A LOOK AT EARTH SPILLWAY DESIGN AND EVALUATION AFTER MORE THAN 50 YEARS OF EXPERIENCE

Paul G. Schweiger, P.E.[1], Darrell M. Temple, P.E.[2]
Danny McCook[3], P.E., & Amanda J. Hess, P.E.[4]

ABSTRACT

More than 23,000 dams have been constructed in the United States that rely on earth and rock auxiliary spillways to safely pass flood flows around dams. In the absence of analytical tools to estimate spillway integrity, many of these spillways were designed based on empirical methods and engineering judgment without any formal analysis of the spillways' performance during the design storm. The design philosophy recognized the fact that auxiliary spillways are used infrequently and some damage to the spillway was acceptable provided the spillway did not breach and the integrity of the dam was not compromised.

Flood events throughout the United States have tested the integrity of some of these spillways. Many of the spillways suffered extensive damage and even complete breaching during storm events less severe than the design storm. As a result, the United States Department of Agriculture, Natural Resources Conservation Service (NRCS), and the Agricultural Research Service (ARS), completed a laboratory research and field data acquisition program to assess the performance of existing earth spillways, improve the prediction of the risk of spillway breach, and to develop procedures for spillway design and analysis. Their efforts led to the development of a state-of-the-art computer program released in 1998 called "SITES", as well as updating procedures and requirements for earth spillway design. Since the release of these technical resources, more and more state dam safety regulatory agencies have begun requiring dam owners to perform stability and integrity analyses using the SITES program to evaluate the performance of both existing and new earth spillways.

The purpose of this paper is to provide a brief historical background of earth spillway design practice and experience in the United States, including lessons learned from spillway failures and the application of recent developments in earth spillway design and analysis. Common mistakes relating to the analysis, design, construction, and maintenance of earth spillways are discussed along with specific recommendations to designers, regulatory agencies and dam owners to maximize the performance and reliability of these spillways. Recommendations for field data collection and application of the SITES program are also presented based on the Authors' experience evaluating existing and designing new earth spillways.

GENERAL HISTORY OF EARTH SPILLWAY DESIGN

Since 1950, over 23,000 dams were constructed by the Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS). A plot showing the number and authority under which these dams were constructed by year is presented as Figure 1. Concrete riser principal spillways with earth and vegetated earth auxiliary spillways have been used extensively at these dams. These auxiliary spillways are excavated through natural materials and are usually designed as a wide trapezoidal channel having a subcritical inlet reach, a level crest or control section, and one or more supercritical outlet reaches. They are normally covered with a layer of topsoil and vegetated with grasses adapted to the local environment. The purpose of these spillways is to safely pass major flood flows around the structure and prevent dam overtopping. They are typically designed with only a one to four percent chance of operating in a given year (USDA NRCS, 2005). A typical NRCS flood control dam with an auxiliary spillway is shown in Figure 2.

---

[1] Senior Project Manager, Gannett Fleming, Inc.; [2] Private Consultant/Gannett Fleming, Inc.; [3] NRCS/Gannett Fleming, Inc.; [4] Project Manager, Gannett Fleming, Inc.

