Western Dam Engineering

Technical Note

Spillways: Spilling the Right Way

Introduction

Unlined earthen spillways are common features of small earthen dams. They can be principle, emergency or auxiliary spillways made to pass rare flood flows around the embankment. While many spillways may never pass a significant flow or volume of water, one large event could result in significant erosional consequences.

Historically there was little engineering design of the spillways for small dams. The spillway was often situated in the dam borrow area or incorporated as part of an auxiliary dam. Today there has been much more research conducted on spillway performance and there are many tools available for spillway design and evaluation. Some of the most popular tools are discussed in this article. Spillways should be designed to experience flow from a known recurrence interval storm and earthen spillways can expect to suffer some erosion damage during events that cause them to flow. However, where erosion enlarges enough to destabilize the structure or cause an uncontrolled release, it could lead to a dam failure with downstream consequences.

Inadequate spillway capacity is one of the most common safety deficiencies in small dams and can occur due to original design deficiencies or changes in conditions. The necessary capacity may have changed due to a change in the watershed, downstream channel, design flood, hazard class, or spillway condition. Earthen spillways are common at small dam sites and present additional deficiencies regarding erosion and stability as compared to concrete lined spillways. Spillway erosion occurs when a precipitation event increases the reservoir elevation above the spillway crest, resulting in water flowing down the spillway channel. Due to the force of the flowing water, erosion of the vegetation on the surface of the spillway will begin to occur. After the water has removed the vegetation, erosion of the soil will enlarge and deepen the eroded area. As the flow area increases in size and depth, the flow becomes more turbulent, increasing the rate of erosion. With continued flow, headcutting begins as the eroded area continues to grow and progress upstream. Depending on the configuration of the dam, the headcutting could proceed to the spillway crest, eventually reaching the reservoir and creating an uncontrolled release as the embankment erodes away or concrete structures destabilize, allowing them to slide or overturn. A typical event tree of a spillway erosion or headcutting failure mode is described below

Spillway Erosion Failure Mode

- ➢ Reservoir level reaches spillway crest and begins to flow
  - ➢ Vegetation (if present) is removed or eroded
    - ➢ Concentrated flow erosion begins (downcutting forms headcut) and worsens
      - ➢ Headcut advancement begins (deepens and advances towards spillway crest/control section)
        - ➢ Intervention is attempted and unsuccessful (more likely to be successful if attempted early)
          - ➢ Headcut advances through crest of spillway or headcut undermines control structure/section and flow control is lost
            - ➢ Headcut advances into reservoir pool and breaching occurs

The erodibility of a spillway is a function of the geology, channel geometry, and the expected volume, velocity and duration of the flood flow. Fine granular materials such as silts and sands are more likely to erode as compared to cohesive clayey materials. Soils with cohesion have a plasticity or inherent 'stickiness' that holds the particles together. The performance of rock is more complex to predict due to weathering, fracturing, joints, process of formation, and strength. In general, vegetation improves the performance of spillways to a certain point, if it is uniform grass or ground cover. Discontinuities and obstacles such as trees, shrubs, groins, roads, paths, ditches, and changes in slope will concentrate flow and create areas prone to turbulent flow, leading to erosion.

Areas that experience hydraulic jumps are particularly susceptible to erosion due to pressures created by the energy change. This occurs most commonly at the end of the spillway where the flow meets the downstream river channel, stilling basin or areas of change in slope of the spillway. Narrow steep channels will increase the depth and speed of flow, increasing the likelihood of turbulent flow and erosion. Movement of larger particles requires higher velocities and or steeper slopes. There are several methods available to assess the risks of spillway erosion. This article will present five of the most common. Any spillway analysis for design or modification should be approached in more detail than discussed below. The references at the end of this article provide more information for each method.

