DOMINANT FACTORS IN VEGETATED EARTH SPILLWAY FAILURES [1]

by
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ABSTRACT

Performance characteristics of four flood control reservoir vegetated earth auxiliary spillways are examined. The spillways are selected to represent worst case conditions from a field study of spillway performance. Three of the spillways selected for discussion experienced flows resulting in erosion sufficient to breach the spillway crest, although only one breach was sufficient to completely drain the reservoir. Erosion in the fourth selected spillway stopped at the upstream end of the spillway crest. Each of the spillways had one or more identifiable factors that accentuated erosion during operation. These factors included highly erodible material in the soil profile, steep and/or nonuniform outlet conditions, and flow concentrating discontinuities in the exit channel. The contribution of each of these factors to the spillway failure process is discussed for the selected spillways and related to the more general problem of spillway design and maintenance.

INTRODUCTION

Earth and vegetated earth auxiliary spillways have been used extensively on flood control reservoirs over the past 30 years. These spillways are usually designed as wide trapezoidal channels having a subcritical inlet reach, a level crest or control section, and one or more supercritical outlet reaches. Outlet conditions are variable. 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 (SCS, 1985a).

Although these spillways have generally performed satisfactorily, increased development downstream of flood control structures and an increased emphasis on dam safety in recent years has led to an increased interest in the dominant processes and variables governing performance of these spillways. In 1983, the USDA, Soil Conservation Service (SCS) established a team to monitor field performance of this type of spillway. The USDA, Agricultural Research Service (ARS) has worked cooperatively with this team as well as studying associated failure processes in the laboratory. From the time of its formation to May of 1989, there were in excess of 800 spillway flows reported to the study team. Of these, 116 either experienced heads in excess of three feet or were judged to have major damage. Only 4 of these spillways were breached sufficiently to lower the crest control, and only one spillway breached to the point of completely draining the reservoir. A similarly small number experienced sufficient erosion in or near the crest to be considered in danger of breaching should subsequent flows occur prior to repair.

A subset of 88 of the spillways which experienced large flows or major damage were selected for further documentation. Reports on the performance of these spillways either have been, or are being, prepared (SCS, 1984, 1985b, 1986, 1987, 1988). Additional general discussions of the performance characteristics of these structures are presented by Ralston and Brevard (1988) and by Temple (1987). The following discussion focuses on an even smaller subset of the data through selection of four spillways representing extreme cases of "typical" problems resulting in failure or near failure. Although examination of these spillways serves to enhance our understanding of the failure process and identify conditions which should be avoided, it should be recognized that failures of properly designed vegetated earth auxiliary spillways are an unusual phenomena.

SPILLWAY PERFORMANCE

Each of the spillways selected for discussion experienced major damage or breach during an extreme

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flood event. Each of the spillways also exhibited conditions which tended to accentuate the flow attack and increase the damage. The discussion which follows provides an abbreviated description of the attack and the way in which these conditions contributed to spillway failure.

Black Creek Site 53

The most complete vegetated earth auxiliary spillway failure observed during the course of this study was that of Black Creek Site 53 in Mississippi which failed in May of 1983. Details of this failure have been previously described in a spillway performance report (SCS, 1986) and in reports by Merkle (1985), Ulmer (1985), and Temple (1989). The breach was unique in that observations during the flood allowed a more complete reconstruction of breach conditions than would normally be possible.

The reservoir inflow hydrograph shown in Fig. 1 was generated by a 9 inch rainfall over a 19 square mile watershed which had experienced a 5 inch rainfall earlier in the week. The outflow hydrograph shown in Fig. 1 includes the spillway breach flow and was generated by the analysis given by Temple (1989). Maximum elevation of the water surface above the original spillway crest was computed to be 5.1 ft. The time from beginning of spillway flow to complete spillway breach was approximately 60 hours.

