

Do Yesterday's Earth-Cut Spillway Designs Meet Today's Standards? The Ins and Outs of Earth Spillway Design and Integrity Analysis

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Abstract--The Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS), assisted local sponsors in implementing more than 29,000 dams throughout the United States, most of which have an earth-cut auxiliary spillway. An earth-cut auxiliary spillway is a spillway excavated through natural soil and/or rock materials, often protected with vegetation. NRCS designed many of these auxiliary spillways more than 50 years ago using design criteria based upon quasi-empirical methods and engineering judgment, without any formal analysis of their performance during the design storm. Unfortunately, some earth-cut auxiliary spillways did not perform satisfactorily when activated, and a few have completely breached or caused erosion and breaching of the embankment.

As dams are being re-assessed and rehabilitated, designers can evaluate the integrity and hydraulic performance of earth-cut auxiliary spillways using new tools developed by the Agricultural Research Service (ARS) and NRCS, such as the SITES and WinDAM B software. To properly apply these tools and understand the results, it is helpful to understand past design criteria and practices as well as the limitations of these new and powerful analytical tools.

The purpose of this paper is to present the history and rationale of early earth-cut auxiliary spillway design using examples from the past. This paper describes both good and bad examples of earth-cut auxiliary spillway designs and their performance when activated. The paper also discusses the use of SITES and WinDAM B software for performing screening level assessments using limited data, and comprehensive analyses using detailed subsurface data. The authors share lessons-learned and provide recommendations on how to best use available information, whether it be old or new, to evaluate the performance of earth-cut auxiliary spillways.

I. WHY AUXILIARY SPILLWAY INTEGRITY IS IMPORTANT

Older NRCS design references described minimum requirements for earth-cut auxiliary spillway capacity and activation frequencies based on hazard class, ranges of Manning's "n" and permissible velocities for various surface conditions, and acceptable auxiliary spillway layout and alignments relative to the dam embankment geometry. The minimum requirements attempted to ensure the dam embankment would not overtop during the freeboard hydrograph design storm, the control section of the auxiliary spillway would not breach (integrity), and the flow through the auxiliary spillway would not result in erosion of the downstream portions of the dam embankment. Elements of the design considerations included in the older design references parallel today's concerns regarding the design of the auxiliary spillway. However, today's design criteria references design handbooks and design-aiding computer programs/tools that predict erosion based on current science and soil and geologic conditions. The auxiliary spillway integrity evaluation for today's criteria include modeling the spillway for headcut development and advancement during passage of the freeboard storm. To meet the integrity requirements of today's criteria, the spillway design must ensure that the spillway will not breach during passage of the freeboard storm. While the design concerns regarding the performance of the spillway are similar to past concerns, the design methodology has changed.

In May of 1983, the Black Creek watershed of the Yazoo basin in Mississippi endured severe flooding. This flooding activated the auxiliary spillway of Black Creek Site 53 and resulted in failure of the dam by erosion and breaching of the auxiliary spillway. The local landowner constructed a farm access road into the exit channel of the spillway perpendicular to the flow, creating a very steep drop in grade. Investigators determined that this drop was the point of primary attack by erosion and the location of the initial headcut formation. The final spillway breach measured 40 feet deep and 160 feet wide, and effectively drained the flood control pool. The constructed auxiliary spillway was

100 feet wide. Approximately 187,000 cubic yards of spillway material was eroded (Temple, 1989b). Figure 1 shows Black Creek Site 53 following complete breaching of the auxiliary spillway. This dam provides one of several examples where an earth-cut auxiliary spillway did not perform as originally intended.



Figure 1. Failure of Black Creek Site 53 Auxiliary Spillway (Photo courtesy of Darrell Temple)

The Black Creek Site 53 failure, along with other similar spillway failures, brought to light the importance of spillway design considerations and related processes during headcut formation and progression. The original design requirements included several considerations to help ensure spillway integrity; however, the design guidance did not include modern day considerations and related processes.

II. BACKGROUND OF EARTH-CUT SPILLWAY DESIGN CRITERIA

The majority of the NRCS-assisted dams across the United States were constructed in the 20-year period between 1960 and 1980. During the peak of the dam building period between 1963 and 1965, more than 600 dams per year were constructed. NRCS dams generally consist of an earth embankment, a concrete principal spillway riser structure with either a plunge pool or an impact basin outlet, and an earth-cut (vegetated, earth, or rock) auxiliary spillway. Typically NRCS designed trapezoidal open channel auxiliary spillways excavated at one of the dam abutments in soil, rock, or a combination of soil and rock. The auxiliary spillways included a subcritical inlet reach, a level crest or control section, and one or more supercritical exit channel reaches. The majority of the spillways were lined with a layer of topsoil and vegetated with grasses adapted to the local environment. The purpose of the auxiliary spillway is to safely pass major flood flows around the structure and prevent dam overtopping.