1. USACE Repair, Evaluation, Maintenance and Rehabilitation (REMR)
2. Cohesionless Soil
3. Annandale
4. Water Resources Site Analysis Program (SITES)
5. Computation Fluid Dynamics (CFD)

USACE REMR

The method developed by the USACE REMR is a qualitative classification of erodibility based on spillway characteristics. The method predicts whether erosion is likely to occur but does not provide information regarding the extent or severity of erosion. The method involves assessing the erosion 'risk' as a function of spillway channel slope, flow velocity and the effect of anomalies in the spillway geometry. Based on these characteristics, the spillway is assigned an "A" rating as outlined below.

<u>Soil or rock classification:</u>
AAAA = Erosion-resistant rock
AAA = Moderately erosion-resistant rock
AA = Moderately erodible material
A = Erodible soil (nonvegetated)

Table 1: Erosion Risk Class

Spillway Characteristic	Erosion Risk Class			
	AAAA	**AAA**	**AA**	**A**
Slope (percent)	30-45	15-30	4-15	<4
Flow velocity (ft/s)	10-15	7-10	4-7	<4
Anomaly Effect	Minor	Moderate	Major	Severe

The erosion 'risk' is compared to the erosion 'potential,' which is based on geologic material behavior factors as shown in Table 2.

Table 2: Erosion Potential Class

Spillway Characteristic	Erosion Potential Class			
	AAAA	**AAA**	**AA**	**A**
Lithology				
Sandstone	■	■	■	■
Shale & Limestone	■	■	■	
Limestone	■			
Granular Soil (Low PI)				■
Cohesive Soil (High PI)			■	■
Intrusive Igneous	■			
Extrusive Igneous	■	■	■	
Massive Metamorphic	■	■		
Foliated Metamorphic	■	■	■	
Substance				
Density (pcf)	>140	140-125	125-116	<116
Uniaxial Strength (psi)	>6000	6000-2000	2000-150	<150
Genesis				

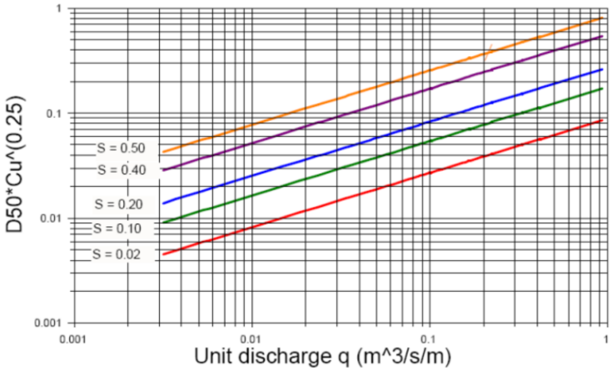
Table 2: Erosion Potential Class

Spillway Characteristic	Erosion Potential Class			
	AAAA	AAA	AA	A
Vertical Consistency (ft)	>6	6-2	2-0.25	<0.25
Lateral Consistency (#)	1	2	>2	>2
Tectonics: Unit Orientation Related to Flow Direction	Flat	Dip Toward	Dip Parallel	Dip Away
Rock Mass				
Fracture Spacing (ft)	>3	3-1	1-0.5	<0.5
Particle Diameter (ft)	3-5	1-3	1-0.5	<0.5
Fracture Size/Opening (in)	<1/8	1/8-1/2	>1/2	Open/clean
Fracture Sets (No.)	2	2-3	>3	shattered

For each factor, an A rating is assigned and the number of A's (between 1 and 4) is averaged for the erosion risk and the erosion potential. If the erosion risk average is higher than the erosion potential average, it is estimated that the spillway is likely to erode. If there are multiple distinctly identifiable geologic units within the spillway this process should be repeated for each unit to identify the most critical. Refer to USACE Technical Report REMR-GT-3 Supplement (1998) for a more detailed description of the method. It is important to note this analysis method is empirical and engineering judgment is required to make any decisions regarding the safety of a spillway.