The constructed spillway channel was 100 ft wide with side slopes of 3:1. It consisted of an inlet reach of approximately 140 ft on a 2 percent adverse slope, a level crest section 20 ft in length, and an exit reach of approximately 160 ft on a 2.7 percent slope. The three constructed reaches were apparently well vegetated at the time of the flow.

The constructed portion of the auxiliary spillway exited into a draw forming a natural channel to carry the flow to the valley below the dam (Fig. 2). A roadway constructed along the spillway side of the draw crossed the constructed spillway at the outlet forming a near vertical drop of approximately 6 ft onto the roadway and another drop of approximately 8 ft to the floor of the draw.

The site geology was somewhat unusual. The spillway was constructed through a loess material. Approximately 6 feet below the surface of the constructed spillway was a lense of noncohesive sand and gravel on the order of 1 to 3 feet thick. Below this sand-gravel lense was another 10 to 12 ft of loess underlain by another layer of highly erodible noncohesive material. Near the valley floor elevation was an erosion resistant shale.

When subjected to the attack indicated by the auxiliary spillway hydrograph shown in Fig. 1, the spillway breached to the valley floor as shown in Fig. 2. The final breach was approximately 40 ft deep and 160 ft wide at the narrowest point. The mode of breach was apparently the upstream movement of two vertical overfalls based in the highly erodible noncohesive materials (Temple, 1989). The roadway at the spillway exit initially concentrated the flow attack at points where the erodible material had minimum cover at the roadway cut and the floor of the draw. Once exposed, the noncohesive material was easily removed, undercutting the loess and allowing it to break off and be washed away as large blocks.

Misteguay Site 4

The vegetated earth auxiliary spillway for Misteguay Site 4 in Michigan experienced similar, but less severe, problems in September of 1985. Details of the flood and spillway performance are described in the spillway performance report (SCS, 1987). The inflow and spillway hydrographs shown in Fig. 3 are those developed during preparation of that report.

The flood described by Fig. 3 was a result of up to 9 inches of rainfall in approximately 9 hours. Analysis required routing of the flood through two upstream flood control reservoirs in addition to Site 4 (SCS, 1987). Maximum reservoir water surface elevation was approximately 3.8 feet above the spillway crest, and the spillway flowed for about 38 hours.

The constructed spillway consisted of 4 reaches. The curved inlet reach of variable length and slight adverse slope formed a depressed forebay ending in a 30 ft reach having an adverse 20 percent slope. A 20 ft long level crest reach and a 4.05 percent exit channel reach were separated into 6 bays by dikes 2 ft high having 3:1 side slopes. The 50 ft wide bays varied in length with the bay nearest the dam (referred to as bay 1 in the following discussion) being the shortest with an exit channel length of approximately 250 ft. The 2 bays farthest from the dam had exit channel lengths of approximately 500 ft each.

The differing exit channel lengths were a result of excavating to the intersection of the constructed spillway with natural ground in the vicinity of the downstream channel. This also resulted in bay 1 exiting at a higher elevation and onto a steeper slope than the other bays. The natural ground at the end of bay 1 had a slope of approximately 16 percent for a distance of about 20 to 30 ft downstream of the end of the excavated channel.

The spillway was excavated in a dense glacial till underlain by an erosion resistant clay at or below valley floor elevation. There was a lense of fine sand 0.5 to 2 ft thick approximately 1.5 ft below the surface in bay 1. This lense tapered to zero thickness in the other bays. All bays apparently had a good vegetal cover well rooted in a silty top soil at the time of the flow.

