Rapid Drawdown at Embankment Dams, Is it a **REAL** Concern?

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I. INTRODUCTION

The potential for upstream slope failure due to rapid drawdown occurs in embankments constructed of cohesive soils in which excess pore water pressures dissipate at a slower rate than the drop in the reservoir level. These excess pore pressures can lead to reduced shear strength of the embankment soils and slope failure. A rule of thumb for a safe drawdown rate of a reservoir supported by an earth embankment dam is one foot per day. What is the source of this “rule”? Is this “rule” appropriate for all earth embankments? How should total drawdown of a reservoir be completed when analysis indicates the “rule” of one foot per day results in safety factors less than 1.0? What should be the definition of rapid drawdown? How should this scenario be modeled in design and analysis? In an emergency or state of distress, what should the practice and standard of care exercised be when lowering the pool in order to reduce the risk of dam failure?

This paper and accompanying presentation will explore these questions, evaluate the current models for rapid drawdown, and suggest opportunities for improvement and consideration by the profession. The paper will also address the aforementioned questions through a case study of the upstream slope safety evaluation and rehabilitation at the NRCS New Creek Site 14 Dam located south of Keyser, WV. Details of the rapid drawdown analysis performed for this dam in accordance with NRCS and Army Corps of Engineers (USACE) procedures will be discussed. The case study discussion will include the procedure developed for a controlled drawdown which was established to reduce the risk of upstream slope failure during reservoir draining.

Design manuals provide guidance and may even prescribe methods to evaluate the effect of changes in reservoir level on the stability of the upstream slope of the embankment. Regulations written by state dam safety officials require a minimum safety factor against the “sudden drawdown” scenario. These same regulations rarely provide a definition of “rapid drawdown.”

A. REGULATIONS

Regulations available for review do not reference “upstream slope failure” of a dam as a result of rapid drawdown. Several do make mention and discuss the situation of reservoir drawdown. The authors searched these regulations regarding safe and/or rapid drawdown. We found the following examples of regulations which discuss this issue:

- Indiana’s Dam Safety Inspection Manual also implies that up to “1 foot per day” is safe and states:
  - “A general rule of thumb for safety is that pool level drawdown rates should not exceed 1 foot per day, except during emergency situations. Relatively flat slopes or slopes with free draining upstream zones can withstand more rapid drawdown rates. Rapid drawdown of the pool may leave the upstream slope saturated and without support, and could result in sloughs and slides. If there is any question about the allowable drawdown rate, a qualified dam safety professional should be contacted.”

- New Jersey Dam Safety Standards, NJAC 7:20-1.9.(i) requires dams to safely lower reservoir five feet in 10 days at a:
  - “rate not to exceed one foot per day. This requirement shall not apply to dams whose intended purpose and whose design allows faster drawdown times.”

- Pennsylvania Division of Dam Safety, specifically PA Code 025 S105.96, implies that up to “1 foot per day” drawdown provides an adequate safety margin against upstream slope failure. It states:
  - “Under normal conditions, the maximum rate of drawdown for reservoirs impounded by earthfill dams should not exceed 1 foot per day without prior approval by the Department. Under emergency conditions, the maximum rate of partial or complete drawdown of reservoirs must be approved by the Department, when feasible.”

- South Carolina Dams and Reservoirs Safety Act Regulations 72-3.D.2.a.6 implies that 6-inches per day drawdown is safe. It states:
o “Any slope subject to drawdown that exceeds 6 inches per day shall be designed to remain stable under the maximum anticipated drawdown conditions.”

B. DESIGN GUIDANCE

Searching through reference materials yielded the following regarding safe and/or rapid reservoir drawdown. From “Earth and Earth-Rock Dams” by Sherard Et al. (1963), we find: “A study of upstream slides in 12 dams indicates that the majority were caused by a drawdown approximately between maximum water surface and mid-height of the dam at average rates varying between 0.3 and 0.5 ft./day.” These rates, being slower than the rule of thumb value of one foot per day and resulting in upstream slope failure, indicate that the one foot per day “rule” is not as conservative as one may think and may result in upstream slope instability.

The Bureau of Reclamation’s “Design of Small Dams” has discussion of drawdown conditions on pages 242 and 243 of the 1987 edition. Tables 6.5 and 6.6 provide recommended slopes for small dams subject to rapid drawdown and defines rapid drawdown as “6 inches or more per day after prolonged storage at high reservoir levels”. From this reference one could assume that pool-lowering rates slower than 6-inches per day provide safety against upstream slope instability.

