EXPERIENCE USING RISK-INFORMED DESIGN STANDARDS

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ABSTRACT

The Corps of Engineers is currently revising many of its critical regulations and manuals related to dams and levees. Each of these manuals is explicitly incorporating risk analysis as a requirement and the concept of tolerability in the decision process. However, during the next five years as these manuals are being revised, the Corps of Engineers is using risk concepts along with traditional standards to make design decisions. The Corps of Engineers has begun to implement this approach in major modifications of dams and over $17 Billion U.S. dollars in levee modifications and new construction. This paper will describe lessons learned from this approach along with two case histories where risk has been used to inform design decisions with consideration to the associated design standards. The paper will additionally discuss some of the challenges associated with decisions and liability that have been encountered.

1. BACKGROUND AND INTRODUCTION

Prior to 1900, dam design and construction lacked a strong scientific basis. Engineering organizations, private consultants, and government agencies have been using regulations, manuals, and guidance published by a variety of sources for nearly 75 years. The currently published guidance originates by incorporating many of the lessons learned by the profession from their experience observing the performance of dams and levees worldwide. The approach taken by our predecessors, to pass that knowledge to future generations, has led to an improvement in the design and construction processes over time. In the Corps of Engineers, some fundamentals of guidance documents have not changed significantly since the 1940's. The small number of fundamental changes is a tribute to the robustness of the approaches taken during the development of those documents.

However, there are opportunities to learn and improve. Few of the dam failures in the last 25 years have happened as a result of mechanisms that are described in the design standards – with the exception being internal erosion. The profession in the United States has experienced a number of failures including the levee system in New Orleans, the failure of Teton Dam, the failure of Taum Sauk Dam, and the failure of Swift No. 2 Dam. There have also been a number of notable incidents including the spillway at Oroville Dam and the Lower San Fernando embankment. Many of the failures would have met existing design standards.

A small number of entities have attempted to either replace deterministic design standards or augment deterministic standards with additional requirements. The bulk of these methods are reliability-based. Most notable amongst these are the Eurocodes (Eurocodes 1990) and the Dutch (Vrijling 1998, 2001). Although the Eurocodes are not specific to dams, they highlight a process to approach designs that attempt to incorporate uncertainty in to the limit-state equations and provide different target reliability values depending on the magnitude of the consequences. This is philosophically similar to the concepts of risk which include explicit consideration of hazards, likelihood of unsatisfactory performance, and consequences.

1.1. USACE Design Standards

The Corps of Engineers uses a variety of standards to evaluate the safety of existing dams and levees and to design new dams and levees. Although a large number of standards exist and many of them are used to evaluate or design dams or levees, but the most critical manuals for dams and levees include:

- EM 1110-2-1901 Seepage Analysis and Control for Dams
- EM 1110-2-1902 Slope Stability

- EM 1110-2-1913 Design and Construction of Levees
- EM 1110-2-1914 Design, Construction, and Maintenance of Relief Wells
- EM 1110-2-2200 Gravity Dam Design
- EM 1110-2-2300 General Design and Construction Considerations For Earth and Rock-Fill Dams
- EM 1110-2-2502 Retaining and Flood Walls
- EM 1110-2-2902 Conduits, Culverts, and Pipes

1.2. Transition to Risk-informed Decision-Making

The Corps of Engineers has been working to transition to risk-informed decision-making since releasing an update to ER 1110-2-1156 in 2010 (USACE, 2010). Since 2010, the Corps of Engineers has been planning to transition to an Enterprise Risk Management System to incorporate risk into all its decisions. These efforts changed the USACE decision framework to explicitly incorporate risk, which necessitated a subsequent change to USACE guidance documents including design standards. The dam and levee safety programs in USACE developed guiding principles for this transition in 2015 (Snorteland, 2015). These have changed and adapted as USACE has used risk in conjunction with its standards from 2010 to 2019.