Damage done by the flow indicated in Fig. 3 was essentially limited to bays 1 and 2 as shown in Fig. 4, although surface damage in the form of developing "pot holes" in the other bays indicated that the vegetal cover had been stressed to the point of incipient failure. The damage to bays 1 and 2 was apparently initiated on the 16 percent outlet slope below the exit channel with erosion exposing the highly erodible sand lense underlying the topsoil in bay 1. An overfall 2 to 3 ft high followed the sand lense to the upstream end of the level crest section. Movement of this overfall stopped with termination of the sand lense (just out of the Fig. 4 photo to the left). A second overfall (Fig. 4) progressed upstream approximately 90 ft from the outlet and had a height of about 14 ft at flow termination. This overfall eroded the glacial till material with overfall height controlled by the elevation of the valley floor. Erosion associated with this second overfall removed the dike between bays 1 and 2 downstream of the overfall as shown in Fig. 4. The final position of this overfall in bay 2 was only slightly downstream of its position in bay 1. Because the sand lense was not present, or at least not continuous, in bay 2, the shallow overfall was also not present at flow termination. The extent to which the sand lense may have been present near the outlet of bay 2 and thereby contributed to dike removal and failure initiation in the bay is unclear.

Buck and Doe Run Site 33

Another of the spillway failures observed was Buck and Doe Run Site 33 in Missouri which flowed in September of 1986. This reservoir was substantially smaller than those described above and was constructed primarily as a debris basin. The spillway performance report for this site is presently in process, and information on the flood and the spillway are provided by Curry and Edwards (1987). The reservoir inflow and spillway hydrographs presented in Fig. 5 are those prepared by SCS for inclusion the spillway performance report.

The flows indicated in Fig. 5 were the result of approximately 12 inches of rain over a 173 acre watershed in about a 12 hour period. The maximum reservoir water surface elevation as a result of these flows was approximately 1.5 ft above the original auxiliary spillway crest. The auxiliary spillway hydrograph shown in Fig. 5 includes breach outflow and was generated using the National Weather Service dam break model. Although it is recognized that this model is not entirely consistent with the overfall mode of failure observed in spillways, there were insufficient observations and data available for this site to justify more detailed analysis.

The constructed auxiliary spillway was straight and consisted of a single level reach approximately 90 ft in length. The spillway was trapezoidal in cross-section with a 20 ft bottom width and 3:1 side slopes. The constructed channel was apparently well vegetated at the time of flow.

The natural ground in the reservoir at the entrance to the auxiliary spillway was covered with a good stand of grass on an adverse slope of approximately 12 percent. The excavated spillway exited to a natural hill slope on the order of 30 percent about 20 ft above the valley floor. The natural slope was wooded with a cover sufficiently dense to prevent any undergrowth of grass. Vegetal erosion protection on this slope was, therefore, minimal for the type of flow experienced.

The hill in which the auxiliary spillway was excavated consisted of a deep deposit of sandy clay and sandy silt material with very little erosion resistance. There appeared to be little variation in materials from the elevation of the spillway crest to the valley floor. The susceptibility of this material to erosion had been previously recognized and the design modified to reduce flow frequency (Curry and Edwards, 1987).

Exposure of the spillway to the flow shown in Fig. 5 resulted in the damage shown in Fig. 6. Because there were no observations of conditions during the breach, reconstruction of the failure is somewhat speculative. It appears, however, that the erosion began on the hill slope near the exit of the constructed channel and progressed upstream through the crest into the reservoir. It is believed that the original breach was to the level of the bench appearing in the left center of Fig. 6, and that the deeper meandering erosion channel to the right was a result of the recession limb of the hydrograph and subsequent low flows. In any case, the elevation of the auxiliary spillway control section in the reservoir following the breach was only slightly above the elevation of the principal spillway and about 10 ft below the original auxiliary spillway crest.

Twin Caney Site 17-3

The auxiliary spillway on Twin Caney site 17-3 in Kansas which flowed in October of 1986 was counted as a breach in the numbers previously presented. Information on the area geology and on the 1986 storm is presented by Smith (1987). The spillway performance report which will include this site is currently in process. The reservoir inflow and auxiliary spillway hydrographs presented in Fig. 7 are those constructed by SCS in preparation of that report.

The flows indicated in Fig. 7 were the result of approximately 23 inches of rain on the 2.7 square mile watershed during a 5 day period (Smith, 1987). The SCS DAMS2 flood routing suggested 2 periods of auxiliary spillway flow during this time with a cumulative duration of 51 hours. Maximum reservoir water surface elevation, based on a survey of reservoir high water marks following the flood, was 4.2 ft above the crest of the auxiliary spillway.

