed information about this dam is provided in Figure 6.

### *Example*

Evaluation began by following the fault tree on the bottom right of the user interface screen (Figure 7). The fault tree was followed from the bottom to the top, and the information to the left of the fault tree was used to assist with the intermediate evaluations. The first event on the bottom of the fault tree was occurrence of the flood event, in this case the PMF. Next, the dam responds to the flood. Each high-hazard dam has been analyzed using a flood routing model to determine maximum water surface elevation during various events. The results of the flood routing model had been entered into the system prior to the evaluation and were displayed to the left of the fault tree. The system used maximum water surface elevation during the flood and embankment crest elevation to calculate the depth of overtopping, and the duration of overtopping was taken directly from the database. The KBES interpreted the depth as “deep” and the duration as “very long.” The system used a rule to determine if the user should have been advised to reconsider the depth and duration of overtopping. The rule was based on the amount of precipitation runoff that the dam can store at top of dam elevation, the likelihood of each of the spillways clogging, and the amount of flow that each spillway passes. For storage, the runoff in inches was a simple calculation from the database, and the KBES evaluates the number and provided an interpretation next to it. In this particular case, Cowan Lake had “medium storage” and the principal spillway has a “low” potential to clog. The system advised “no adjustment needed.” If the dam had “low storage” and the potential for clogging of the spillway was “high,” the system would have advised the user to consider modifying the flood routing with reduced flow in the spillway. This would increase the depth and duration of overtopping. The first intermediate evaluation was to describe the overtopping: “Evaluation of Overtopping.” The recommendation from the KBES was “very severe,” and the team agreed with this assessment. Next, the user must evaluate the amount of erosion that would occur due to “very severe” overtopping. The system directed the user to a pseudo-rule. The pseudo-rule was a table (viewed using a hyperlink in the program) that guided the user through what should be considered when looking at erosion: ground cover, embankment erodibility, downstream slope gradient, and crest width. Because the fill erodibility was judged to be “high” and there were not extenuating circumstances to compensate for this, such as a very mild downstream slope, the team agreed that there would be severe erosion of the downstream slope. The second intermediate evaluation, “Evaluation of Erosion Connection,” was described as “very severe.” The next evaluation was for formation of the breach given “very severe” erosion of the downstream slope. This corresponded to the final evaluation: “Evaluation of Safety Level.” The reservoir volume was described as “very high storage,” so the conclusion was that there was sufficient water in the reservoir to drive the breach. The final safety level for this scenario was “poor.”

## Results

The system performed well from a work process perspective. The system filtered the data and displayed it on the appropriate screens. The fault trees explained the logic of the system properly and guided the users through the process. The rules assisted with interpretation of the data and with guidance for evaluating the safety levels. The system performed efficiently, provided a consistent approach, and was easy to use. With some minor modifications, Ohio’s dam safety program can transfer the system to a database application and implement it successfully.

The team reviewed the results and agreed that the system determined appropriate safety levels with respect to failure mode and overall safety for each dam (Figure 8). This confirmed system accuracy. The team agreed that overall safety levels of the dams could be compared to one another. This is important for prioritizing emergency response activities and enforcement action.

Ohio’s dam safety program used a risk indexing system to prioritize 66 dams for repairs in 2000. The risk indexing system used formulas based on standardized data to generate a score for each dam between 0 and 200. The standardized data included the percentage of flood capacity and types of required engineering repairs. After reviewing the results of the risk indexing system and having personal experience with some of the dams, dams could be sorted into groups with generally similar safety levels based on their scores. Most dams with high safety levels scored less than 12; dams with moderate safety levels scored between 12 and 40; dams with poor safety levels scored between 40 and 75; and dams with very poor safety levels scored more than 75. It is important to note that the delineation of the groups was not part of the risk indexing system; the groupings could only be determined after reviewing the results. The risk indexing results for the three dams used to validate SLESD are provided in Figure 8.

For perspective, the team compared the results of the SLESD with the results of the risk indexing system. For Rupert Lake Dam, the results were similar. This was not surprising. Both systems considered deficiencies with the dams, and Rupert Lake Dam did not have any. For Forked Run Lake Dam, the final safety levels were similar, but not for the same reasons. An investigation of how the risk indexing system created its score for the dam revealed that it had not logically reached its final safety level. More of the final score of 53 came from the inadequate flood capacity of the dam than from the very poor structural condition of the spillway. SLESD indicated that poor performance of the spillway was the main problem and inadequate flood capacity was a minor problem. Additional review confirmed that SLESD provided the more accurate evaluation.

For Cowan Lake Dam, the results of the two systems differed significantly. The main problem for Cowan Lake Dam was deterioration of the concrete spillway chute (Figure 6). The spillway chute had a deteriorated concrete section and a void under the top of a sidewall. A periodic inspection report for the dam required a registered professional engineer to investigate condition of the spillway and prescribe repairs. This was a valid requirement considering these types of problems. Most of the final score of 24 came from the spillway deficiency. However, the risk indexing system did not consider the full context of the problem. SLESD guided the user to a similar result with regard to the condition of the spillway. SLESD also guided the user through the remainder of the failure mode, and it was realized that the problem areas were relatively far downstream from the control section and the spillway rests on a rock foundation. There did not appear to be a significant risk of a large uncontrolled release because of failure of the spillway. SLESD provided a safety level of high. Additional review confirmed that SLESD provided the more accurate evaluation. It is important to note that spillway still needs to be repaired even though the safety level of the dam estimated as high.