Revisions are routinely made to USACE standards to keep up with advancements in the state of the practice which includes our understanding of system behavior and technological advancements for monitoring and analyzing system performance. The Corps of Engineers continues to have several objectives of transitioning to risk-informed design guidance as it revises more than 50 guidance documents to address these items. In addition, there are five items that have been identified as fundamental improvements to the philosophies that underpin all guidance. Some of these are a direct result of the Corps moving towards a risk-informed decision process; some are as a result of lessons learned from managing a large dam and levee portfolio; while others are intended to increase consistency in approaches across governmental agencies.

The Corps is challenged to keep a connection with the current guidance. In many respects, these manuals have guided the construction of a robust nation-wide system that has performed well so far – with some notable exceptions. The Corps does not want to abandon the positive aspects of the existing guidance. However, improvements are needed to address lessons learned from those instances where structures did not perform as intended even when designed in accordance with that guidance.

The Corps is adopting some fundamental tenets for inclusion into all relevant dam and levee documents. Each document will include a requirement in each document to:

- **Analyze Potential Failure Modes**

  One of the most significant advancements in the dam and levee industries over the last 20 years has been the use of Potential Failure Mode Analysis (PFMA), which is similar to Failure Modes and Effects Analysis (FMEA). This approach has led to more careful consideration of the weaknesses of engineered structures and their interaction with the natural environment. The objective of this effort is to ensure potentially unique characteristics of the structure are still evaluated given that the guidance cannot explicitly address all possible scenarios.

- **Evaluate Robustness, Redundancy, and Resilience**

  Commonly referred to as the "3 R's", each manual will discuss robustness, redundancy, and resilience at least at the fundamental level. They may be either requirements or considerations. The objective is to ensure designs consider how a structure might fail and design structures that perform well over a large range of loading and conditions, prevent fragile or brittle failures, and increase the reliability of structures by providing primary and backup features to prevent failure modes from developing.

- **Incorporate Risk and Reliability for Potential Failure Modes**

  One of the weaknesses in the existing procedures is that the variability of input parameters is not addressed with the guidance. Designers used what was assumed to be conservative assumptions, but that conservatism was not as conservative as assumed because the natural variability is so high. Conversely, simply following guidance and choosing a combination of conservative assumptions has led to designs that are less efficient than optimal. Several risk and reliability methods are available to compensate for this issue, and each manual will address this in a slightly different way, but incorporating these concepts into the design process will improve our ability to develop sound designs.

- **Explicitly Address Monitoring and Intervention**

  Designers strive to achieve economical designs that perform as intended when loaded. Current guidance typically addresses many of the uncertainties and unknowns by increasing the robustness of the design. Despite this approach, structures still occasionally exhibit signs of distress when loaded such as settlement, movement, or seepage. Each year, the Corps "flood fights" a variety of structures in its inventory based on observed performance. Not all of this intervention is done because failure is imminent – it is part of sound practice and may even be part of the operational expectations from design, such as for truncated seepage berms. Some of these behaviors may be benign while others may indicate a developing failure mode. In either case, intervention is part of sound practice even though it has not often been explicitly considered in the design phase of a project. Where applicable, each guidance document will discuss monitoring and inspection requirements, expected performance, potential distress signals, and intervention strategies. In some cases more robust designs will be justified and in other cases an intervention strategy will be adopted. This new paradigm will allow the designer to explicitly consider intervention as a strategy for managing risk when it is economical and effective to do so.

- **Examining the Intersection Between Different Guidance or Between Separate Structures**

  One weakness that has been observed in the existing guidance involves the interface between disciplines because most Corps manuals are currently organized by discipline (e.g. geotechnical, structural, hydraulic). The Corps recognizes that different project features may be designed by different disciplines with different objectives. The intent is to explicitly identify those areas that require a multi discipline perspective and highlight where additional consideration is warranted.

1.3. Current Guidance

In 2019, USACE published ECB 2019-15, the Interim Approach for Risk-Informed Designs for Dam and Levee Projects (USACE, 2019) to provide interim guidance while each of the agency's design manuals were being updated.