The constructed auxiliary spillway was a trapezoidal channel 40 ft wide with 3:1 side slopes. It consisted of 4 reaches with a smooth transition to the valley floor. The approach reach was approximately 50 ft long on center with an adverse slope of 1 percent. The level crest section was curved with a radius of 65 ft and length of 100 ft at the center line. The first exit channel reach was 90 ft long on a slope of 10 percent. This was followed by a 2.7 percent slope reach approximately 100 ft long blending into existing ground at the valley floor. All 4 constructed reaches were well vegetated at the time of the flood. However, the spillway was being used as an access road for the reservoir, and well defined tire tracks with little or no vegetation were present in all reaches.

The natural ground in which the spillway was excavated was a deep deposit of low plasticity clay. The exit channel reaches had some areas of fill up to approximately 5 ft of depth. Performance of the spillway and examination following the flood suggested that the fill material was of the same general nature and comparative in erodibility to the undisturbed material.

Exposure of the spillway to the auxiliary spillway hydrograph shown in Fig. 7 resulted in the damage shown in Fig. 8. Although the spillway was technically breached through degradation of the level crest in the area of the roadway, the elevation controlling spillway discharge was changed only slightly. Since there were no observations during the flow, reconstruction of the failure is again somewhat speculative. It seems likely, however, that flow and stress concentrated in the 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 in the level crest and on the 2.7 percent downstream slope. Vegetated areas outside of the area of the roadway were undamaged.

SUMMARY DISCUSSION

The spillways briefly described in the previous paragraphs were selected as a "worst case" subset of those observed to have experienced major flows or damage during the past 6 years. Although these spillways differ significantly in capacity, geometry, and geology, they also have some common characteristics. They were, obviously, all constructed in materials capable of being eroded at the applied stress levels. Three of the four contained materials which would be classed as highly erodible. In the case of the first two spillways described, however, the highly erodible material was neither the surface material nor the material present in greatest volume. These highly erodible materials were still able to dominate the failure or damage process once exposed to attack.

The second common characteristic exhibited by these "worst case" spillways was a surface condition capable of concentrating energy dissipation at the erodible boundary. In the case of 3 of the sites, the energy concentrating discontinuity was associated with the outlet conditions. At the Black Creek site, the energy concentration associated with the steep outlet slope was further aggravated by the roadway cut and fill banks forming drops at the spillway exit. In the case of the Buck and Doe Run site, it was the nature of the vegetal cover coupled with the steep outlet slope that allowed increased attack on the erodible material. In the case of the Twin Caney site, the spillway was formed and vegetated to the valley floor, but the flow resistance discontinuity formed by the tire tracks was sufficient to concentrate stress and energy at the erodible boundary and negate the benefit of the grass cover.

CONCLUSIONS

The earth and vegetated earth auxiliary spillways which have experienced flow over the past 6 years have generally functioned satisfactorily. Those spillways which have exhibited the most severe problems have had energy concentrating discontinuities and/or highly erodible materials in the profile. Construction of spillways such that the energy is dissipated uniformly over the maximum boundary area available and optimizing use of protective vegetal cover has the potential of decreasing failure risk and reducing post flow maintenance costs.

As might be expected, the greatest problems involve highly erodible sandy materials. If these materials are present in the profile, provision must be made to protect them from direct attack by the flow during the passage of the hydrograph. The experiences described suggest that failure may be relatively rapid once the energy dissipation becomes concentrated in these materials.