NRCS auxiliary spillways for high hazard dams are typically designed with a one percent chance of operating (flood events greater than the 100-year flood) in a given year (USDA NRCS, 2005). Figure 2 illustrates a typical layout of a NRCS flood control dam with an auxiliary spillway at the right abutment. This particular site layout includes a curved outlet beyond the exit channel. At the time that these dams were constructed, engineering and geotechnical judgement was the primary basis for the design of the spillway. Analytical tools to evaluate the spillway integrity did not exist. In addition to the activation frequency requirements, the design criteria at that time included discharge capacity requirements, ranges of permissible velocities, and layout considerations. The spillway design

criteria allowed significant damage to the auxiliary spillway as long as activation is infrequent 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. Damage to the spillway due to flow during a design event 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. The design philosophy recognized infrequent auxiliary spillway activations and subsequently some damage to the spillway was acceptable. Criteria required the auxiliary spillway exit channel alignment to be straight and perpendicular to the control section; however, curvature may have been introduced at the outlet of the exit channel at a point where the discharge will not impinge on the dam. Often earth training dikes were installed to contain the auxiliary spillway flow in the exit channel to protect the dam embankment. Furthermore, design criteria recommended raising the spillway crest elevation to increase flood storage to reduce spillway activation and duration and minimize the potential for breaching the spillway.



Figure 2. Typical NRCS Flood Control Dam with Auxiliary Spillway (Lost River Site 27, Hardy County, West Virginia)

In 1967, the NRCS distributed the original Structure Site Analysis program (DAMS). This program developed inflow hydrographs and used stage-storage and stage-discharge relationships to route hydrographs through the spillways. Later versions of the program released in the 1970s and 1980s introduced more capabilities and included improvements to the original DAMS program. These useful program features aided in the design and analysis of NRCS dams; however, they did not possess the capability to perform auxiliary spillway erosion prediction analyses.

In 1973, NRCS recognized the importance of headcut erosion relative to the performance of earth-cut spillways and 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 needed to be eroded 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 passage of the freeboard or maximum design storm. The NRCS 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, and “ b ” is the spillway bottom width in feet. Soil and/or rock classification and spillway bulk length determined the maximum permissible values of O_e/b ratios. 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) duration of hydraulic attack [USSD, 2003].

The NRCS also provided guidance for the preferred direction of the strike and dip of the rock within the auxiliary spillway. The design guidance preferred the strike and dip in the upstream direction or away from the dam so that any fractures within the rock would divert flow in that direction (USDA SCS, 1980). Figure 3 shows NRCS preferences of strike and dip within an auxiliary spillway; illustrating good, fair, and poor geologic orientations relative to the dam and auxiliary spillway alignment. This guidance improved upon older references; however, no quantitative way to analyze spillway erosion existed.

Souhegan Site 15, located in Hillsborough County, NH, is an example of a dam designed using older design spillway criteria that was later determined to not provide adequate erosion resistance. NRCS designed the dam in 1962 as a flood control structure. The original geologic design report documents the subsurface exploration within the spillway and provides a discussion of the geology at each abutment of the dam. Two test pits excavated at the foot of the slope of the selected spillway location (right dam abutment) showed: *“4 feet to 5 feet of silty sand underlain by 5 feet of horizontal interbedded layers. An additional 2 feet of silty sand was found below the interbedded SM-CL in one of the pits. **No bedrock or unconsolidated materials were found in any of the test pits. The bottom of the spillway excavation will be in compact silty sand material.**”* (SCS, 1962).”

The original geological design report also described the geology at the left dam abutment for an alternate auxiliary spillway location and stated: *“three holes were used to investigate the alternative emergency spillway which is located in the vicinity of the left abutment. All three holes show 1.5 feet to 3.0 feet of relatively coarse silty sand underlain by weathered gneiss or schist **which becomes sound bedrock at about 2.0 feet.**”* The designers did not select the alternative location for the auxiliary spillway. This location would have served as a better spillway location from an integrity perspective having erosion resistant bedrock material at shallow depths. The spillway was located at the right abutment where there was silty sand (a highly erodible material) and no bedrock. The SITES integrity analyses performed 55 years after the dam was constructed showed the existing spillway would breach during passage of the freeboard hydrograph (FBH). At many dams, complex site conditions presented designers with significant challenges, resulting in competing design consideration. The selected spillway locations were sometimes pushed beyond known limits of the natural materials erosion resistance properties.