What is the risk of a failure of the upstream slope due to a rapidly lowering of the reservoir pool? In 1963 it was Sherard Et al.’s opinion (Earth and Earth-Rock Dams) that: “Upstream slides have not caused complete failure or loss of water from the reservoir, although they have occasionally blocked the entrances to outlet conduits and made these useless for further lowering of the reservoir, sometimes creating a very awkward and dangerous situation.” In addition, “Most drawdown slides have developed when the reservoir was lowered for the first time, though a few have occurred after many years of successful operation. In some of the latter, the delay may have been due to a decrease in the shear strength of the clay embankment or foundation with time. In every case studied by the authors, however, the slide was caused by a drawdown which was either faster or over a greater range than had occurred previously.”

In actuality, determination of the rate of drawdown that would prevent upstream slope instability is dependent on permeability and geometry of the embankment zoning. USACE 1970’s method recommended a two-stage analysis. First stage is the analysis of pre-drawdown conditions to determine pressures. Second stage includes utilization of the consolidated normal stress at the base of each slice of the failure surface and the bi-linear strength envelope to calculate the safety factor. In 1992, Duncan, Wright and Wong (DWW) provided the most recent method by which to model the rapid drawdown scenario. DWW recommend determining which soils will be drained and which will be undrained during the drawdown event. Second step is to estimate strength envelopes for each strata, accounting for anisotropy of the undrained materials. Third step includes a three-stage transient analysis where soil strengths prior to drawdown are compared with conditions after drawdown, strengths are reduced to drained strengths for all slices where drained strength is less than undrained strength. The three stage analysis is easily modeled in several commercially available slope stability software packages. DWW also puts forth that rapid drawdown is not a critical case if the embankment’s undrained strength is greater than the drained strength.

C. CASE STUDY

New Creek Site 14 (NC14) is a multiple purpose dam, flood control and water supply, located on Linton Creek in Grant County, West Virginia. NC14 is part of the New Creek Sub-watershed of the Potomac River Watershed Project (PL534) providing flood control to downstream areas and water supply to the City of Keyser.

The Soil Conservation Service (SCS, now Natural Resources Conservation Service or NRCS) designed NC14 in 1962 as a high hazard classification dam (Class C) in accordance with the design criteria established in SCS Engineering Memorandum EM-27. It remains a high hazard classification dam in accordance with NRCS National Engineering Manual and WV DEP Dam Safety Rule. Original construction started and was completed in 1963.

The project consisted of a zoned earth fill dam approximately 93 feet high, containing 670,000 cubic yards of fill. The fill material was obtained from nearby borrow areas, with a majority of it coming from the areas inundated by the permanent water supply pool and adjacent to the pool. The dam was designed to have a compacted core section of low permeable materials that extended from a positive cutoff with the underlying rock foundation to the height of the control section of the auxiliary spillway (ASW). Specifications required removal of cobbly material that was too large to compact well and disposal in a berm along the downstream toe of the dam. The auxiliary spillway was cut into the left hillside adjacent to the embankment.
Figure 1: New Creek Site 14 Dam As-Built Zoning

Based on the as-built drawings, the upstream portion of the embankment included two major zones, Zones II and III. See Figure 1. The two zones were constructed using materials from several borrow areas. The lower zone, Zone III, of the upstream embankment was constructed of material described as a SC material and was intended as a backup core material according to the design documentation. The zone above Zone III was Zone II and was constructed of materials from several borrow areas. The materials from these borrow areas range from GC-GP, CL, flood plain materials with boulders and cobble sandstone, CL and GC, and material from the ASW excavation, respectively. It was the intent of the designers to utilize flood plain material with boulders and cobble sandstone (GP-GC), for the shell zones. Zone IIA, consisting of sandstone boulders, was a thin facing layer placed on top of Zone II.

NRCS finalized the Final Supplemental Watershed Plan-Environmental Assessment for the Rehabilitation of New Creek Site 14 in 2008. During the planning process NRCS focused on perceived deficiencies including dam proportioning (top of dam elevation and width of auxiliary spillway to pass the PMP without overtopping), installation of a new intake riser, PSW Conduit lining, installation of an impact basin, installation of embankment drainage system, and restoring the fishery that would be eliminated during construction. A historic seepage zone existed on the downstream face of the embankment near the transition from Zone III to Zone III-A.

In 2009 NRCS contracted with Gannett Fleming, Inc., Harrisburg, PA, to complete the design of the dam rehabilitation. The initial phase of design included collecting data and performing analyses to evaluate the dam and address the deficiencies identified during the planning process in preparation for preliminary and final design work. Due to several project constraints the upstream slope investigation and evaluation was completed later as a supplement to the final design of the dam rehabilitation package. The upstream slope subsurface investigation and subsequent evaluation was performed as the reservoir was dewatered in preparation for the dam rehabilitation construction. The final design of the dam rehabilitation proceeded with the understanding that the upstream slope may require modifications to address the rapid drawdown slope stability condition.