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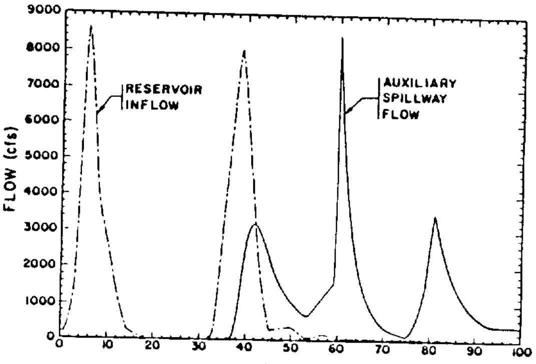

Figure 1. Reservoir inflow and auxiliary spillway hydrographs for Black Creek Site 53, May 1983 flood.

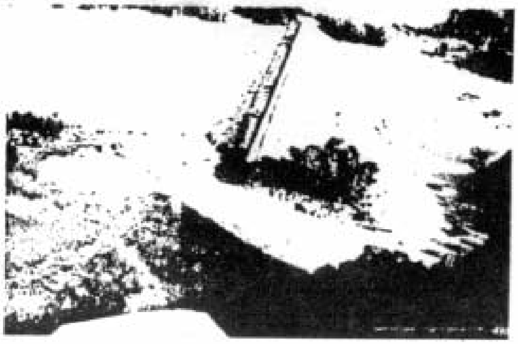

Figure 2. Black Creek Site 53 following Breach of the auxiliary spillway.

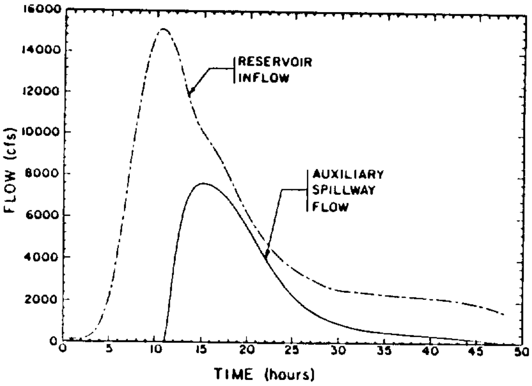

Figure 3. Reservoir inflow and auxiliary spillway hydrographs for Misteguay Site 4, September 1985 flood.

Figure 4. Damage to Misteguay Site 4 auxiliary spillway in bays nearest the dam.

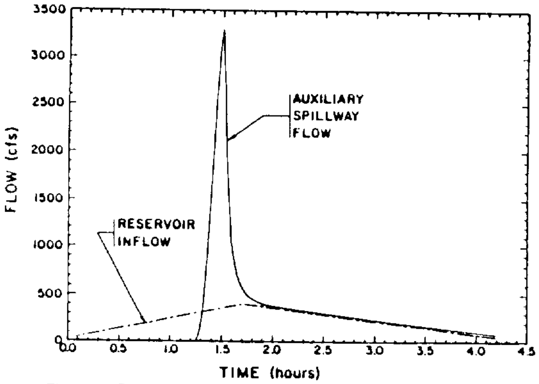

Figure 5. Reservoir inflow and auxiliary spillway hydrographs for Buck and Doe Run Site 33, September 1986 flood.

Figure 6. Buck and Doe Run Site 33 following breach of auxiliary spillway (viewed looking upstream).

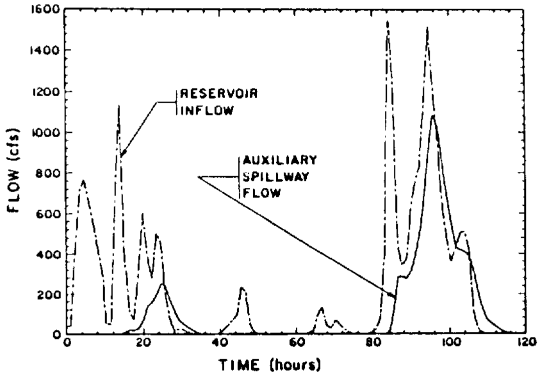

Figure 7. Reservoir inflow and auxiliary spillway hydrographs for Middle Caney Site 17-3, October 1986 flood.

Figure 8. Middle Caney Site 17-3 following breach of auxiliary spillway.