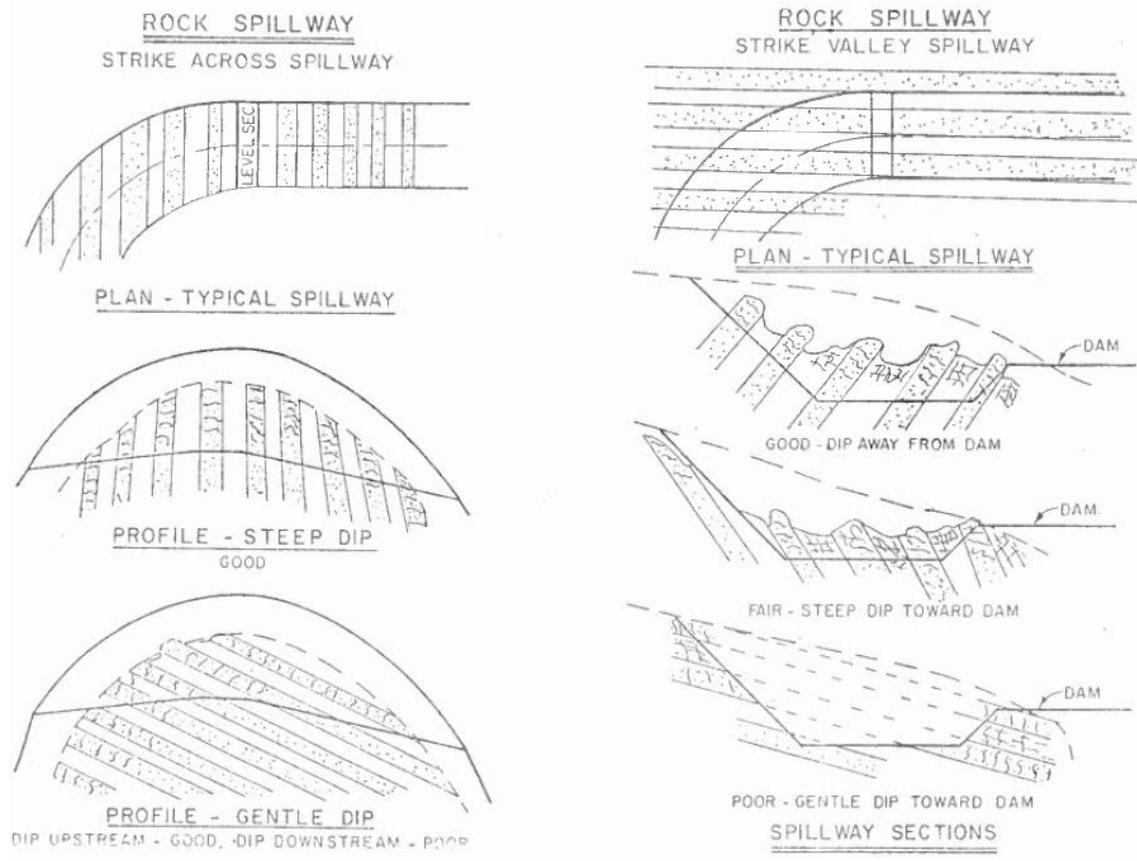


Figure 3. Example of NRCS guidance for the Strike and Dip of Rock within an Auxiliary Spillway (USDA SCS, 1980)

III. SITES MODEL FOR EVALUATING AUXILIARY SPILLWAY EROSION

To better understand the performance of auxiliary spillways, the NRCS formed an Emergency Spillway Flow Study Task Group to collect data from field spillways that experienced flow greater than three feet in head. The ARS assisted in the data acquisition effort and conducted laboratory research to quantify the associated erosion processes. This effort compiled data from more than 83 dam sites representing 13 flood events in 10 states over a period of 8 years. A joint NRCS/ARS Design and Analysis of Earth Spillways team formed in 1991 with the charge of developing new technology for use in the design and analysis of earth-cut spillways (Temple and Hanson, 1994). The efforts of that team led to the development of the Stability and Integrity Technology for Earth Spillways (SITES) software, first released in 1998. The model combined flood routing capabilities to determine required spillway crest and top of dam elevations with spillway stability and integrity analyses. In doing so, it was the first model capable of evaluating all three of the variables that have the most impact on headcut erosion: hydrodynamic properties (erosive power of water), geophysical properties (forces and materials resisting scour) and time (duration of hydraulic attack). This provided significant improvements to the bulk length method for evaluating spillways described previously.

The spillway integrity analysis portion of the model calculates erosion damage to earth-cut spillways in three separate phases. The first phase is erosion resulting in the local failure and removal of the vegetal cover, if any, and the development of concentrated flow. The second phase is the downward and downstream erosion resulting from the flow and stress concentration leading to the formation of a vertical or near vertical headcut. The third phase of the erosion process is the upstream advance of the headcut, which may also be accompanied by further widening and deepening (Temple and Hanson, 1994). The model calculates these three phases in time steps over the passage of the hydrograph through the spillway based on user inputs of the spillway including surficial dimensions and vegetal cover conditions as well as subsurface profiles of both soil and/or rock and their physical properties. Sections A, B, and C

below describe in more detail the three separate erosion phases simulated by the SITES model and their importance to auxiliary spillway integrity.

A. Phase 1 Erosion Process

Vegetal cover failure is generally the result of erosion through the vegetal elements eventually undermining and locally removing the vegetal elements to form an area of flow and stress concentration. The SITES model calculates Phase 1 erosion by relating the erosionally effective stress relation for grass-lined channels (Temple, 1987b) coupled with a linear detachment rate model. The observations made in the laboratory were calibrated for application using data from field spillways. User inputs into the model such as the plasticity index of the topsoil, potential rooting depth, Vegetal Retardance Curve Index (or Manning's "n" value), and vegetal cover factor have a significant impact on Phase 1 calculations.

Because the failure of the vegetal cover is a local phenomenon, discontinuities in the cover may reduce or even negate the protective value of the cover by sharply reducing the time associated with Phase 1 erosion. The user can account for this by defining the maintenance code as either uniform cover over the entire area subject to flow, minor discontinuities in the cover, or major discontinuities in the cover. An example of a minor discontinuity is a foot-path running perpendicular to the direction of flow, and an example of a major discontinuity is a road running parallel to the direction of flow. Trees or bushes in the spillway constitute minor discontinuities unless they cause larger areas devoid of all vegetation. The program accounts for these discontinuities computationally by appropriately varying the parameters used to calculate the erosionally effective stress.

When the vegetal cover lacks adequate rooting depth due to shallow topsoil, the mode of Phase 1 erosion is changed, and the protective capability of the cover is sharply reduced. Data from field spillways indicate that for covers with average available rooting depths less than 1 foot, the sod tends to be stripped or rolled from the underlying material. This action referred to as "sod stripping" begins at points of shallow or non-existent cover and progresses downstream as a result of hydrodynamic pressures developed at the material interface (Temple, 1993).