The interim guidance was necessary due to a large investment by the U.S. Federal Government in flood protection following Hurricanes Harvey, Irma, and Maria in 2017. These hurricanes caused significant damage to the flood protection infrastructure in the Gulf Coast and Caribbean in addition to damages caused by flooding in unprotected areas. These projects had been planned over 30 years using a variety of standards. USACE wanted to be sure that the infrastructure constructed to address issues caused by that flooding was completed in the smartest way possible.

The guidance provides the following guiding principles:

- Hold life safety paramount. Although USACE considers risks to property and the environment, life safety will be the priority.
- Make risk-informed decisions. Decisions will be made commiserate with the level of risk.
- Ensure open and transparent engagement. All the entities that would be affected by the risk-informed decision will be consulted.
- Learn and adapt. Design standards will be used in conjunction with risk.
- Do no harm. Designs should not increase risk to downstream areas or leveed areas above what is currently experienced.

The risk-informed process follows the general steps shown in Figure 1 below.

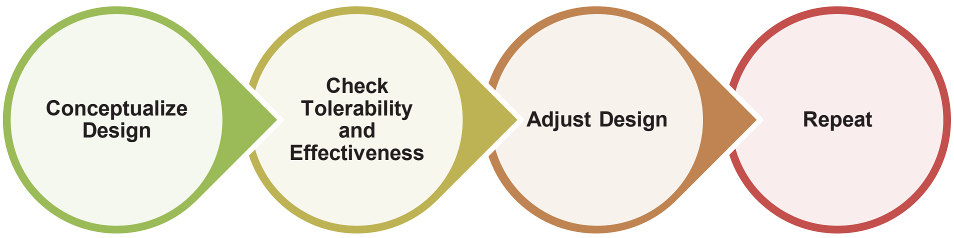

Figure 1 : Risk-informed design process.

2. RECENT EXAMPLES

2.1. Moose Creek Dam

Moose Creek Dam is located along the Tanana River near Fairbanks, Alaska. It was constructed between 1973 and 1979. It was constructed to protect the city of Fairbanks from flooding, most notably the large flood seen in 1967 (Figure 2). The dam is a zoned earthfill structure constructed on a large and very pervious glacial outwash deposit approximately 250m deep. The dam is 15m high and 13km long and stores 280 million cubic meters of water at maximum capacity. The dam has several unique features, the most notable of those being permafrost in the foundation that has been affected by the construction of the dam. The foundation is very pervious. The dam is cited as an example in Harry Cedergren's seepage textbook (Cedergren, 1967) in the section describing pumping tests due to the pervious nature of the materials being tested.

Figure 2 : 1967 flood in Fairbanks, Alaska.

In the 1970's, 1980's, 1990's, and 2010's, the structure had a large number of sand boils when it was loaded with moderate floods (Figure 3). A series of seepage channels, sandbag rings, seepage berms, and relief wells were constructed to address these seepage issues. However, due to the deep and pervious foundation, the seepage continued to cause significant problems. Due to the nature of this layer, a cutoff wall concept was determined to be the most efficient way to keep erosion from happening in potential uniform sand/silt layers that could be just under the embankment. However, the cutoff wall cannot be economically be constructed to an impervious foundation layer.

Figure 3 : Sand boils observed downstream of Moose Creek during 2018 floods.

The current USACE seepage guidance (USACE 1986) lists a variety of factors of safety for the exit gradient for seepage depending on the application. In this case, the factor of safety against heave was calculated to be less than 1.0 for walls less than 4m below the embankment. Using this guidance, the design team developed a cutoff wall that extended 6.5m into the foundation below the embankment. However, because the depth of the wall directly related to the cost of the project, the team was asked to optimize the design to minimize the cost of the modification.