The time to complete a dam evaluation was not specifically measured. It is estimated that it took about 30 minutes after the records had been reviewed and all of the needed information had been entered into the database. This is a significant time-savings compared to a more complicated system to measure safety such as a risk assessment. The true time-savings come from integration of SLESD into the normal work processes. The system is intended to be used at times when the engineer has already become familiar with the project records as part of normal program responsibilities, such as at the end of a repair project or at the end of a periodic inspection.

## Limitations and Modifications

- The system is only as strong as the user's ability to apply it and the knowledge base. The system is not a black box that will blindly take data and produce a reliable answer. The user must understand how the system works and have experience for it to work properly. In addition, the knowledge base is a reflection of the dam safety program's experience and interpretation. The knowledge base needs to continue to develop.

- Some of the pseudo-rules and guidance need more development. Due to limited time for the project, the pseudo-rules and guidance were developed in rough form. Additional work is needed to better represent them, especially for seepage.
- For making comparisons, the system works well when there is a relatively wide spread of safety levels for the dams being evaluated. It is not intended to differentiate between dams in the same safety level.
- Conceptually, omission is a potential problem. It was acknowledged during development of the system that a failure mode for earthquakes was not addressed. The system could have included this failure mode, but the amount of work that would have been necessary was beyond the resources of this project. Ohio's dam safety program currently does not have much experience with earthquakes.
- As designed, the system does not accommodate additional appurtenances. Not all dams fit into the system configuration of an embankment and two spillways. Although this modification does not require a significant redesign, it needs to be included. It should be noted that the validity of the results remains even when additional appurtenances are added.
- The user interface and database need to include comment areas. It was found that entry of brief notes in different parts of a dam's evaluation made future review much easier.

## Conclusions

Safety Level Evaluation System for Dams effectively incorporates aspects of risk assessment, risk indexing, KBES, and database capabilities to provide an efficient tool for measuring safety. The system is consistent and efficient. It offers insight that is useful for many parts of the program. It allows the program to assemble an archive of dam safety knowledge and to make the archive accessible to the program staff. It also has shown areas where the program needs improvement and better understanding. The system is flexible for unique conditions and has the potential to develop as the program develops. The goals for this stage of development have been met: the system accurately determines the safety level of dams and the overall structure of the system is appropriate for implementation into Ohio's dam safety program.

## Acknowledgements

The author would like to thank Dr. Fabian Hadipriono of the Ohio State University, the dam safety staff who assisted with development of the system, and rest of the dam safety staff for their help with this project.