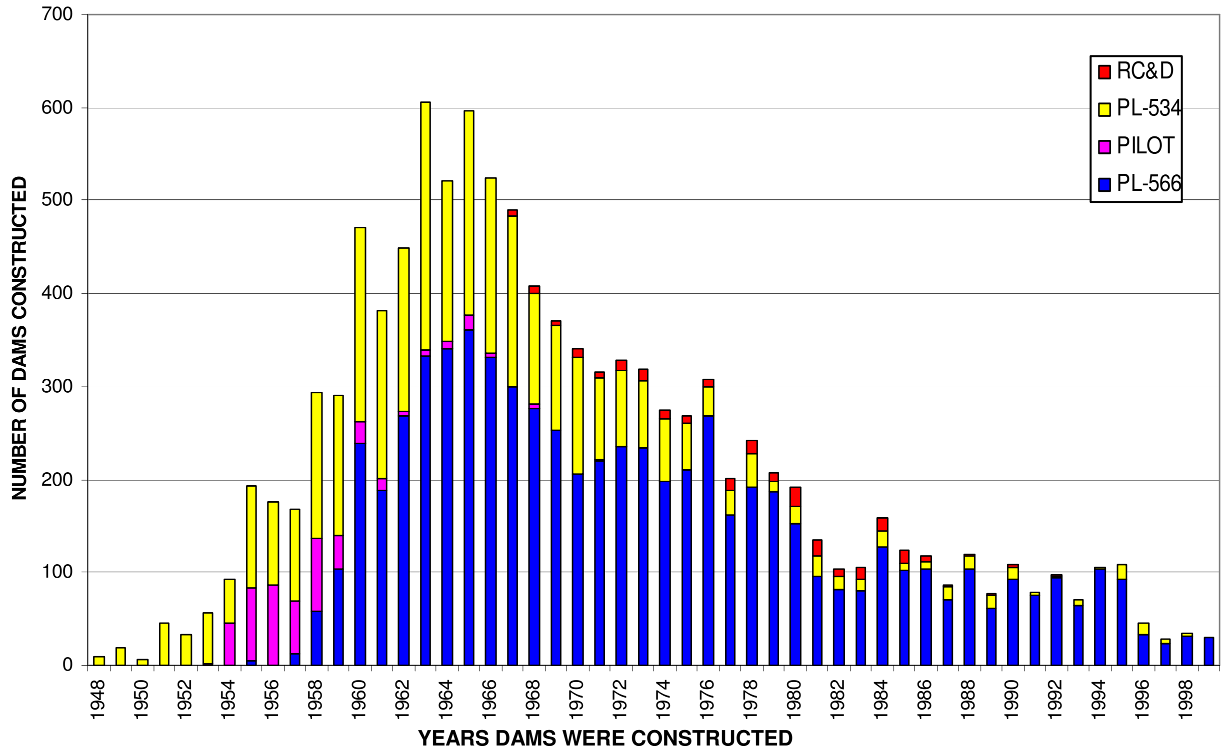


Figure 1. Plot of NRCS/SCS Dams Constructed Nationwide Between 1948 and 2000

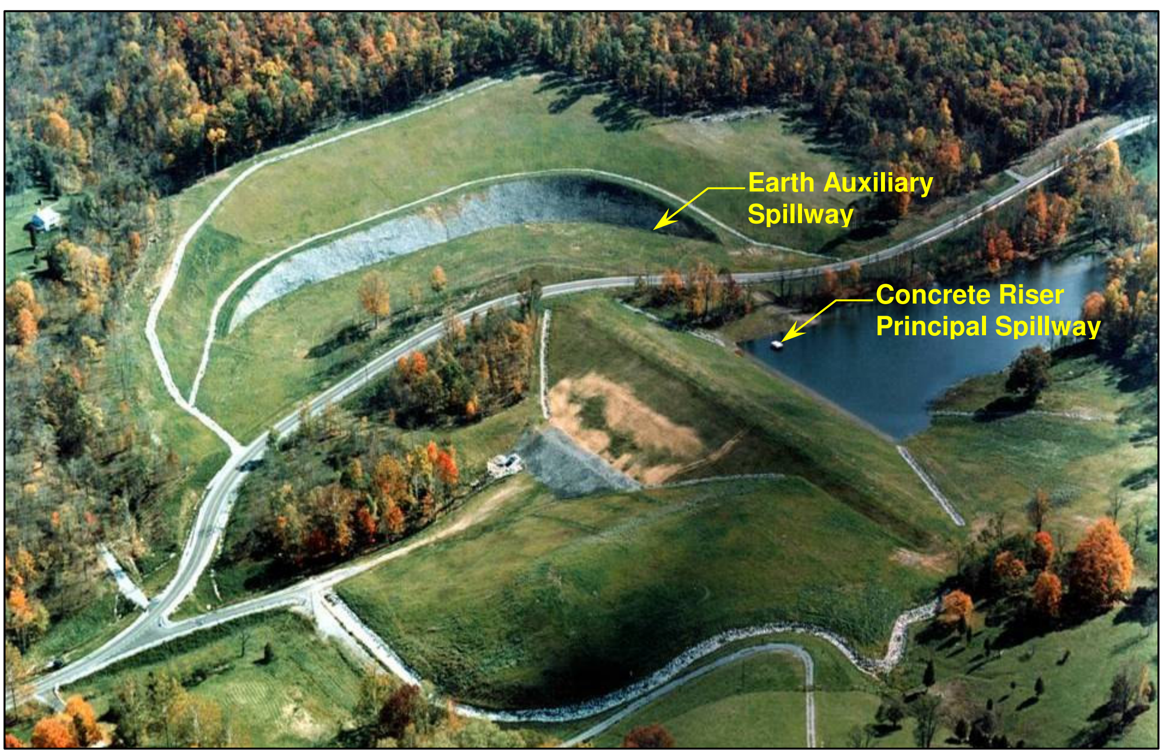


Figure 2. Typical NRCS Flood Control Dam with Auxiliary Spillway (Lost River Site 16, Hardy County, West Virginia)

Early auxiliary earth spillway design criteria provided by the SCS allowed significant damage to the auxiliary spillway as long as it was activated infrequently with relatively short periods of flow duration, the crest of the auxiliary spillway was not breached, and the main dam was not endangered by the spillway flows [SCS 1978, 1985]. Damage to the spillway was determined to be acceptable provided the reduced initial construction costs outweighed the costs of the infrequent anticipated damage and increased maintenance to the spillway.

In the absence of analytical tools to estimate spillway integrity, the design of these spillways used quasi-empirical methods and engineering judgment. The SCS adopted a design procedure based on the concept of providing an adequate bulk length through which the headcut must progress for the breach to develop (USDA, SCS, 1973). The bulk length was defined as the horizontal distance through the spillway using a specified depth below the spillway crest. The bulk length required for a given spillway was a function of the geologic material in the spillway and the volume of water discharged through the spillway during the freeboard or maximum design storm.

The SCS developed a spillway attack ratio (O_e/b) parameter where “O_e“ is the volume of the freeboard storm flow through the spillway in acre-feet per foot, and “b” is the spillway bottom width in feet. Maximum permissible values of O_e/b ratios were assigned based on soil classification and spillway bulk length. This approach relied heavily on judgment and did not address the actual physical variables that cause erosion and scour including: (1) the erosive power of the flowing water, (2) the material characteristics resisting scour, and (3) time (duration of hydraulic attack) [USSD, 2003].