Earth-cut spillways that are uniformly vegetated can significantly prolong the period of time before Phase 1 erosion occurs. Conversely, spillways that cannot support vegetation and spillways that have major discontinuities will likely result in rapid Phase 1 failure when activated. Vegetal cover is observed to have the greatest impact on overall performance when the cover is uniform, the exit slopes are less than 6 percent, the maximum head on the spillway is less than 3 feet and the flow duration is less than 100 hours (Temple, 1993).

B. Phase 2 Erosion Process

Phase 1 of the erosion process is complete once the stresses from the flow have removed vegetation. Phase 2 of the erosion process begins once the flow becomes concentrated. At this point, the underlying earth material no longer has the protection of vegetal cover and therefore, it must withstand all of the stress generated from the flow. If the underlying material is relatively erodible, erosion is accelerated and a headcut tends to form rapidly. If the underlying material is relatively erosion resistant; however, headcut formation may be delayed or prevented.

Phase 2 erosion computations within the model are based on a linear excess shear erosion rate relation with the applied stress computed assuming maximum possible flow concentration. The rate of erosion is a function of the percent clay and dry bulk density for each material (Temple and Hanson, 1994). Actual measurements of bulk density are important for cohesive materials; estimates are usually adequate for rock. Once the headcut has formed, the depth is computed as a function of time through integration of the erosion rate relation. Phase 2 erosion is complete once the headcut has progressed downward until it reaches an erosion resistant material or the elevation of the valley floor, which is a user-defined input. At this point the headcut will be vertical or near vertical (Temple, 1993).

C. Phase 3 Erosion Process

Phase 3 of the erosion process begins once the headcut has formed to a sufficient depth, and the flow tends to plunge downward as it enters the eroded area with hydraulic attack focused near the base. Turbulent stresses combine with gravitational and hydrostatic forces to advance the headcut upstream. As an eroded gully develops, the flow can cause detachment of material from the floor or sides of the gully causing the headcut to deepen or widen as it advances.

The headcut erodibility index (K_h) and representative diameter of the "particle" being detached during erosion have a significant impact on the advancement of the headcut upstream. The headcut erodibility index is a measure of the strength of the material and its resistance to headcut advance. The index is determined quantitatively through

laboratory soil strength tests and field determination of rock material and mass properties. It ranges from 0.01 for sand to greater than 10,000 for massive rock. The representative diameter is used in calculating detachment due to surface hydraulic stresses. For soil materials, it represents the diameter for which 75% of the material is finer, by weight; and for rock materials, it represents the cube root of the volume of the representative "particle."

The three phases described above are the basis for evaluating the formation and advancement of a single headcut through a spillway. *"Because different phases may dominate the erosion process for different conditions, the model is applied iteratively to different erosion scenarios to determine the scenario creating the greatest potential to generate a breach. As the headcut progresses through multiple materials, the advance rate of secondary headcuts following material interfaces is examined in addition to evaluating the advance rate of the headcut that continues deepening. As applied, each scenario is evaluated independently without consideration for other erosion that might be taking place in the spillway"* (USSD, 2003).

It is important to note that the erosion process computed by the SITES model is a simplification of complex physical processes. Whenever possible, the user should base the development of input parameters on field examination of spillway materials. Professional judgement should be used when reviewing model input parameters as well as the output generated by the model. It is important to understand that the SITES model is a quasi two-dimensional estimation of the erosion process that takes place in an earth-cut auxiliary spillway, and many factors can affect the actual performance of the spillway during flow activation including downstream conditions, irregularities in the subsurface strata, debris obstructing the spillway, etc.



Figure 4. Summary Photos of 3 Phase Erosion Process (Photos courtesy of Darrell Temple)

IV. SPILLWAY STABILITY VERSUS SPILLWAY INTEGRITY

The SITES model performs both spillway stability and integrity analyses, and it is important to differentiate between the two. Although both analyses are related to spillway erosion potential, they are different approaches, applied to varying hydrographs, for different purposes. Spillway stability seeks to answer the question: will there be surficial erosion to the vegetal cover in the spillway during the stability design hydrograph (SDH)? Spillway stability criteria seeks to identify spillways that will have maintenance issues for the dam owner. The SITES computer model computes both the exit channel velocities and effective stresses for use in evaluating the spillway exit channel stability. The user should compare the values to the maximum allowable stresses provided in the Agriculture Handbook 667 (AH-667). If the computed stresses from the SITES model exceed the maximum allowable values, stability criteria is not satisfied. The stress limitations are based on the peak discharge in routing the SDH and the assumption that uniform flow conditions exist in the exit channel.

A stability analysis should be evaluated for the 6-hour SDH while an integrity analysis should be evaluated for both the 6-hour FBH and the 24-hour FBH. The SDH is a smaller (more likely) event than the Freeboard Hydrograph (FBH). Spillway integrity criteria seeks to ensure that the spillway will not breach (i.e., headcut will not advance beyond the upstream edge of the level control section), and the dam embankment will not be endangered during passage of the FBH (USDA NRCS, 2005). This portion of the analysis does not incorporate any impacts that the spillway flow may have related to the alignment of the spillway and the downstream toe of the dam embankment.