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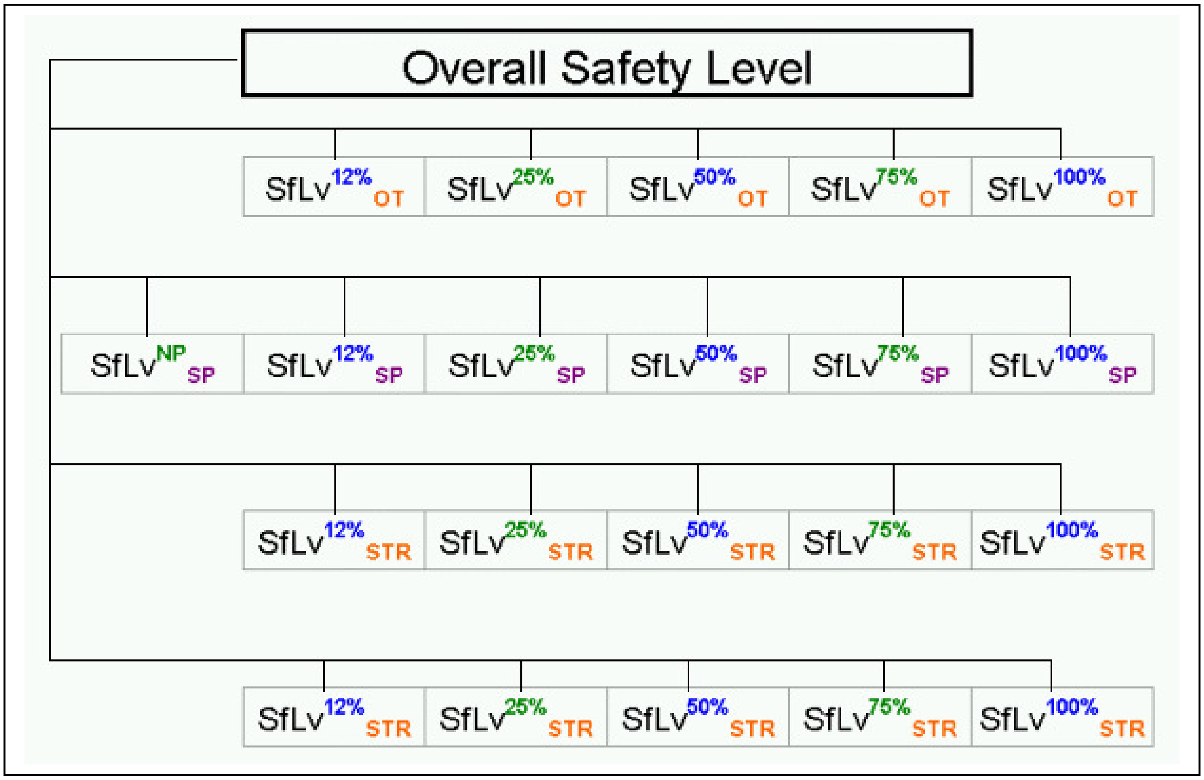
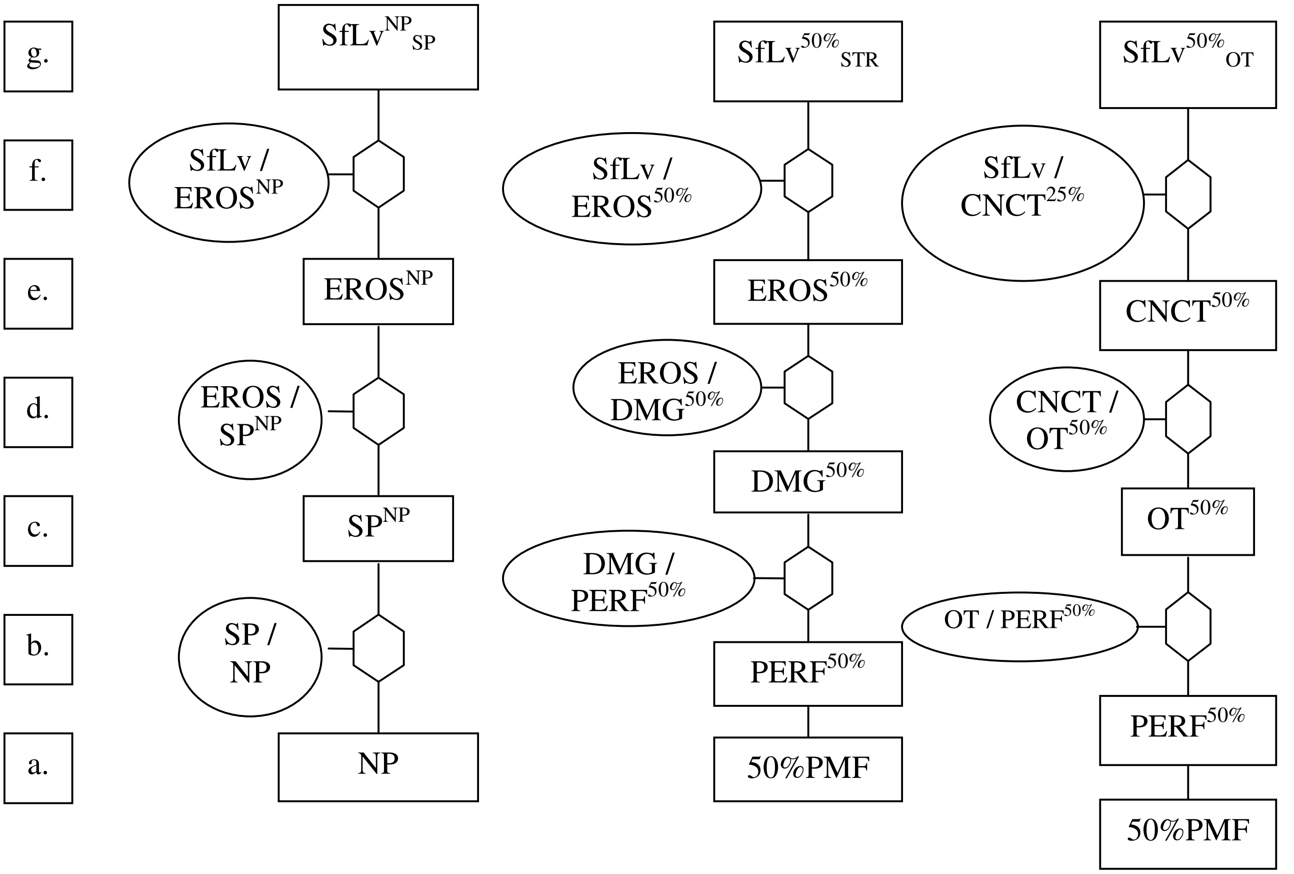
## Figures and Tables

Figure 1 – Matrix of Safety Level Evaluations



$SfLv^{12\%}_{OT}$ represents the safety level of the dam with respect to an overtopping failure during 12%PMF; it is the safety level for one scenario.
$SfLv^{NP}_{SP}$ represents the safety level of the dam with respect to seepage failure during normal pool.
$SfLv^{12\%}_{STR}$ represents the safety level of the dam with respect to structural collapse of the spillway during 12%PMF.