Cohesionless Soil

If the spillway includes cohesionless materials with a D_{50} larger than 4 inches, the curves developed by Frizell et al. (1998) can be used to estimate the flow at which erosion could occur. The data is based on the slope (S) of the spillway, the D_{50} grain size, the coefficient of uniformity ($C_u = D_{60}/D_{10}$) and the unit discharge.



Unit Conversion 1 $m^3 = 35.3\ ft^3$

Figure 1 – Erosion Potential of Cohesionless Soil

Source: *Best Practices Dam and Levee Safety Risk Analysis*, Chapter 15

Plotting on the line represents a 20 percent chance of erosion beginning and below the line means an increase in probability. These curves do not represent the probability of breach, only of erosion, and the data are based on testing with uniformly sized angular riprap in ideal conditions.

Annandale

The analysis method developed by Annandale (1995 and 2006) quantifies two properties: the erodibility index (K_h) and stream power (P). The erodibility index K_h represents the susceptibility of a material to erode and is computed as follows:

$K_h = M_s K_b K_d J_s$

M_s = Material strength number, relates to unconfined compressive strength

K_b = Block or particle size, based on RQD/J_n where J_n is the joint set number

K_d = Inter-particle bond shear strength, taken as J_r/J_a (joint roughness/joint alteration)

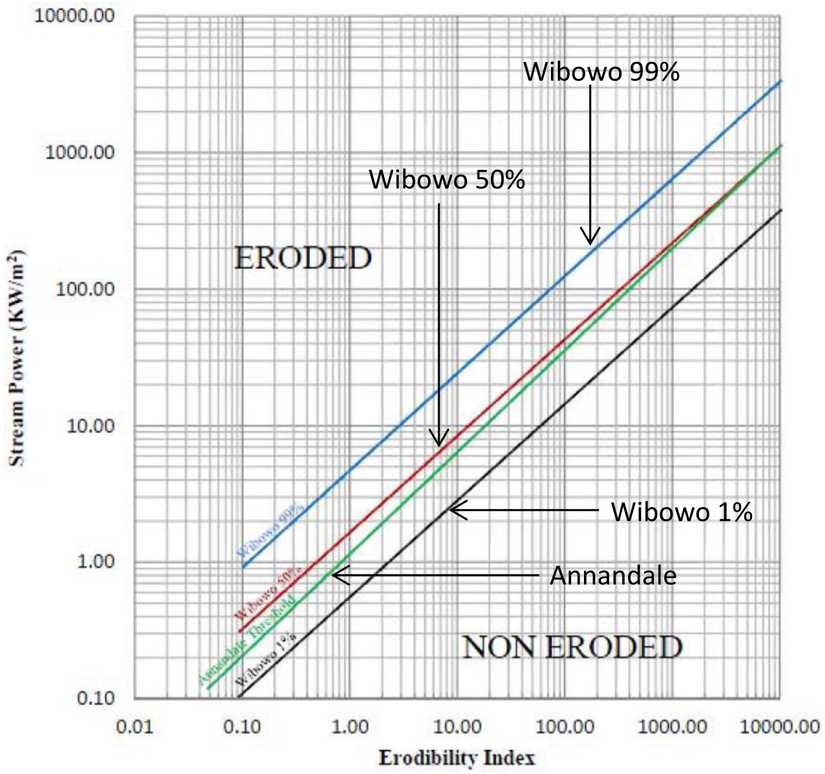
J_s = Relative shape and orientation of blocks, ease with which water can penetrate discontinuities and dislodge blocks (is equal to 1 for soils)

Values associated with the J variables can be obtained from tables developed by Annandale and are available in the USBR and USACE *Best Practices Dam and Levee Safety Risk Analysis* (Chapter 15, tables 15-1 through 15-4). The stream power P represents the rate of energy dissipation per unit of surface area and is computed as follows:

$P = \gamma U h S$

γ = Unit weight of water
U = Flow velocity
h = Flow depth
S = Slope

Annandale developed an erosion threshold curve based on approximately 150 field observations from spillways and plunge pools. The curve is shown on Figure 2, along with confidence curves developed by Wibowo et al. (2005). As with any simplified analysis method, engineering judgment is required in using the curves and multiple conditions and assumptions should be considered. The data are particularly sensitive to the K_b value. However, the curves are helpful in providing a range of likelihood for erosion and progression of headcutting.