Following discussions with the design team, USACE determined that the only mechanism that was of concern was backward erosion piping or contact erosion of a uniform sand/silt layer just beneath the embankment as shown in Figure 4. Any lower, the glacial outwash was too coarse to allow erosion for the relatively low gradients at the site. The critical design objective changed from meeting heave factor of safety requirements to instead intercept erodible foundation materials just below the embankment.

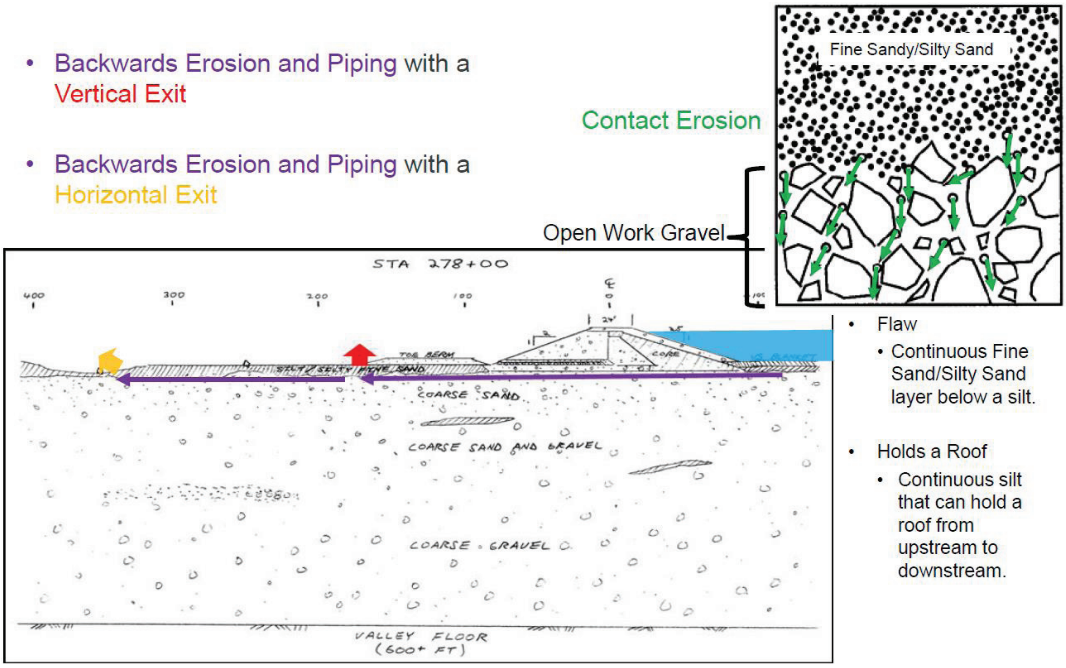

Figure 4 : Failure mechanism for Moose Creek Dam's embankment.

The team divided the project into 5 reaches that required modification, each of which had different risks due to the specific geology beneath each reach. In 4 of those reaches, the wall was shortened to 3.5m. In the other, the wall was shortened to 5m. The total cost savings to do this was approximately $80USD million. This was done while keeping risks within tolerable levels using USACE standards.

The factor of safety requirement against heave from EM 1110-2-1901 will not be met for the dam after construction. USACE used a risk-informed process to determine that although there may be some sand boils and some performance issues during large floods, the modifications would prevent catastrophic failure of the embankment by preventing erosion from progressing beneath it.

Figure 5 : The Dallas Floodway levee system through Dallas, TX during floods in 1990.

2.2 Dallas Floodway

The Dallas Floodway protects the northern and southern halves of the downtown areas of the city of Dallas, Texas. It is part of a large system of dams and levees in the Trinity River Basin designed to reduce flows in the Trinity River through Dallas. They are approximately 17km long on each side of the river and range from 2m to 11m tall. They are nearly all homogeneous embankments constructed from highly plastic clays with high liquid limits. The levees have been constructed over 40 years using a variety of methods. The levees have had several performance issues over that time period – mostly surficial slides on the land side of the system during periods of high rainfall and some surficial slides on the river side of the system when river levels fell rapidly.