Figure 2 – Fault Trees for Modes of Failure



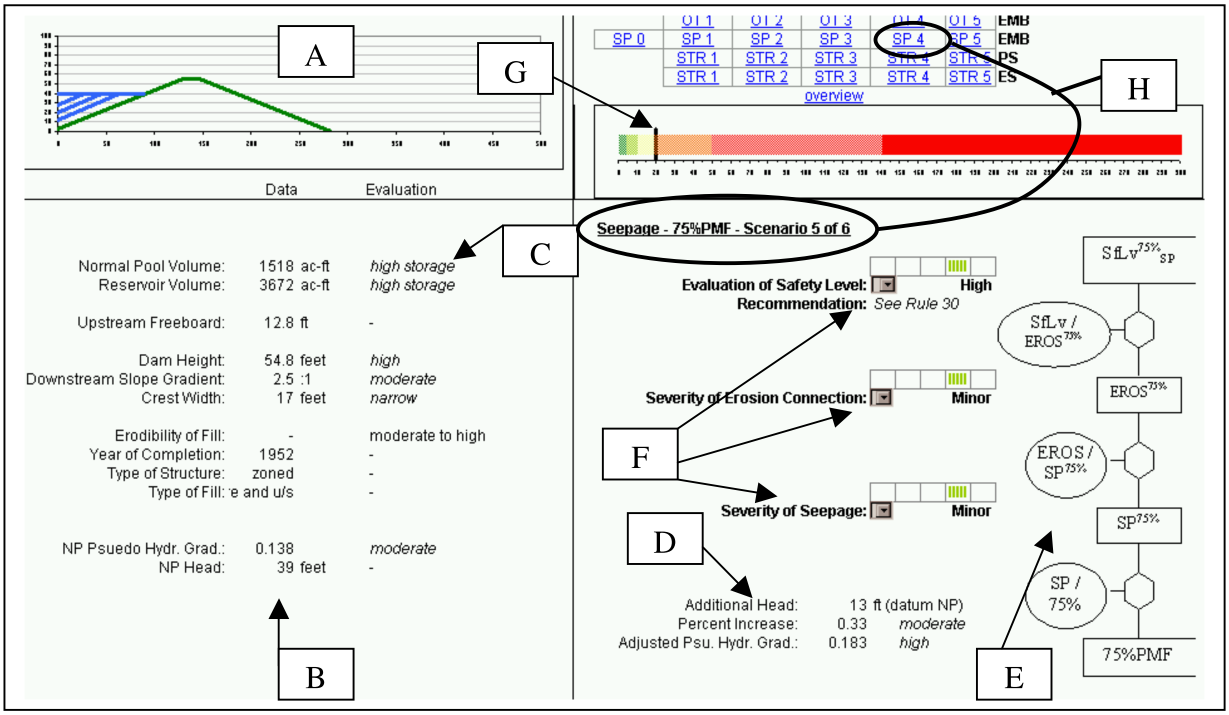
Fault tree for seepage mode of failure during normal pool loading

Fault tree for structural collapse of spillway mode of failure during 50% PMF loading

Fault tree for overtopping mode of failure during 50% PMF loading

Interpretation of Left Fault Tree:
a. Dam under loading – normal pool
b. What is seepage level given loading?
c. Intermediate evaluation: level of seepage
d. How much erosion takes place given level of seepage?
e. Intermediate evaluation: level of erosion
f. What is safety level of the dam given level of erosion?
g. Final evaluation: safety level of the dam

Figure 3 - User Interface for One Scenario (Seepage Mode of Failure during 75% PMF)



| | Data | Evaluation |
|---|---|---|
| Normal Pool Volume: | 1518 ac-ft | *high storage* |
| Reservoir Volume: | 3672 ac-ft | *high storage* |
| Upstream Freeboard: | 12.8 ft | - |
| Dam Height: | 54.8 feet | *high* |
| Downstream Slope Gradient: | 2.5 :1 | *moderate* |
| Crest Width: | 17 feet | *narrow* |
| Erodibility of Fill: | - | moderate to high |
| Year of Completion: | 1952 | - |
| Type of Structure: | zoned | - |
| Type of Fill: | 'e and u/s | - |
| NP Psuedo Hydr. Grad.: | 0.138 | *moderate* |
| NP Head: | 39 feet | - |