V. WINDAM CAPABILITIES

In addition to SITES, the ARS, NRCS and Kansas State University have been working jointly to develop and refine Windows Dam Analysis Modules (WinDAM) software. WinDAM A was released in 2008. In this version of the software the user could evaluate slope protection for an embankment overtopping analysis. In 2011, WinDAM B was released which allowed the estimated of erosion of a homogeneous earthen embankment caused by overtopping of the dam embankment. This analysis required detailed geotechnical information of the embankment material including undrained shear strength, critical shear stress, total unit weight and the detachment coefficient. The software also allows the user to input data for up to three auxiliary spillway evaluations conducted simultaneously for either a stability analysis or integrity analysis. WinDAM B uses the same computations to evaluate spillway stability and integrity as those developed for SITES. WinDAM B is a very useful tool in evaluating dams with inadequate spillway capacity which will likely be overtopped during a FBH event, however, Win-DAM B does not create a reservoir inflow hydrograph. Therefore, another program, such as SITES, must be used to develop a hydrograph which can then be imported to Win-DAM B. Win-DAM C was released in 2016. This version possesses all the same capabilities as Win-DAM B as well as the ability to estimate erosion of the earthen embankment caused by internal erosion (Visser, 2013). The WinDAM software versions are very useful resources that can be used in junction with SITES when evaluating spillway integrity. They further exemplify the fact that new research and technology will continue to lead to more tools to allow for a better understanding of how embankment dams and earth-cut auxiliary spillways perform during design events.

VI. LESSONS LEARNED EVALUATING THE INTEGRITY OF AN AUXILIARY SPILLWAY

The first step in evaluating the integrity of an existing auxiliary spillway is to gather all available pertinent information. This may include As-Built drawings, watershed work plans, design reports, geology reports, boring logs, previous inspections, and original construction photos. Some dams may have most of these items available for review while others may have few or none of them. The amount of information available and the scope of work will determine the level of detail of the spillway integrity analysis. Integrity analyses can range from a screening level assessment to a final design detailed analysis. The paragraphs below provide a brief discussion of examples of integrity analyses performed with varying degrees of information available along with some lessons learned and recommendations.

Huff Creek Site 5B Dam provides a good example of performing a limited detail integrity analysis of a spillway with very little information available. Huff Creek Site 5B is an NRCS flood control dam constructed in Greenville County, SC in 1961. Figure 5 shows the only available subsurface information relevant to the auxiliary spillway, profiles from the As-Built drawings. The reviewers developed the auxiliary spillway surface profile for input into SITES from the 'profile along centerline of emergency spillway' shown in Figure 5 and then projected that profile to the inside edge of the spillway based on the plan view of the dam. **It is important to note that the profile entered in SITES should be the most erodible profile within the spillway.** If it is not clear where the most erodible profile is located within the spillway, the user should evaluate multiple profiles to determine which one presents the worst-

case scenario. For most spillways, the most erodible profile is located along inside edge of the auxiliary spillway (edge closest to the dam); however, situations exist where most erodible profile is located on the outside edge of the auxiliary spillway or somewhere in the middle. The geologic profile along the inside edge of the spillway generally has the most weathered and weakest material, due to its relative location and depth to the original ground surface, and experiences the greatest erosion. In extreme cases, like the one shown in Figure 6, the terrain at the dam abutment was so steep that the designer(s) elected to construct the spillway with no natural bulk between the dam embankment and the spillway. In this case, the geologic profile along inside edge of the spillway consists of highly erodible fill material.

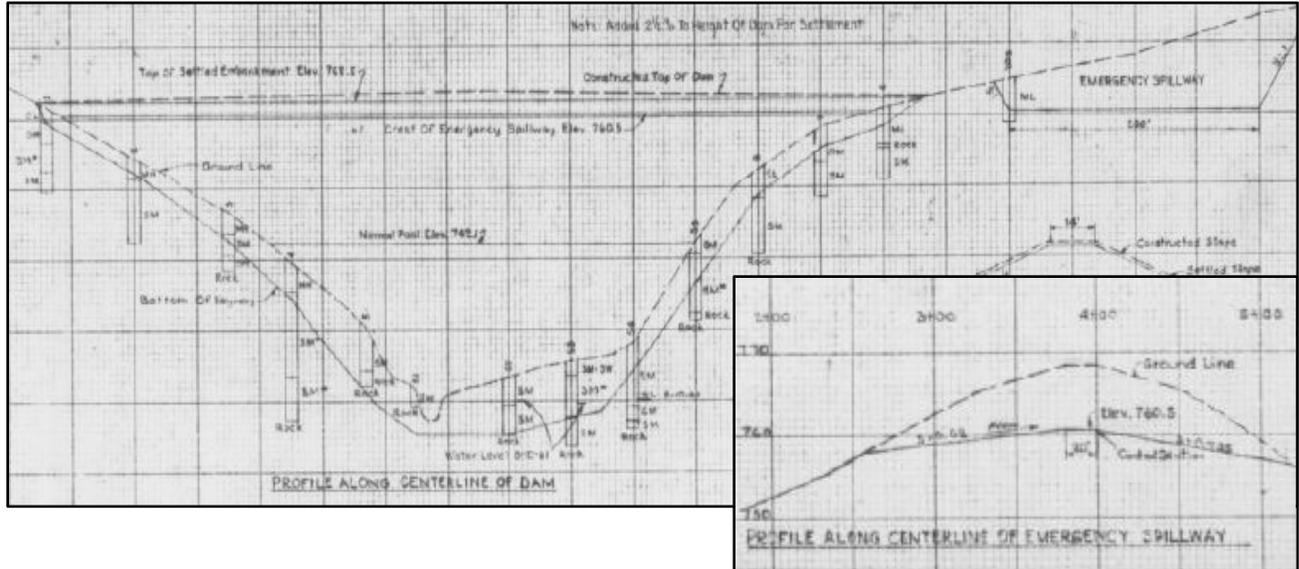


Figure 5. As-Built Drawing Profiles of Huff Creek Site 5B (As Built Drawings courtesy of NRCS)