Sound engineering practices were used to establish the layout and alignment for most earth spillways. The general practice was to locate the spillway at either dam abutment and configure the spillway to minimize flow concentrations, and to locate the spillway, to the extent possible, to take advantage of zones of earth material that are erosion resistant with respect to the anticipated flow conditions. At some dams, complex site conditions presented designers with significant challenges, resulting in deviations from recommended criteria. For these cases, the spillway design was sometimes pushed beyond known limits of the natural materials involved, the maximum discharge experienced, or well established spillway layout guidelines.

LESSONS LEARNED FROM EARTH SPILLWAY INCIDENTS

In 1983, the USDA Soil Conservation Service (SCS) established a team to monitor field performance of earth auxiliary spillways. The USDA Agricultural Research Service worked cooperatively with this team as well as studying associated failure processes in the laboratory. Since 1983, there have been in excess of 1,000 spillway flows of earth auxiliary spillways, many of which were judged to have major damage. Some of these spillways breached to the point of completely draining the reservoir or experienced sufficient erosion in or near the crest to be considered in danger of breaching should subsequent flows occur prior to repair. Several extreme cases are briefly described below to illustrate the most common causes of failure for earth auxiliary spillways.

Although examination of these case studies serves to enhance our understanding of the failure process, identify specific conditions which should be avoided, and maintenance practices that have the potential of improving performance, failures of properly designed earth auxiliary spillways are an unusual phenomena. For the flow ranges experienced, most of the observed vegetated earth and rock auxiliary spillways performed as intended.

Lesson 1 – Minimize Flow Concentrations By Prohibiting Obstructions and Discontinuities. A good uniform cover of vegetation in the spillway reduces the tractive stress applied to the soil and provides the first line of defense against erosion. For spillways constructed in erodible materials, such as sand, that are unable to adequately resist the erosion processes when exposed to direct attack, maintenance of a vegetal cover to delay or prevent head-cut formation can be an important part of preventing spillway breaching. To obtain full advantage from vegetal protection, the spillway needs to be maintained below flood tailwater elevation. Major discontinuities such as roadways, trails, and drainage ditches will negate the benefit of the vegetal cover. Lesser discontinuities such as fences, sign posts, staff gages, guide rails, utility poles, etc., will compromise the effectiveness of the vegetation. For erosion-resistant materials such as sandstones and shales, maintenance of surface cover is less important, however, major discontinuities will again negate the benefit of the cover and can create increased maintenance costs. Photos of some major discontinuities in auxiliary spillways are presented in Figures 3 and 4.

Figure 3. Twin Caney Site 17-3 Kansan in October 1986 provides an extreme case of headcutting when breaching of the spillway was initiated by a roadway paralleling the flow. The flow and stress concentrated in the unvegetated roadway tire tracks on the 10 percent exit channel slope resulting in the development of an overfall. Once formed this overfall moved both upstream and downstream along the lines of flow concentration formed by the tire tracks. Vegetated areas outside of the area of the roadway were undamaged.

Figure 4. Example of a discontinuity (small tree) in an auxiliary spillway. Flow concentrates around the discontinuity causing higher stresses and local erosion of the grass cover.

Lesson 2 – Spillway Breaching Can Occur Despite Significant Downstream Bulk Length. Although uncommon, spillways with significant bulk length have failed as a result of flow conditions significantly less than the design flood. These failures illustrate the weaknesses in prior analysis methods that do not adequately account for the hydrodynamic forces, geophysical properties of the spillway materials, and the duration of the flow. Black Creek Site 53 in Mississippi is a spillway failure example where a significant volume of spillway material was eroded.

Black Creek Site 53 consisted of a 50-foot high flood control earth embankment on a 19 square mile watershed. The auxiliary spillway was 100-feet wide with 3H:1V side slopes. The spillway was vegetated with grass that was in good condition at the time of the failure. No major discontinuities existed within the spillway. A road crossed the spillway exit channel perpendicular to the flow, forming two sharp drops shown in Figure 5. These drops were determined to be the points of primary attack and initial headcut formation. The spillway materials consisted of GM, ML and SM materials in lenses as shown in Figure 5.