In 2011, USACE and the City of Dallas were evaluating the safety of the levee systems that protected the city of Dallas and considering how flood protection could be improved in those areas. Complicating the analysis were two factors. First, the levees and their foundations were composed of high liquid limit clays which had strengths measured near the fully-softened strength (FSS) range similar to strengths originally researched by Skempton in the 1950s (Skempton, 1952). Second, the levees had high exit gradients calculated using USACE's levee design manual (USACE, 2000). Alternatives to address these issues for the entire system had cost estimates between $1 Billion USD and $2 Billion USD.

Although the slides were concerning, the combination of FSS and floods might have been doubly so given the low factors of safety that result from saturated FSS clay material. However, the hydrology is an important consideration when determining the loading conditions. EM 1110-2-1913, the USACE levee design manual, was developed primarily for flooding along the Mississippi River, where floods can last weeks and even months. This is not true for the Trinity River basin. Even extreme floods last no more than two weeks. Additionally, since the Dallas Floodway was originally constructed, a series of 12 flood control reservoirs were constructed upstream (Figure 6). This construction has significantly changed the hydrology of the basin – particularly when considering extreme events. The effect of this construction was to attenuate high flows in the Dallas Floodway. The assumption in the levee design manual does not hold true for this area. The hydrology study indicated that the levee would be loaded between 50% and 100% of the levee height for no more than 2 weeks. Given the highly plastic nature of the clay levees, this meant that full saturation was extremely unlikely.

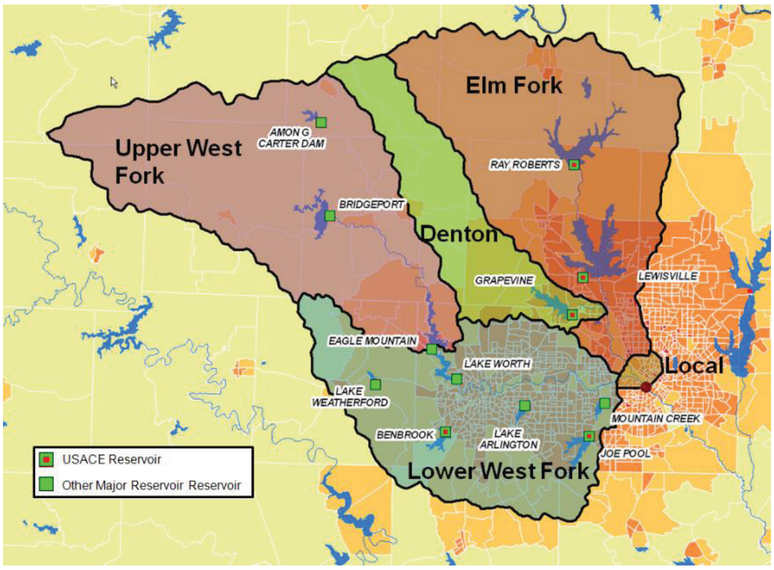

Figure 6 : Flood control reservoirs above the Dallas Floodway.

The design team instead evaluated the seepage conditions that would likely exist and the resulting factors of safety for extreme events. A typical seepage and stability section is shown in Figure 7. Transient seepage analysis is not typically done and the methods to do this are not as well established as they are for steady-state seepage analysis. The team did almost a thousand seepage and stability analyses to evaluate the effects of different modeling assumptions to try and understand the uncertainty of the situation. These analyses were used to evaluate the risk posed by the system to the city of Dallas.

Ultimately, USACE determined that the factor of safety requirement for steady-state stability from EM 1110-2-1913 will not be met for the levee. The team did a risk analysis with USACE and the City of Dallas in 2011 and 2012 and determined that the risks are within tolerable levels using USACE standards. USACE used a risk-informed process to determine that although there may be shallow slides during rain events, these slides could be repaired and would not likely affect the safety of the levees.