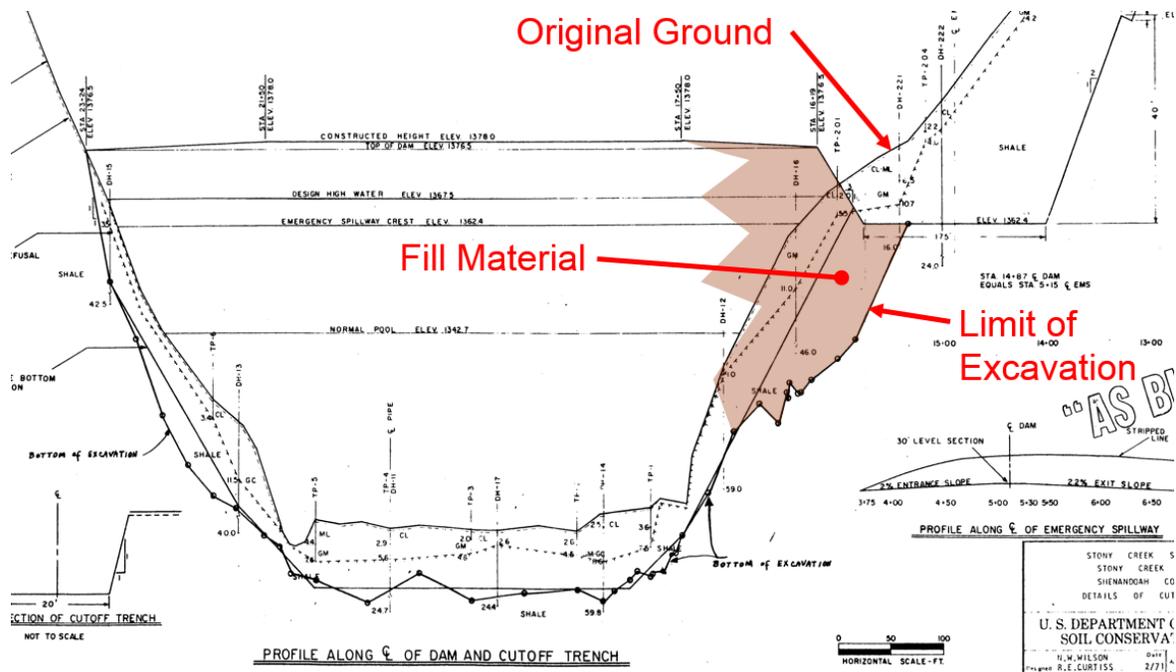


Figure 6. Example of an Auxiliary Spillway Constructed on Dam Embankment Fill (As Built Drawings courtesy of NRCS)

The surface conditions such as the vegetal retardance curve index, vegetal cover factor, maintenance code and potential root depth can be approximated based on observed conditions at the time of the site inspection. The subsurface materials and their properties can be estimated based on the profile along the centerline of the dam in Figure 5. It can be difficult to develop a subsurface profile when there is only one boring located within the auxiliary spillway and its depth only goes a few feet below finished grade. For this particular site, the strata within the borings along the dam embankment were traced and projected to the profile along the inside edge of the auxiliary spillway. The material properties can be estimated using judgement based on soil and rock classifications. One resource that can be helpful when limited data is available is to research geological maps to obtain information on typical rock formations in the area of the dam site. The SITES model for the Huff Creek Site 5B spillway showed that the spillway would breach during passage of the 24-hour FBH. In most cases the 24-hour duration hydrograph is the event which shows the most erosion to the spillway because of the longer duration and volume of flow through the spillway, however there are instances where the more intense 6-hour duration hydrograph is the governing case. For this reason, the model users need to evaluate both events for an integrity analysis.

Although SITES provides a physically based means of estimating the performance of earth-cut auxiliary spillways, considerable judgment is often required to select the input parameters, especially when little information is available. Therefore, the authors recommend that the user performs a sensitivity analysis by developing hypothetical material properties representing the most erodible and least erodible conditions possible and evaluating the spillway integrity through trial and error within this range of material properties to see if the outcome changes and at what point it changes. Individual parameters can also be varied to determine their significance and influence on the results.

Brush Creek Site 9 Dam is a flood control and water supply dam located in Mercer County, WV constructed in 1964. Dam rehabilitation planners performed a detailed spillway integrity analysis of the dam in 2016 which included a topographic survey of the site, subsurface drilling in the spillway and dam embankment, and a detailed analysis of the auxiliary spillway. The topographic survey provided accurate surface elevations along the profile within the auxiliary spillway and outlet. The subsurface exploration included two bore-holes along the inside edge of the spillway. The planners prepared detailed boring logs and performed field tests during drilling. The investigation team performed field tests to classify the exhumed soil and rock. Laboratory testing of soil and rock samples was also performed.