Unit Conversion 1 kW/m^2 = 0.093 kW/ft^2

Figure 2 – Annandale Likelihood of Erosion

Source: *Best Practices Dam and Levee Safety Risk Analysis*, Chapter 15

SITES

The SITES spillway erosion analysis software was developed by the National Resource Conservation Service (NRCS), the Agricultural Research Service (ARS) and Kansas State University. It is a one-dimensional hydraulic simulation of flow through the spillway channel. It was developed based on lab testing and field data of headcutting in soil- and grass-lined spillways, but has also been applied to rock channels. The analysis estimates whether headcutting will occur and whether flow duration is long enough to deepen the headcut and advance upstream. The model assumes failure when the erosion reaches the spillway sill. The model represents a three-phase analysis as follows:

- Phase 1: Surface Erosion
    - Flow persists long enough to initiate erosion and the flow concentrates at a location and removes vegetation.
    - The model can account for surface discontinuities.
    - Erosion is estimated based on effective stresses and bond strength of underlying soil.
    - If no vegetation exists, Phase 1 is negligible.
- Phase 2: Concentrated Flow Erosion
    - Flow enlarges and deepens erosion

  - Assumes that flow continues to be somewhat uniform.
  - Erosion is estimated based on effective and critical stresses, and bond strength of underlying soils.
  - Critical stress is a function of clay and density properties for soils and particle size for rock.
- Phase 3: Headcut Advance and Deepening
  - Flow is turbulent.
  - Headcutting is considered in two parts: downward movement and headward movement
  - Rate of headcut migration is a function of the material strength (erodibility index K_h) and hydraulic power being dissipated.
  - Numerous layers of material require determination of a representative value using a depth-weighted log averaging scheme.

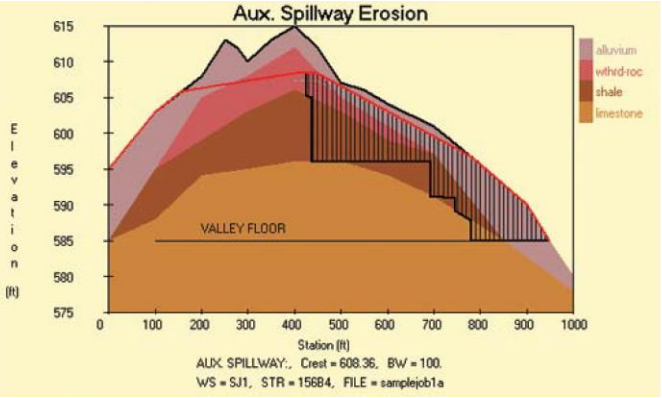


Figure 3 – SITES Output of Predicted Erosion

Source: *SITES 2005 Water Resources Site Analysis Computer Program User Guide*

The SITES software is available for public use. NRCS, ARS and Kansas State University have developed WinDAM B which can incorporate data from SITES into analysis of full breach development.

Hydraulic Models

There are a number of hydraulic models that could be used to help assess the spillway erosion potential, from the popular one-dimensional model HEC-RAS (USACE HEC), to the two-dimensional models such as MIKE-21 (Delft Hydraulics Institute) and RiverFlow2D (Hydronia), to the more complex three dimensional Computational Fluid Dynamics (CFD) models. CFD is becoming a popular and powerful tool for evaluating spillway erosion potential in recent years because of the increasing accuracy of CFD against prototype measurements, ease of use, and dramatic increase in computer processing speed. CFD programs, such as FLOW-3D, FLUENT, CFX, OpenFOAM, STAR-CD, and others, simulate hydrodynamic characteristics of flow, such as velocity, pressure, shear stress, etc., over the spillway and further downstream in three-dimensions and thus provide more detailed information that can be used to assist the evaluation of spillway erosion potential. Some CFD programs, such as FLOW-3D, also have sediment scour modules that could be used to evaluate sediment erosion.