**Seepage - 75%PMF - Scenario 5 of 6**

**Evaluation of Safety Level:** **High**
**Recommendation:** *See Rule 30*

**Severity of Erosion Connection:** **Minor**

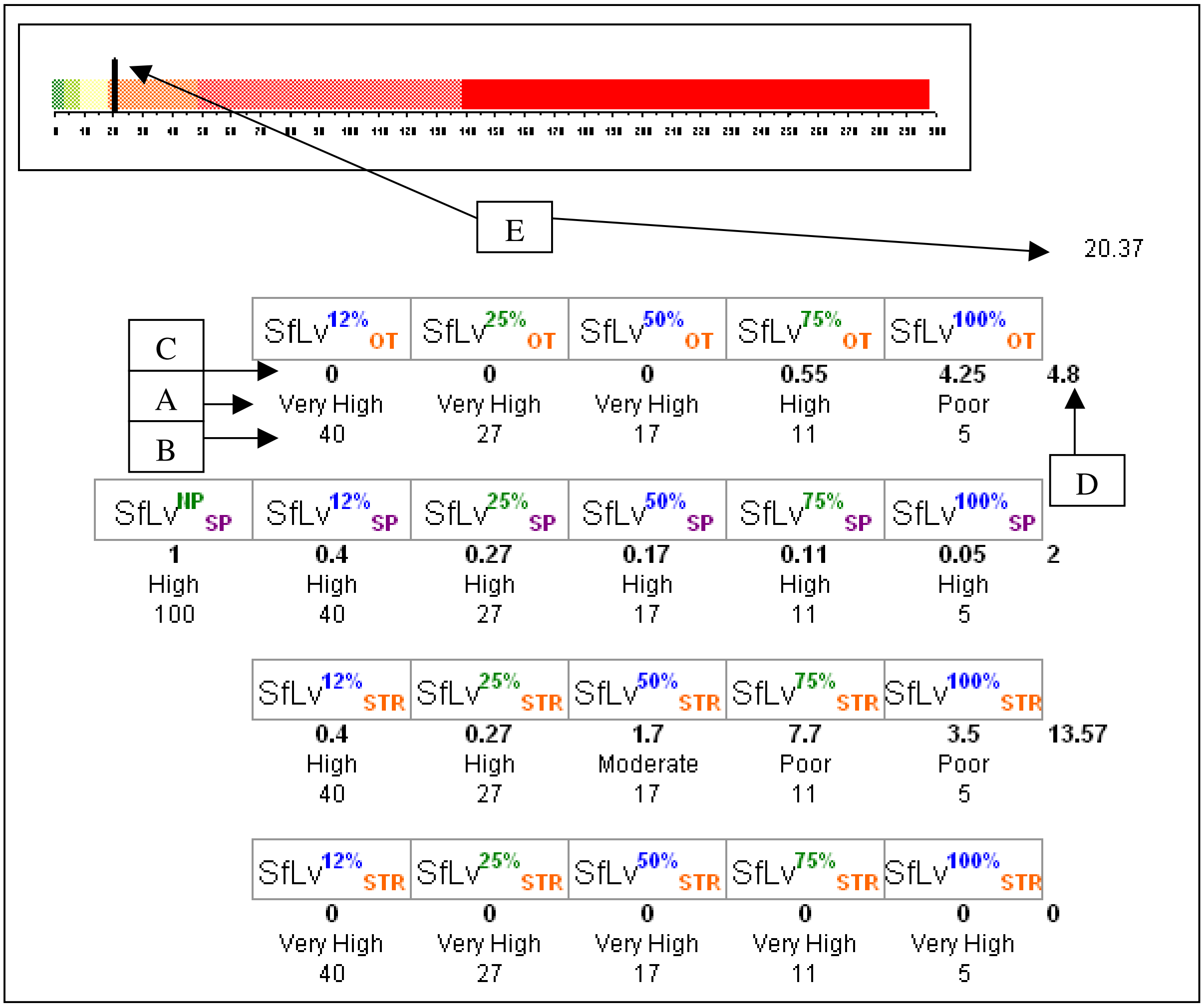
**Severity of Seepage:** **Minor**

| | | |
|---|---|---|
| Additional Head: | 13 | ft (datum NP) |
| Percent Increase: | 0.33 | *moderate* |
| Adjusted Psu. Hydr. Grad.: | 0.183 | *high* |

A – Maximum section of dam with normal pool
B – Information from database and calculations
C – Information from rules
D – Information from database, calculations, and rules
E – Fault tree
F – User entry of evaluations (works from the bottom to the top; bottom two are intermediate evaluation and the top is the final evaluation; top evaluation goes into the matrix – "A" on Figure 4)
G – Overall safety level of dam (left side is higher level of safety and right side is lower level of safety)
H – Top matrix provides navigation to all 21 scenarios using hyperlinks

| Table 1 | | |
|---|---|---|
| <u>Safety Level</u> | <u>Description of Safety Levels (for Overtopping)</u> | <u>Percentage</u> |
| Very High | Does not overtop | 0% |
| High | Overtops, uncontrolled release is unlikely, nominal damage to dam | 10% |
| Moderate | Overtops with significant damage, uncontrolled release not likely but not out of the question | 50% |
| Poor | Overtops, uncontrolled release is likely | 85% |
| Very Poor | Overtops and failure is almost certain | 100% |

Figure 4 – Scoring of Safety Level Matrix



| $SfLv^{12\%}_{OT}$ | $SfLv^{25\%}_{OT}$ | $SfLv^{50\%}_{OT}$ | $SfLv^{75\%}_{OT}$ | $SfLv^{100\%}_{OT}$ | |
|---|---|---|---|---|---|
| **0** | **0** | **0** | **0.55** | **4.25** | **4.8** |
| Very High | Very High | Very High | High | Poor | |
| 40 | 27 | 17 | 11 | 5 | |