The planning team evaluated the data gathered during the subsurface exploration and laboratory testing program to define the different strata within the spillway and determine the material properties. When more detailed information is available, the integrity analysis can be much more refined; however, judgement is still required to develop the SITES input parameters and interpret the results. The first step in this process for Brush Creek Site 9 was determining the strata breaks. In this case, the drilling inspector performed this step in the field and recorded the information in the boring logs. Significant change in plasticity, blow counts, or percentage of fines can indicate a soil material break. Changes in Rock Quality Designation (RQD) percentage can indicate a break in strata with the bedrock. RQD is a rough measure of the degree of jointing or fracture in a rock mass, measured as a percentage of the drill core in lengths of 10 cm or more. High-quality rock has an RQD of more than 75%, low quality of less than 50%.

The planners created a full profile of the spillway once the strata breaks were established in both of the bore-holes in the spillway of Brush Creek Site 9. This process also involved review of the original design files and As-Built drawings to extrapolate beyond the limits of the two bore-holes. The material properties were calculated based on the laboratory testing results of soil and rock samples. The soil sample testing included particle size, dry unit weight, and plasticity index. The rock core testing included unconfined compressive strength and slake durability which measures weathering resistance. The values obtained from the lab testing were used to calculate K_h values for each material. The calculated values were then compared to the K_h photo reference within SITES. The photo reference provides additional guidance in identifying common ranges in index values for similar materials and an empirical means of back checking the calculated values. Figure 7 shows the SITES output profile for Brush Creek Site 9 including the material properties. The integrity analysis of Brush Creek Site 9 showed erosion of the downstream end of the auxiliary spillway but no breaching of the spillway crest during passage of the 24-hour FBH.

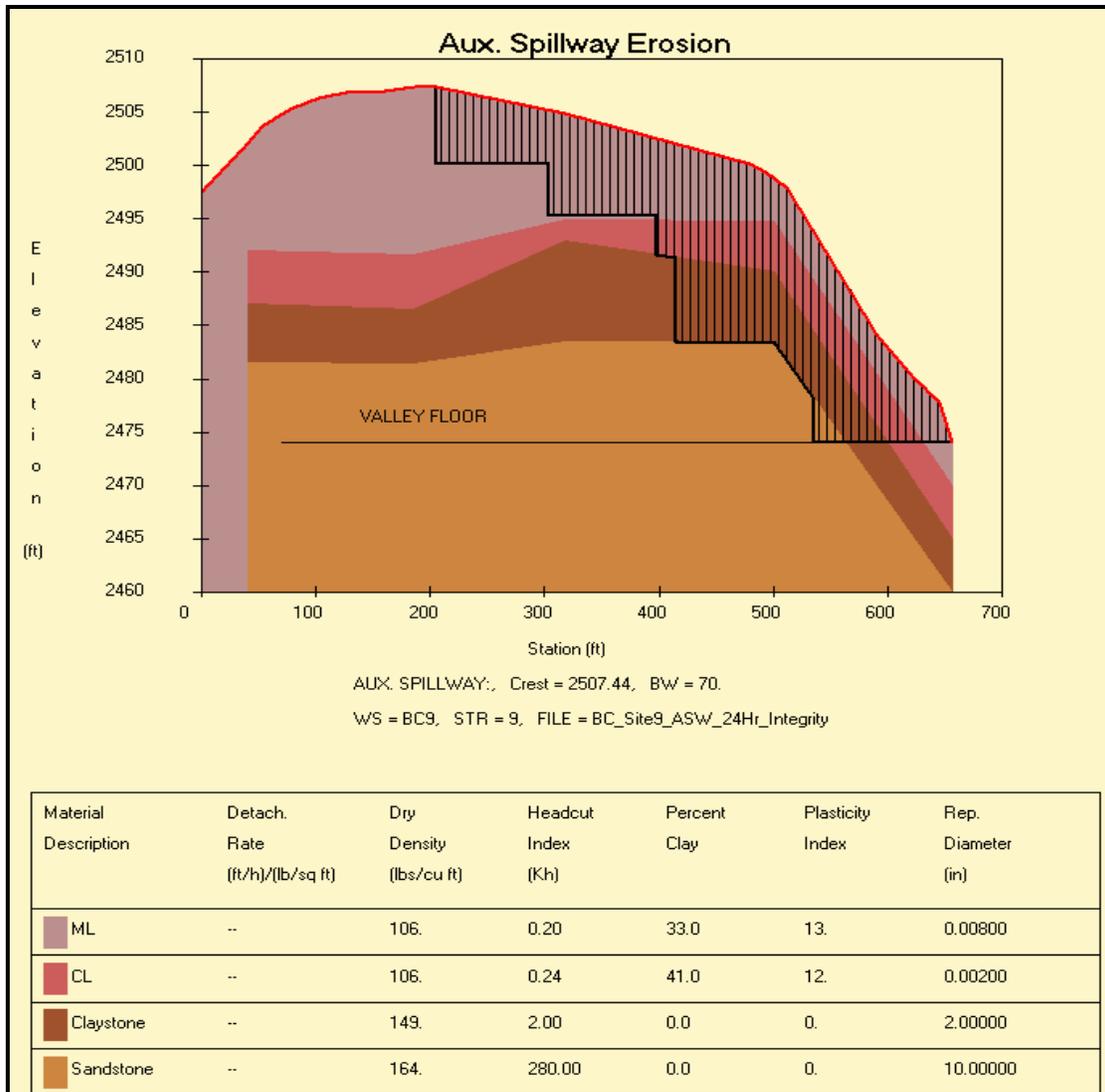


Figure 7. Plot of Auxiliary Spillway Profile and Extent of Erosion from Integrity Analysis for 24-hour Class C Freeboard Hydrograph (PMF) Obtained from SITES Model Output