Typical outputs from CFD model include flow velocity, dynamic pressure, bed shear stress, shear velocity, turbulence energy, etc. The stream power used in the Annandale Method could then be easily calculated based on the results from the CFD, using equations such as the following (Annandale, 2010):

$$P = 7.853\,\rho \left(\sqrt{\frac{\tau_o}{\rho}}\right)^3$$

where P = stream power in w/m^2

ρ = fluid macro density in kg/m^3, 1000 kg/m^3 for clear water

τ_o = bed shear stress in N/m^2.

CFD is widely used in spillway design to help identify alternatives that could minimize adverse hydraulic conditions leading to potential erosion or other undesirable hydraulic conditions. However, the current cost of the analysis may be prohibitive for small projects.

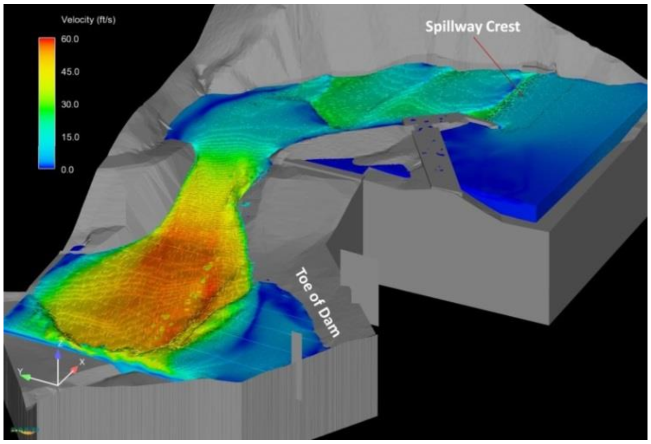


Figure 4 – CFD Model Estimated Velocities

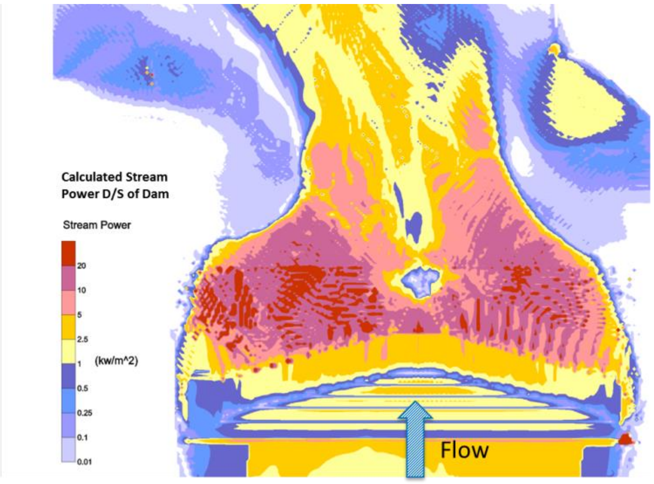


Figure 5 – CFD Model Estimated Stream Power

Case Study: Sugar Creek L-44

Sugar Creek L-44 is a 550-foot long embankment dam constructed in Southwest Oklahoma in 1971. The dam is 64 feet high with an auxiliary spillway width of 40 feet. In August 2007, the area around the dam experienced 8 to 10 inches of rainfall in 3 to 4 hours, exceeding the 100-year, 6, 12, and 24-hour event as well as the 500-year, 3-hour event. The flow through the spillway during the rain event was estimated by SITE analysis afterwards to be 740 cubic feet per second. The flow resulted in erosion of the inside training dike, the spillway down to the underlying bedrock, and the downstream toe of the dam near the spillway outlet (causing embankment instability). The event also washed out a county road 300 feet downstream, inundated a house, and caused activation of the Emergency Action Plan.