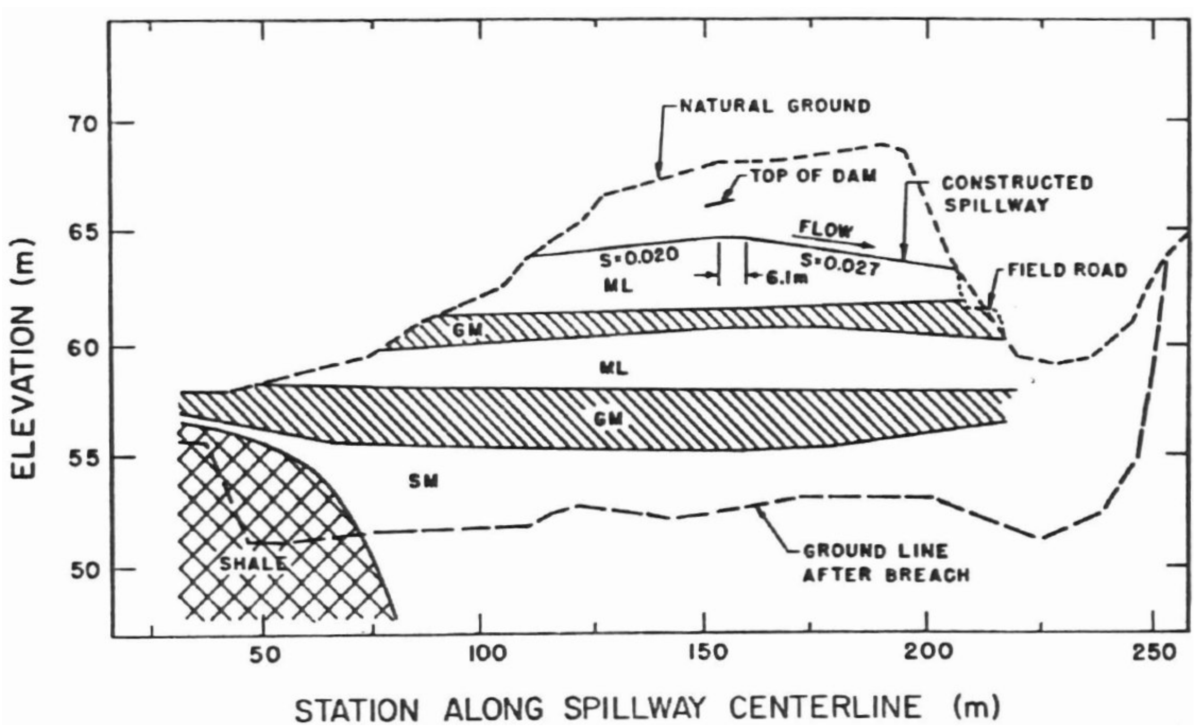


Figure 5. Black Creek Site 53 auxiliary spillway profile and geology (Temple, 1989).

On May 20, 1983, two storms released 5 and 9 inches of rain, respectively, in less than a week. The first storm raised the reservoir water surface and decreased the flood storage available to contain runoff from the second storm. The second storm generated enough runoff to activate the auxiliary spillway and caused it to discharge flow for over 60 hours. The maximum head on the spillway was 5.1 feet and the peak unit discharge was 84.7 cfs per foot. The final breach through the spillway was approximately 40 feet deep, 160 feet wide, and over 500 feet long. The breach effectively drained the flood control pool. It was estimated that 187,000 cubic yards of spillway material was eroded. A photo of Black Creek 53 following complete breaching of the auxiliary spillway is presented in Figure 6.

Figure 6. Black Creek Site 53 following breach of auxiliary spillway (Temple, 1989).

This auxiliary spillway example illustrates the importance of inspection, maintenance, and owner education. The roadway located at the downstream end of the spillway was credited with initiating and accelerating the headcut formation. This feature was not on the original plans for the site. It is likely that the roadway was constructed by non-technical parties unaware of its possible impact on spillway operation. The Black Creek Site 53 spillway failure also showed the importance of understanding material variations in the observed failure process and the need for thorough geologic investigation and evaluation in spillway siting.

Lesson 3 – PMF Events Do Occur. When designing structures for extreme events like the Probable Maximum Flood (PMF), it is sometimes difficult to imagine the occurrence of such an extreme event and to take seriously the need to adequately design spillway structures to safely pass PMF magnitude flows. The reality is that PMF storms can and do occur, and auxiliary spillways for significant and high hazard dams need to be designed for PMF events. For reference, the number of storms that have exceeded various percentages of the PMP for 10 square miles, for 6- and 24-hour durations, are presented in Table 1 [Huffman, 1999]. It should be noted that these precipitation values represent measured events, and that the greatest rainfall amount in a storm may not have been observed and documented. White Oaks Dam in Madison County, Virginia provides an example of a recent extreme precipitation event activating an earth auxiliary spillway and the unanticipated damage it can cause.

TABLE 1
Number of Storms Exceeding Various Percentages of PMP
East of the 105th Meridian for 10 Square Miles, 6- and 24-hour Durations
(Source: Huffman, 1999)

	Percent of PMP Rainfall				
	50%	**60%**	**80%**	**90%**	**100%**
East of the 105th Meridian	59	32	19	7	3
West of Continental Divide	77	39	13	4	0

White Oaks Dam is a 63-foot high earthen embankment with a 63-foot wide auxiliary spillway constructed in 1964 for flood control and water supply. The dam is located in Madison County, Virginia. The contributing drainage area is 5 square miles in rural mountain terrain. On June 27, 1995, over 21 inches of rain fell within an 18-hour period, activating the auxiliary spillway and creating a maximum head on the spillway of 10 feet, and a peak unit discharge of 138 cfs per foot.

This extreme flow eroded approximately 300 feet of the spillway to a maximum depth of 50 feet and width of 130 feet downstream of the control section. It was estimated that 10,500 cubic yards of spillway material was eroded. Boulders as large as 6 feet by 12 feet were observed immediately downstream of the spillway [Clements, 1998]. The control section was originally constructed by blasting a 75-foot wide channel in an unweathered granite formation which fortunately prevented breaching of the spillway and failure of the dam. Photographs of the White Oak Dam auxiliary spillway showing the erosion caused by the June 1995 flood event are presented in Figure 7.