VII. MISTAKES TO AVOID IN AUXILIARY SPILLWAY INTEGRITY ANALYSES

When inspecting, evaluating or designing an earth-cut auxiliary spillway, there are many factors to keep in mind that can have a major impact on spillway integrity evaluation results. A few common mistakes to look for include poor maintenance conditions, non-uniform vegetative cover; not extending the straight section of the spillway exit channel beyond the toe of the dam; failing to account for what takes place downstream of the constructed auxiliary spillway; and modifications made to the spillway after construction. The importance of a uniform vegetative cover cannot be overstated. Non-uniformities within the spillway can lead to rapid Phase 1 failure. These non-uniformities can include sparse vegetation, tire ruts, fences, signs, roads and road drainage ditches, trails, rodent borrows, etc. Figure 8 shows an example of how a fence can initiate the headcut process. Note the uniform cover and uniform flow on the downstream slope prior to flow reaching the fence. The photo in Figure 8 depicts a dam overtopping event; however, the same principal applies to an auxiliary spillway.



Figure 8. Effect of Non-Uniformities (Photo courtesy of Gregg Huddock, Golder Associates)

It is essential that designers orient auxiliary spillways in a manner that does not direct flows towards the dam embankment. In most cases this can be avoided if the exit channel is straight, perpendicular to the level control section, extends beyond the toe of the dam, and has an unobstructed outlet. Obstructions should be avoided that could direct flow back towards the dam embankment. Designers should evaluate spillways down to the valley floor elevation. The valley floor is defined as the elevation below which the spillway will not erode because of downstream control. Headcutting can develop downstream of the constructed portion of the auxiliary spillway exit channel and progress upstream into the spillway crest, resulting in a breach. Figure 9 shows an example of a well-maintained auxiliary spillway with a sharp drop in grade and an access road beyond the constructed portion of the spillway. Figure 10 shows a similar spillway flowing. Note how flow is plunging downward and initiating the formation of a headcut whereas the flow within the constructed section above the drop is smooth and uniform.



Figure 9. Well maintained auxiliary spillway with steep drop (road cut) beyond constructed section



Figure 10. Headcut initiation at the outlet of the constructed portion of the auxiliary spillway

Sometimes an auxiliary spillway is modified from its original design; this modification can adversely impact its performance. Figure 11 illustrates an example of a spillway modification by a local farmer who placed fill within the level control section of the spillway to construct an access ramp to transport his farm equipment over the dam. By flattening the spillway bank slope at the crest and adding fill material within the spillway cross section, the farmer reduced the spillway discharge capacity and created a non-uniform flow condition.



Figure 11. Ramp to Top of Dam across Auxiliary Spillway Control Section

Deviations from the established spillway layout guidelines often include: (1) not extending the exit channel of the auxiliary spillway far enough downstream from the dam to preclude damage to the dam, (2) locating a portion of the auxiliary spillway directly on embankment fill (see Figure 6), (3) allowing unpaved roads and drainage ditches through the spillway parallel to the flow, (4) incorporating abrupt changes and very steep slopes in exit channel and outlet, and (5) including obstructions and irregularities within the spillways. Figure 12 shows examples of some of the aforementioned deviations.

When designing the downstream exit channel and negotiating related landrights/flowage easements, 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 constructed many years after the dam, obstruct and redirect the flow towards the dam. Sugar Creek Dam L-44 in Oklahoma, shown in Figure 13, is an example of an auxiliary spillway exit channel condition that nearly breached the dam embankment. In this case the higher ground beyond the constructed portion of the exit channel directed the flow back towards the dam embankment causing erosion of the downstream slope.



Figure 12. Photos Showing Typical Examples of Observed Deviations From Recommended Auxiliary Spillway Practice; (a) Dirt Road Parallel to Flow, (b) Sparse Grass Cover Due to Livestock, (c) Fence Across Spillway, (d) Spillway Exit Channel Along Toe of Dam, (e) Road Across Spillway and Obstructions In Spillway, (f) Utility Pole In Spillway.



Figure 13. 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.

VIII. SUMMARY

Although NRCS designed most of the earth-cut auxiliary spillways without analytical tools to evaluate the integrity, new research and technology is now available to enable re-evaluating these spillways. The NRCS helped develop programs such as SITES and WinDAM B and pioneered their use to help determine the integrity of these spillways to ensure that they meet current design criteria and can safely pass flows when activated. SITES possesses the ability to route hydrographs through a dam site and calculate the erosion within the auxiliary spillway based on the spillway's surficial and subsurface properties. WinDAM B can estimate erosion of a homogeneous earthen embankment caused by overtopping of the dam embankment. It is important to note that the new programs have limitations when considering spillways with non-uniform conditions or features within the spillway that can accelerate erosion. When analyzing the integrity of auxiliary spillways, it is essential to apply proper engineering judgement in reviewing all information available, selecting input parameters and evaluating model outputs. By using the SITES program with sound engineering judgment, the potential for a breach developing within an earth-cut auxiliary spillway can be identified. By following good NRCS earth-cut auxiliary spillway design practices, breaching of the spillway can be avoided.

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