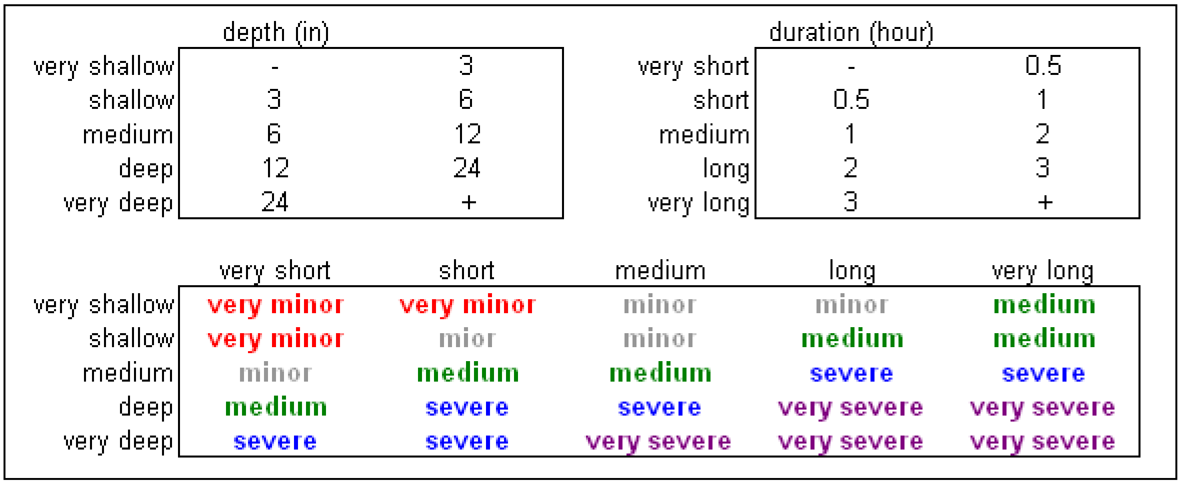
| $SfLv^{HP}_{SP}$ | $SfLv^{12\%}_{SP}$ | $SfLv^{25\%}_{SP}$ | $SfLv^{50\%}_{SP}$ | $SfLv^{75\%}_{SP}$ | $SfLv^{100\%}_{SP}$ | |
|---|---|---|---|---|---|---|
| **1** | **0.4** | **0.27** | **0.17** | **0.11** | **0.05** | **2** |
| High | High | High | High | High | High | |
| 100 | 40 | 27 | 17 | 11 | 5 | |

| $SfLv^{12\%}_{STR}$ | $SfLv^{25\%}_{STR}$ | $SfLv^{50\%}_{STR}$ | $SfLv^{75\%}_{STR}$ | $SfLv^{100\%}_{STR}$ | |
|---|---|---|---|---|---|
| **0.4** | **0.27** | **1.7** | **7.7** | **3.5** | **13.57** |
| High | High | Moderate | Poor | Poor | |
| 40 | 27 | 17 | 11 | 5 | |

| $SfLv^{12\%}_{STR}$ | $SfLv^{25\%}_{STR}$ | $SfLv^{50\%}_{STR}$ | $SfLv^{75\%}_{STR}$ | $SfLv^{100\%}_{STR}$ | |
|---|---|---|---|---|---|
| **0** | **0** | **0** | **0** | **0** | **0** |
| Very High | Very High | Very High | Very High | Very High | |
| 40 | 27 | 17 | 11 | 5 | |

A – Safety level for each scenario as determined by user (see “F” on Figure 2)
B - Weights for each scenario (fixed in the system)
C – Score - percentage of the weight because of the safety level (calculated by system)
D – Score for overtopping mode of failure
E – Score for overall safety level, color-coded graph interprets overall safety level: dark green – very high, light green – high, yellow – moderate, orange – poor, light red – very poor, and dark red - emergency

Figure 5 - Rules



| | depth (in) | |
|---|---|---|
| very shallow | - | 3 |
| shallow | 3 | 6 |
| medium | 6 | 12 |
| deep | 12 | 24 |
| very deep | 24 | + |

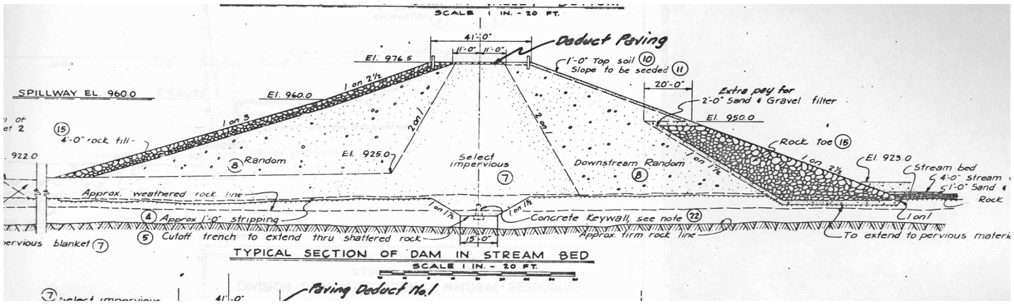
| | duration (hour) | |
|---|---|---|
| very short | - | 0.5 |
| short | 0.5 | 1 |
| medium | 1 | 2 |
| long | 2 | 3 |
| very long | 3 | + |

| | very short | short | medium | long | very long |
|---|---|---|---|---|---|
| very shallow | very minor | very minor | minor | minor | medium |
| shallow | very minor | mior | minor | medium | medium |
| medium | minor | medium | medium | severe | severe |
| deep | medium | severe | severe | very severe | very severe |
| very deep | severe | severe | very severe | very severe | very severe |

Example of a rule for overtopping. The rule takes numeric data about depth and duration of overtopping and provides a description of overtopping. Verbal interpretation of the rules is listed below:
If the depth of overtopping is between 3 and 6 inches, the depth is shallow.
If the duration of overtopping is between 1 and 2 hours, the duration is medium.
If the depth of overtopping is shallow and the duration is medium, the overtopping is minor.