Lesson 4 – Evaluate Downstream Hydraulics for Unusual Flow Conditions that Could Erode The Dam. Any spillway design should ensure that the embankment is not overtopped and that the exit channel of the auxiliary spillway is extended far enough downstream from the dam to preclude damage to the dam. When designing the downstream exit channel, it is important to consider possible unusual flow conditions that could cause the spillway flow to meander, change direction, and return to erode the dam embankment. This condition is not always evident as the subsurface geologic features that can cause this condition can be complex and not well defined. In some cases, man-made features, such as a new highway crossing downstream of the dam, can be constructed many years after the dam was constructed (see Lesson2 and 5) and obstruct and redirect the flow towards the dam. Sugar Creek Dam L-44 in Oklahoma provides a good example of an auxiliary spillway exit channel condition that nearly breached the dam embankment.

On the weekend of August 18-19, 2007, tropical depression Erin swept across Oklahoma. Rainfall amounts fell in parts of Caddo County that greatly exceeded that of a 100-year frequency storm. Preliminary measurements of the rainfall in the drainage area above Sugar Creek Dam L-44 indicate that over eight inches of rain fell in less than 12 hours and activated the auxiliary spillway. Flows from the auxiliary spillway were discharged beyond the toe of the earth embankment, but returned after encountering the Highway 81 road embankment to erode the downstream slope of the dam and nearly breach the dam. Backwater from debris plugging the culvert under Highway 81 may have contributed to unusual flow condition. Photographs of Sugar Creek Dam L-44 showing the erosion caused by the auxiliary spillway flows are presented in Figure 8.

Figure 7. Photos of White Oak Dam auxiliary spillway looking downstream (top) & upstream (bottom) after June 27, 1995 flood when 21 inches of rail fell in less than 18 hours.

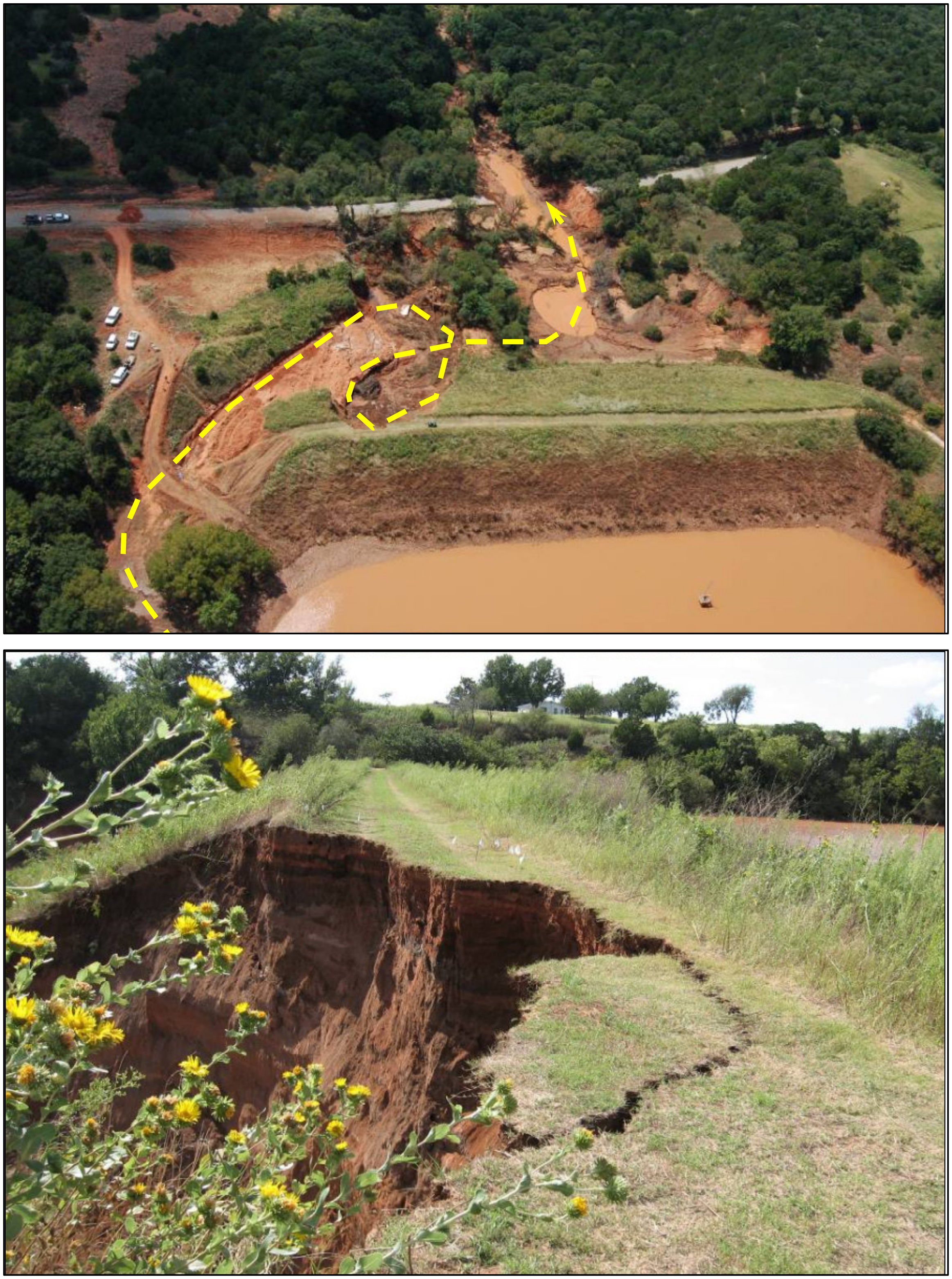


Figure 8. Photographs showing the flow path and erosion in the downstream slope of Sugar Creek Dam L-44 located in Caddo County, Oklahoma following Tropical Depression Erin on August 19, 2007.