Figure 6 – Sugar Creek L-44 Spillway and Dam Erosion

A total of 38 auxiliary spillways flowed in the region due to the rain event but Sugar Creek L-44 was the only site in the area with damage to the embankment. One other site only incurred damage to the spillway. Numerous factors led to the erosion at L-44. The spillway had vegetated silty sands at the surface underlain by sandstone bedrock that dipped towards the embankment. The downstream road had an 18-inch pipe and riser to pass flows that had been reported difficult to keep clear of debris. The flow was observed to be 3 feet over the roadway during the event and led to backing up of water onto the lower 27 feet of the auxiliary spillway. This increase in tailwater at the bottom of the spillway and toe of the dam was determined to have decreased the stability of the soils and increased erosion. However, erosion would have occurred without the increase in tailwater due to the orientation of the spillway. Prior to construction, the design centerline of the spillway was shifted 95 feet towards the embankment, the channel was rotated 9.5 degrees toward the embankment and the exit channel slope was increased from 7.5 degrees to 9.75 degrees. All of the design changes increased the flow velocities on the spillway and at the toe of the dam. Had the tools described above been available to analyze the erosion capabilities of the increased flow on the silty sand material, the design changes may not have been made.

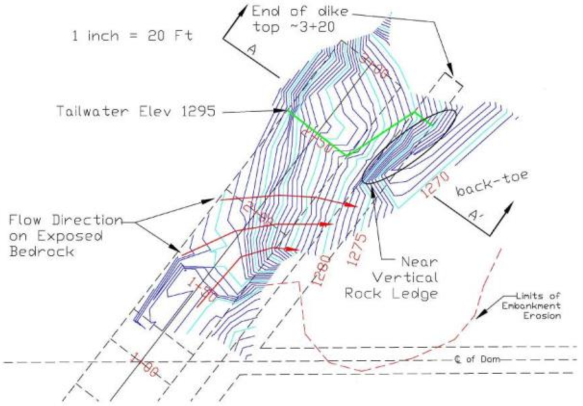


Figure 7 – Sugar Creek L-44 Plan of Erosion Damage

Useful References

[1] Annandale, G.W. 1995. Erodibility, *Journal Hydraulic Research, IAHR*, Vol. 33(4): 471-494.

[2] Annandale, George W. *Scour Technology – Mechanics and Engineering Practice*, McGraw-Hill Civil Engineering Series, First Edition, 2006, 430 pages.

[3] Bass, A.G. and Anderson, D.W., *A Dam Incident at Sugar Creek L-44*, 11TH National Watershed Conference, Wichita, Kansas, May 17-20, 2009.

[4] Frizell, K.H, J.F. Ruff, and S. Mishra, "Simplified Design Guidelines for Riprap Subjected to Overtopping Flow," Proceedings, ASDSO Annual Meeting, Las Vegas, Nevada, October 1998.

[5] Mathewson, C.C. et al, *Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels - Technical Report REMR GT-3 Supplement*, United States Army Corps of Engineers , August 1998

[6] United States Department of Agriculture, *SITES 2005 Water Resources Site Analysis Computer Program User Guide*, Natural Resource Conservation Service, October 2007

[7] United States Department of the Interior: Bureau of Reclamation. (1987). Design of Small Dams

[8] United States Department of the Interior: Bureau of Reclamation. (2012). *Best Practices Dam and Levee Safety Risk Analysis*

[9] Wibowo, J.L., D.E. Yule, and E. Villanueva, "Earth and Rock Surface Spillway Erosion Risk Assessment," Proceedings, 40th U.S. Symposium on Rock Mechanics, Anchorage Alaska, 2005.