| TABLE 2 | **Cowan Lake Dam** | **Rupert Lake Dam** | **Forked Run Lake Dam** |
|---|---|---|---|
| **Year Constructed** | 1947 | 1968 | 1952 |
| **Type of Structure** | Earthfill, Zoned | Earthfill, Homogeneous | Earthfill, Zoned |
| **Length (ft)** | 860 | 1510 | 660 |
| **Height (ft)** | 63 | 40 | 55 |
| **Crest (ft)** | 41 | 15 | 17 |
| **Upstream Slope** | 3H:1V | 3H:1V | 2.5H:1V |
| **Downstream Slope** | 2.5H:1V | 3H:1V | 2.5H:1V |
| **Spillway** | 200-ft Concrete Chute | 350-ft Concrete Weir and Rock Chute | 100-ft Concrete Chute |
| **Freeboard (ft)** | 16.5 | 12 | 13 |
| **Drainage Area (mi$^2$)** | 49 | 22 | 9 |
| **Flood Capacity - Percentage of PMF** | 82% | 95% | 70% |
| **Normal Storage (ac-ft)** | 10300 | 2200 | 1500 |
| **Max.Storage (ac-ft)** | 25000 | 7500 | 3700 |

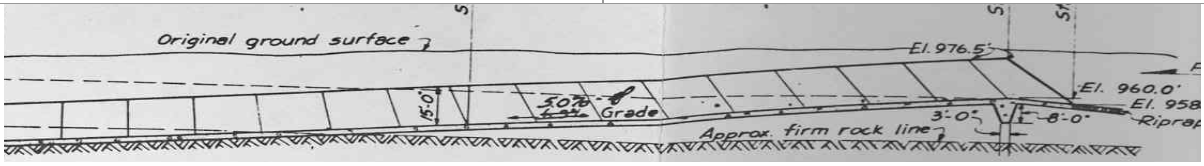
# Figure 6 – Additional Information for Cowan Lake Dam



Cross section through embankment

View of upstream slope from right abutment

Downstream slope viewed from left abutment



Profile of spillway, 200 feet between control section and where chute floor meets firm rock

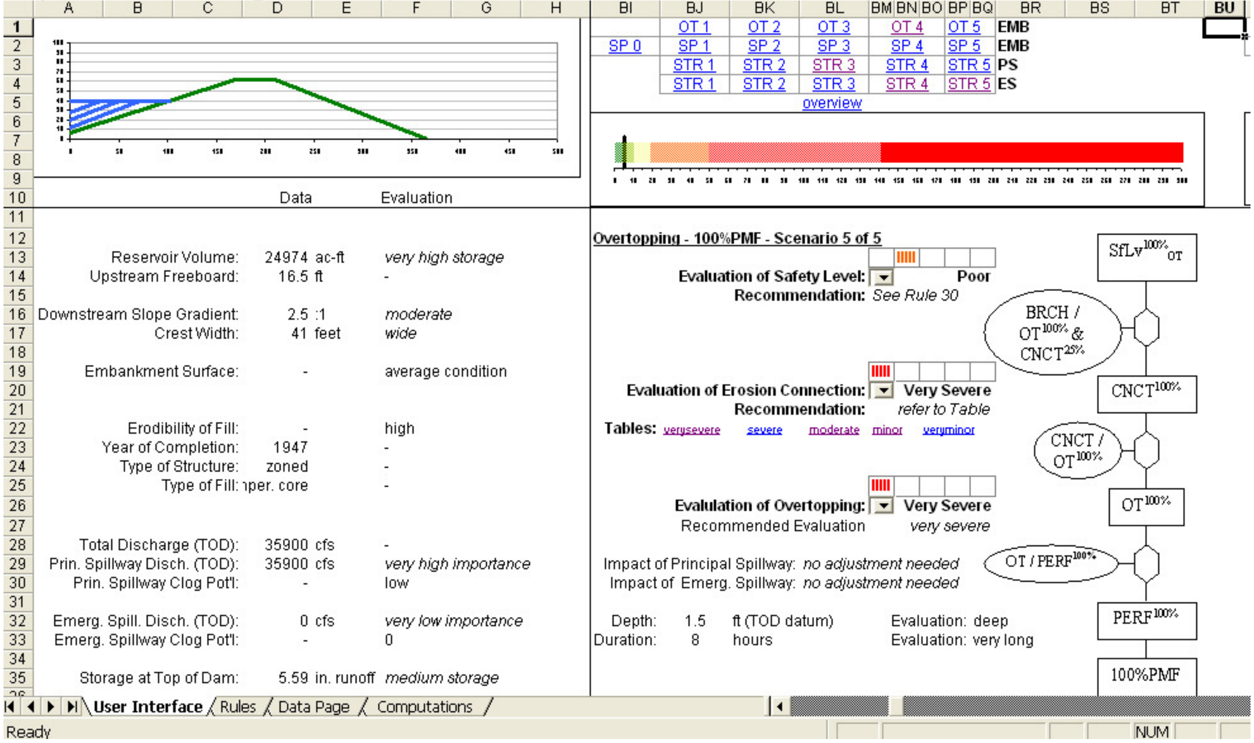
Spillway inlet

Spalled area, 40 feet long and 6 inches deep, 200 feet downstream of control section