Lesson 5 – Anticipate Future Development. As downstream development increases, dams that were once designed as low-hazard structures can become significant or high-hazard structures. Upstream development can also significantly increase the runoff. Auxiliary spillways that were originally designed to be activated infrequently can become undersized and activated more frequently. Since the majority of the 23,000 NRCS dams constructed with auxiliary spillways are more than 40 years old, upstream and downstream development has the potential to have a significant impact on these structures. These changes may not have been anticipated during the design. Pohick Dam No. 4 located in Fairfax, Virginia, is an unusual example of extreme upstream development as well as intense development around and downstream of the damsite.

Pohick Creek Dam No. 4 is a flood retarding dam constructed by the Soil Conservation Service in 1976. The lake created by the dam is used for recreation and has a normal pool which is 13 feet below the crest of the emergency spillway, and 24 feet below the top of the dam. The dam is a zoned earth embankment 1,010 feet long and 42 feet high. The auxiliary spillway consists of a 100-foot wide grass-lined trapezoidal channel excavated at the right dam abutment. The crest or control section of the emergency spillway is also grass-lined and consists of a 30-foot long level section. The side slopes of the spillway channel are 3(H):1(V). Approximately 200 feet downstream from its crest section, the grass-lined spillway channel abruptly transitions into a densely wooded area with a 10 percent bed slope. Intense urban development has occurred within the watershed and in the immediate vicinity of the dam. Townhouses were constructed in 1978 and 1979 within 300 feet of the crest of the emergency spillway and are within the path of flows exiting the emergency spillway channel. Aerial photos of Pohick Dam No. 4 showing the intense urban development within the watershed and immediately downstream of the dam and auxiliary spillway are presented in Figure 9.

THE STATE-OF-THE-ART IN EARTH SPILLWAY INTEGRITY ANALYSES

Over the past several years, scientists in the Hydraulic Engineering Research Unit of the Agricultural Research Service (ARS) have cooperated with the USDA Natural Resources Conservation Service (NRCS) to develop a computer model to evaluate the integrity of earth spillways. In early 1998, the ARS released the SITES Water Resources Site Analysis Software. The SITES model features iterative application of a three-phase approach to predicting the extent of vegetated earth spillway erosion. The three phases are: Phase 1 - the failure of the vegetal cover and development of concentrated flow; Phase 2 - surface erosion in the area of concentrated flow leading to formation of a headcut; and Phase 3 - the downward and upstream advance of the headcut. This new tool introduces a “Headcut Erodibility Index” to describe the resistance of exposed geologic materials to headcut advance during Phase 3. This software is on the leading edge of technology for design and analysis of earth spillways. The model output includes the time of Phase 1 failure, a description of the upstream progression of predicted headcut, and a description of the deepest headcut evaluated. A potential total eroded profile resulting from a composite of all headcuts evaluated is also generated.

This program fills a large gap that existed in the process of designing and analyzing the integrity of earth spillways. This tool is able to account for the existence and condition of vegetal cover, the physical properties of the soil and rock within the spillway profile and the time rate of hydraulic assault on the spillway. Successfully developing inputs to the program and analyzing the program output requires engineering judgment and experience with vegetated earth spillways; however, it is clearly a marked improvement over the bulk length concept. This program provides a means of considering the “lessons” presented above both in the design of new earth spillways and in the analysis of existing earth spillways. A brief introduction to the program with a focus on recommendations of the authors is presented below.

Figure 9. **Aerial photos of Pohick Dam No. 4 showing intense urban development within watershed and immediately downstream of the dam and auxiliary spillway.**

Theory. The earth spillway erosion model provides a physically based means of estimating the performance of vegetated earth spillways subjected to flood flows. The model is based on relations developed from physical principles, laboratory experiments, and data from case studies of actual spillway erosion. Because of the complexity of the physical phenomena involved, the theoretical expressions for solution were simplified. Model input and output therefore needs to be examined critically. In applying the model, it should be recognized that the flow is able to search out and attack the weakest material conditions in the geologic profile. A detailed discussion of the theory used by the model is provided in Part 628 of the National Engineering Handbook, Chapter 51 - Earth Spillway Erosion Model, published by the NRCS.

Input Data Requirements. Spillway data input requirements for the SITES model include a description of the spillway surface conditions, the properties and location of the geologic materials that may be exposed during erosion, and hydrologic data to describe the outflow hydrograph through the spillway. The outflow hydrograph can be input directly or computed by SITES using watershed parameters and reservoir routing through the principal and auxiliary spillways.