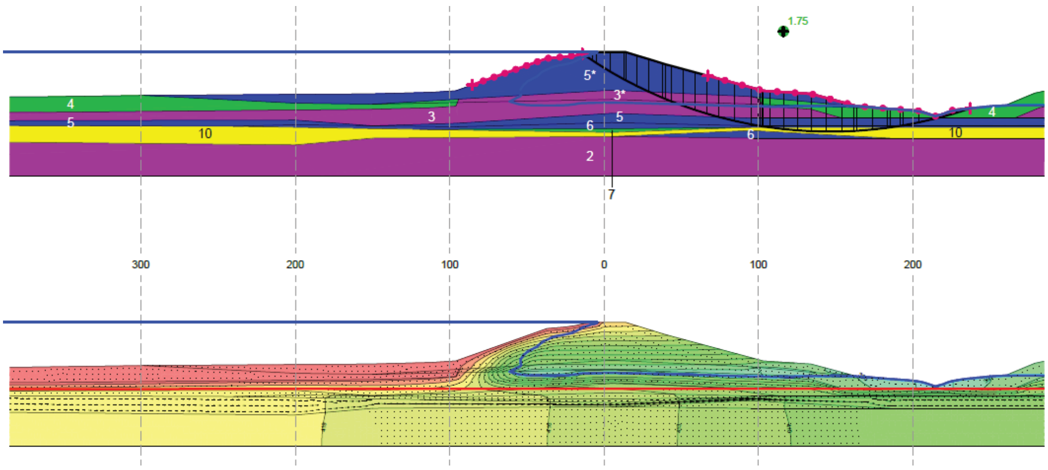

Figure 7 : Typical seepage and stability cross section for the Dallas Floodway.

3. OBSERVATIONS AND CHALLENGES

USACE is only at the beginning of using risk to inform design standards and design approaches. However, several observations can be made given our experience so far.

Communication between design engineers and risk analysts is critical. Experienced designers have a wealth of experience and have a grasp of practicality that is extremely valuable. Risk analysts have a broad understanding of how complex situations and systems behave. Both are needed to integrate risk into design. Relying too much on statistics sometimes ignores the practical aspects of the situation. Relying too much on classical design ignores the advances that have been made in the industry.

Documenting the rationale used to make risk-informed decisions is crucial. USACE now requires its decision documents to have a section describing the design standards that will not be met and the reason behind those decisions.

Using a risk-informed process has helped guide an analysis and conversation towards a reasonable decision in situations where large investments appeared unreasonable. In the case of Moose Creek Dam, given the size of the structure, the small hydraulic gradient, and the failure mechanism it seemed unreasonable to invest significant amounts to reduce an irreducible hydraulic gradient. In the case of the Dallas Floodway, it was clear that the one-size-fits-all design standard did not take into account the nature of the Trinity River basin and the nature of the system.

There has been an unexpected side effect of transitioning to a risk-informed process. Previously, hydrologic and hydraulic loading analyses was divorced from the geotechnical and structural analysis. Integrating risk into the process has caused more communication, interaction, and iteration between the engineers and scientists from all disciplines.

There have been several challenges implementing risk-informed processes. Most importantly, design engineers are grounded firmly in deterministic standards. It is a challenge to change from a standards-based approach to a risk-informed approach. It requires creativity and runs contrary to the conservative nature of some designers. Additionally, each designer has their own risk aversion. Trying to implement a corporate risk aversion has been difficult to do as it requires each designer to compromise their own level of comfort. For large projects with a large number of designers, this becomes increasingly challenging.

The examples shown in this paper highlight cost efficiencies that have been achieved using risk-informed designs. This is not always the case, and there are several examples where risk-informed design increased the scope and cost of designs. This is primarily due to the need for more robustness in structures with high consequences or a large amount of uncertainty driving more robust solutions. USACE hopes to be able to share all these examples in the future.

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