Void under top of slab, 400 feet downstream of control section

End of chute, 800 feet downstream of control section

Figure 7 – Example Safety Level Evaluation of Cowan Lake Dam



| | Data | Evaluation |
|---|---|---|
| Reservoir Volume: | 24974 ac-ft | *very high storage* |
| Upstream Freeboard: | 16.5 ft | - |
| Downstream Slope Gradient: | 2.5 :1 | *moderate* |
| Crest Width: | 41 feet | *wide* |
| Embankment Surface: | - | average condition |
| Erodibility of Fill: | - | high |
| Year of Completion: | 1947 | - |
| Type of Structure: | zoned | - |
| Type of Fill: | ıper. core | - |
| Total Discharge (TOD): | 35900 cfs | - |
| Prin. Spillway Disch. (TOD): | 35900 cfs | *very high importance* |
| Prin. Spillway Clog Pot'l: | - | low |
| Emerg. Spill. Disch. (TOD): | 0 cfs | *very low importance* |
| Emerg. Spillway Clog Pot'l: | - | 0 |
| Storage at Top of Dam: | 5.59 in. runoff | *medium storage* |

Overtopping - 100%PMF - Scenario 5 of 5

**Evaluation of Safety Level:** **Poor**
**Recommendation:** *See Rule 30*

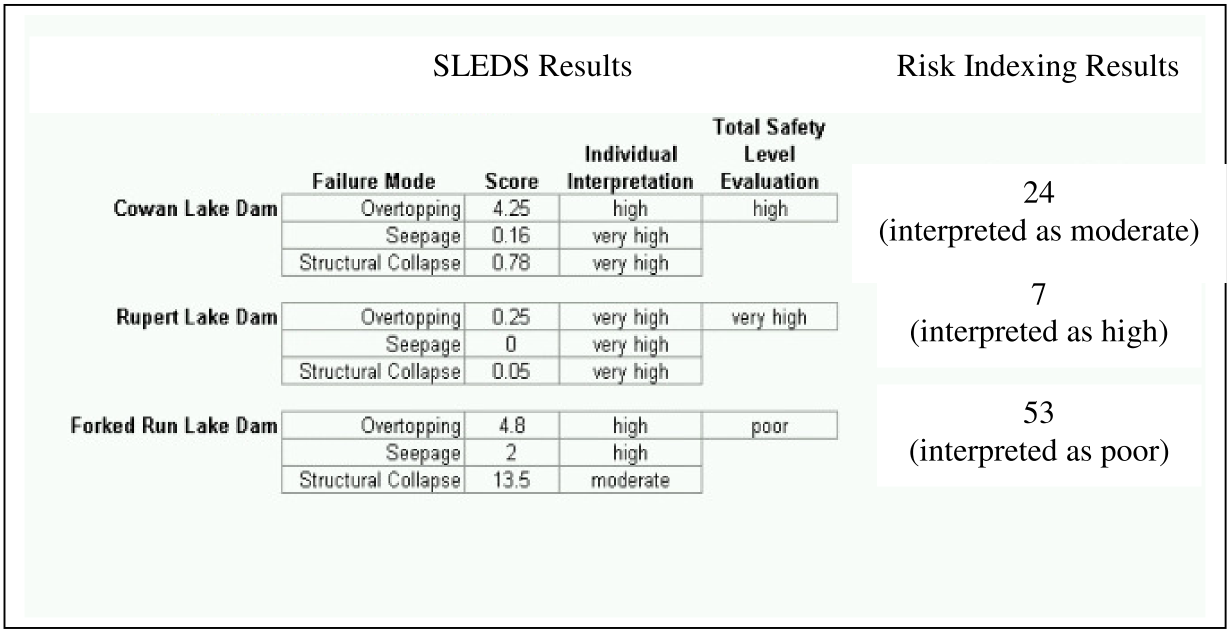
**Evaluation of Erosion Connection:** **Very Severe**
**Recommendation:** *refer to Table*
**Tables:** verysevere severe moderate minor veryminor

**Evalulation of Overtopping:** **Very Severe**
Recommended Evaluation *very severe*

Impact of Principal Spillway: *no adjustment needed*
Impact of Emerg. Spillway: *no adjustment needed*

Depth: 1.5 ft (TOD datum) Evaluation: deep
Duration: 8 hours Evaluation: very long

Figure 8 – Results



| | SLEDS Results | | | | Risk Indexing Results |
|---|---|---|---|---|---|
| | Failure Mode | Score | Individual Interpretation | Total Safety Level Evaluation | |
| **Cowan Lake Dam** | Overtopping | 4.25 | high | high | 24<br>(interpreted as moderate) |
| | Seepage | 0.16 | very high | | |
| | Structural Collapse | 0.78 | very high | | |
| **Rupert Lake Dam** | Overtopping | 0.25 | very high | very high | 7<br>(interpreted as high) |
| | Seepage | 0 | very high | | |
| | Structural Collapse | 0.05 | very high | | |
| **Forked Run Lake Dam** | Overtopping | 4.8 | high | poor | 53<br>(interpreted as poor) |
| | Seepage | 2 | high | | |
| | Structural Collapse | 13.5 | moderate | | |