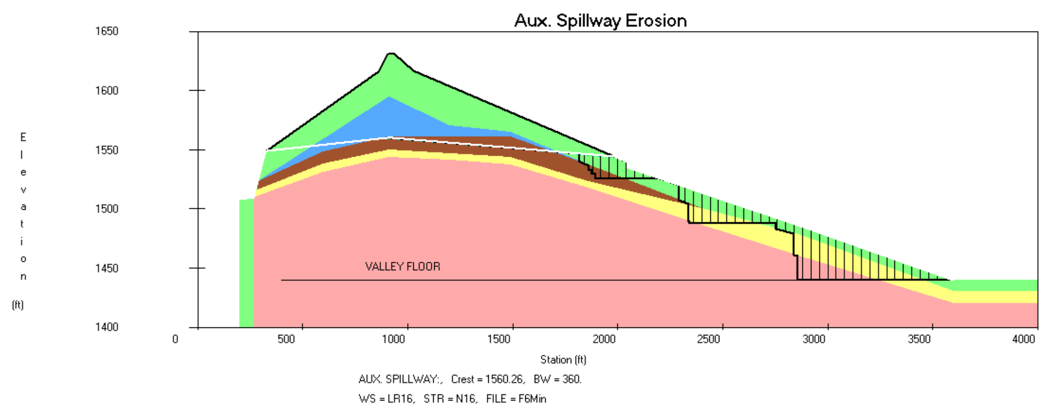
Auxiliary Spillway Surface Conditions. Emergency spillway surface conditions are used in determining the time of Phase 1 failure for the reach or segment used to descript the auxiliary spillway, and in determining the flow depth of Phase 2 flow concentration computations. Auxiliary spillway surface parameters include a flow resistance parameter (either Manning's n or a vegetal retardance curve index), vegetal cover factor, cover maintenance factor (uniform, minor discontinuities, or major discontinuities), potential vegetal rooting depth, and the representative diameter of the surface material.

Geologic Material Parameters Used In SITES Analyses. The geologic material parameters required for each material represented in the generalized geologic profile of the auxiliary spillway include the plasticity index (PI), the representative particle diameter (d_{75}) for fine grained material), percent clay, bulk dry density, and the headcut erodibility index (Kh). For rock materials, the representative diameter is estimated as the cube root of the maximum sized rock blocks. The plasticity index is used in determination of time of Phase 1 failure for materials exposed at the spillway surface. The representative particle diameter is used in the computations of erodible particle roughness, and in the determination of the critical stress, for surface detachment computations in Phases 2 and 3. The percent clay and bulk dry density are used to determine the detachment rate coefficient, and may be replaced by direct input of that parameter. The detachment coefficient is used in surface detachment (erosion depth) computations for Phases 2 and 3. The headcut erodibility index is used in the determination of the headcut advance threshold and rate for Phase 3. The detachment rate coefficient can be directly measured using special "jet index test apparatus" developed by the ARS.

The most important geologic material parameter is the headcut erodibility index (Kh). The erodibility index is a measure of the resistance of the earth material to erosion and mass failure associated with headcut advance and is determined quantitatively through laboratory soil strength tests and field determination of rock material and mass properties. The headcut erodibility index for each layer in the generalized geologic profile can be determined using the Field Procedures Guide for the Headcut Erodibility Index as specified in Part 628, Chapter 52 of the NRCS National Engineering Handbook (August 1997). The index is computed as the scalar product of various indices and rock quality data obtained from subsurface test information.

The computed values of Kh can also be compared to a photo reference developed by the ARS and NRCS, representing examples of various materials for which index values have been determined from actual auxiliary spillway headcut cases. The photo reference provides additional guidance in identifying common ranges in index values for similar materials. Because of the limited subsurface data often available, a determination based on judgment is sometimes needed to bracket key geologic parameters used in the spillway integrity analyses. The resulting analyses can therefore be used to determine maximum and minimum erosion profiles for the auxiliary spillway.

Recommendations for Analyzing Auxiliary Spillways Using SITES. Although SITES provides a physically based means of estimating the performance of vegetated earth spillways, considerable judgment is often required to select the input parameters, especially the inputs used to describe the geologic material properties within the spillway. When evaluating the integrity of vegetated earth spillways using SITES, the authors of this paper recommend that extensive sensitivity analyses be performed in order to fully understand the consequences and sensitivity of key model inputs have on the computed erosion profile. The SITES model is well suited for this type of analyses and was designed with a graphical user interface that enables the user to evaluate multiple scenarios at one time and provides the output in a manner that allows side by side comparisons of results and easy to understand graphs. A typical auxiliary spillway erosion profile plot from the SITES model is shown in Figure 10.



Material Description	Detach. Rate (ft/h)/(lb/sq ft)	Dry Density (lbs/cu ft)	Headcut Index (Kh)	Percent Clay	Plasticity Index	Rep. Diameter (in)
Overburden	--	105.	0.04	40.0	8.	0.10000
Rock Z1	--	110.	0.16	0.0	0.	2.00000
Rock Z2	--	120.	50.00	0.0	0.	18.00000
Rock Z3	--	120.	10.00	0.0	0.	3.00000
Rock Z4	--	120.	50.00	0.0	0.	18.00000
TS_FILL	--	110.	0.05	10.0	0.	0.00400
GEN_FILL	--	105.	0.04	40.0	8.	0.10000

Figure 10. Typical auxiliary spillway erosion profile plot from SITES model.

When performing sensitivity analyses, it is recommended that the geologic parameters used in the spillway integrity analyses be bracketed to provide maximum and minimum erosion profiles for the auxiliary spillway. Individual parameters can also be varied to determine their significance and influence on the results. Since the SITES model analyses terminate as soon as the crest of the auxiliary spillway is breached, the authors of this paper sometimes artificially extend the crest of the auxiliary spillway (in the upstream direction), so that the SITES model will continue to compute the erosion profile beyond the actual crest section. This analysis technique recognizes the fact that a shallow breach through the auxiliary spillway crest may not be a significant performance issue and provides a more comprehensive evaluation of the integrity of the spillway. Care must be used in interpreting this type of analyses since the effect of erosion on the spillway discharge is not accounted for.

A common error made by investigators is to terminate the analysis at the downstream end of the uniform excavated spillway slope. The analysis needs to be extended to the valley floor and include any major discontinuities, including abrupt natural changes in grade. As previously discussed in Lessons 1 and 2, discontinuities in within the auxiliary spillway exit channel can have a significant impact on the spillway integrity. As part of the sensitivity analyses, investigators can input a discontinuity such as an abrupt change in spillway exit channel grade in the SITES model to evaluate the construction of a road or a natural discontinuity.

After an auxiliary spillway has been evaluated and its integrity found to be satisfactory, it may be of interest to perform several SITES runs to determine how much more erodible the geologic parameters would need to be before the spillway experiences unacceptable erosion damage. For this type of analysis the geologic input parameters can be adjusted by trial and error until the hypothetical minimum values are obtained that would result in almost breaching the auxiliary spillway. The trial and error analysis generally involves successively entering lower parameter values for each zone of material represented in the geologic profile of the spillway until the computed headcut begins to breach the level crest section. These “hypothetical worst case” geologic inputs can then be compared with the geologic inputs that best represent conditions in the spillway to provide additional assurance that the auxiliary spillway would perform satisfactorily as designed.

SUMMARY AND CONCLUSIONS

When thoroughly evaluated and carefully designed, earth and rock auxiliary spillways have been proven to economically and safely pass flood flows around dams. Analytical tools such as the SITES computer model and published design guidelines are available to help dam designers reliably predict the integrity of these spillways during the passage of their design storms. These resources are based on years of research and field data for auxiliary spillways excavated in a wide rage of earth materials that have experienced flow. When analyzing the integrity of auxiliary spillways, the investigator must realize that prediction of erosion in earth spillways is currently less than an exact science and should be approached accordingly. Based on the authors’ collective experience researching, evaluating, and designing earth spillways, several recommendations are offered to designers, regulatory agencies and dam owners to help them maximize the performance and reliability of these spillways.

REFERENCES

1. Clements, L. L., S. S. Lin, B. L. Kitzner, T. Street and B. W. Ganoe, *Case Study: Learning From Earthen Spillway Erosion and Rehabilitation*, 1999 ASDSO Annual Conference, St. Louis, MO, October 10-15, 1999.
2. Huffman, R. G., *The Inflow Design Flood for High Hazard Dams*, 1999 ASDSO Annual Conference, St. Louis, MO, October 10-15, 1999.
3. Schweiger, P. G., T.L. Dreese, D. M. Burdick, and V. Tucker, *Evaluating the Performance and Erodibility of Earth Cut Emergency Spillways*, 1999 ASDSO Annual Conference, St. Louis, MO, October 10-15, 1999.
4. Soil Conservation Service (SCS), A Guide for Design and Layout of Earth Emergency Spillways As Part of Emergency Spillway Systems for Earth Dams, U.S. Department of Agriculture, Soil Conservation Service, TR-52, 1973 (Revised 1978)
5. Temple, D. M., K. Robinson, and A. Davis, Stability *Design of Grass-Lined Open Channels*, USDA Agricultural Research Service, Agricultural Handbook No. 667, September 1987.
6. Temple, D. M., *Dominant Factors In Vegetated Earth Spillway Failures*, D. Temple, Proceedings of Transactions of 6th Annual Conference of the ASDSO, October, 1989, pp. 104-109.

7. Temple, D. M., *Mechanics of Earth Spillway Failure*, Transactions of the ASAE, Vol. 32(6), Dec. 1989.
8. Temple, D. M. and J. Moore, *Headcut Advance Prediction for Earth Spillways,* Transactions of the ASAE, Vol. 40(3), pp. 557-562.
9. Temple D. M., H. H. Richardson, J. A. Brevard and G. J. Hanson, *SITES: The New DAMS2,* ASAE Journal of Applied Engineering in Agriculture, Volume 11(6):831-834., 1995.
10. USDA Soil Conservation Service, "A Guide for Layout of Earth Emergency Spillways as Part of Emergency Spillway Systems for Earth Dams", TR-52, February 1973.
11. USDA Natural Resources Conservation Service, *Part 628 Dams, NRCS National Engineering Handbook, Chapter 50 - Earth Spillway Design, Chapter 51 - Earth Spillway Erosion Model, and Chapter 52, Field Procedures Guide for the Headcut Erodibility Index*, August 1997.
12. USDA Natural Resources Conservation Service, *TR-60: Earth Dams and Reservoirs*, July 2005.
13. USDA Natural Resources Conservation Service, *SITES Water Resource Site Analysis Computer Program and User's Manual, Version 2005.1.3, 18 October 2007*.
14. USSD Hydraulic Committee, *Erosion of Unlined Spillways,* Paper prepared by the USSD Hydraulic Committee, S.K. Nada, Chairman, Erosion of Unlined Spillways Sub-Committee, April 2003.