In addition to the upstream embankment work, the dam rehabilitation design included constructing a new intake riser, installing downstream embankment chimney and toe drainage system, flattening the downstream embankment slope, reconstructing the principal spillway plunge pool, realigning the auxiliary spillway, and installing a roller compacted concrete stepped, chute auxiliary spillway.

After completing the on-site subsurface investigation and portions of the downstream slope stability analysis, GF expressed concern regarding the stability of the upstream slope under rapid drawdown condition. This concern was based on preliminary embankment stability calculations using information collected from the subsurface investigation, soil mechanics testing, and review of historical construction records. Assumed values for the upstream soils were based on soil mechanics test results for soils used to construct the downstream portion of the embankment from like borrow areas. Based on this information the design team, consisting of GF and NRCS, decided that a controlled reservoir drawdown plan would be developed and utilized during the reservoir drawdown prior to construction. The information gained from the controlled drawdown would be used to evaluate the rapid drawdown stability of the upstream slope. The plan consisted of seven phases of reservoir drawdown and included acceptable drawdown rates for various reservoir levels with periods of little to no drawdown. These drawdown rates ranged from one foot per day (fpd) for the upper 20 feet of the reservoir to four inches per day for the remainder of the pool lowering. Additionally, the plan to perform the subsurface investigation of the upstream slope included installation of piezometers and inclinometers and survey monitoring pins prior to and during the controlled drawdown procedure. The information collected from the instrumentation and monitoring pins was used to assess slope
stability during the controlled drawdown process and during the upstream slope stability analysis for final design. The Controlled Reservoir Drawdown Plan Phases and Actual Controlled Drawdown Rates are shown in the table below.

The controlled drawdown was regulated by manipulation of the 12-inch water supply gate (Elevation 1623) and the 24-inch reservoir drain gate (Elevation 1594) on the intake riser structure. The City of Keyser provided the manpower to manipulate the gates during the controlled drawdown since they have been the operators of the intake riser gates since original construction. Gannett Fleming provided the controlled drawdown plan and NRCS coordinated the efforts.

Surface monitoring pins and instrumentation were regularly monitored by NRCS and GF personnel through May 2011. NRCS and GF personnel collected the instrumentation and surface monitoring pin data on a regular basis according to the controlled drawdown plan and relayed the information to Gannett Fleming engineers. The information was utilized during the drawdown operations to make modifications to the drawdown, as necessary.

### Controlled Reservoir Drawdown Plan Phases and Actual Controlled Drawdown Rates

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Some reservoir fluctuation after rainfall events in February until final gate manipulation to open 24-inch gate 50% on February 23, 2011.

The reservoir drawdown began on July 28, 2010 when the City of Keyser opened the 12-inch diameter water supply gate to supplement water downstream; this was normal summertime operations. In mid-August NRCS performed survey layout and installed the first set of monitoring pins near the permanent pool elevation. At that time the water level in the reservoir had dropped three feet in two weeks. NRCS installed a total of twenty-nine monitoring pins at eight to ten feet (vertical intervals) from August 2010 to March 2011 as the reservoir level dropped. During that time the monitoring pins were surveyed 45 times for an average of 1.5 times per week. Two double-nested piezometers were installed on the upstream slope of the embankment near the permanent pool elevation. The piezometer tips were placed within the embankment materials in the different zones of the embankment. The second set of piezometers and the inclinometers were installed twenty feet (vertically) down from the permanent pool elevation, near the start of Phase 2 of the drawdown. The inclinometers were installed into foundation rock material. SPT, field strength testing, and soil samples were obtained during the piezometer and inclinometer development. Additionally on-site permeability testing was completed to provide an estimate of soil hydraulic conductivity. As noted in the table above, the reservoir level remained at or near Elevation 1623 for most of January 2011. In early February 2011 the City of Keyser opened the 24-inch reservoir drain gate six inches. After this action the reservoir level dropped considerably from Elevation 1625 to 1605 over the course of nine days. This far exceeded the controlled drawdown plan and also exceeded the rule of thumb rate of one foot per day. The reservoir level fluctuated during the month of February due to rainfall events; the level reached Elevation 1623 on February 22, 2011. The next day the City of Keyser increased the drain gate opening from six inches to 14 inches. The reservoir emptied by the end of the month.
Control of the reservoir drawdown proceeded according to the plan until the reservoir level dropped below the water supply gate. At that time the reservoir level was controlled by the 24-inch reservoir drain gate at the base of the intake riser. When the lower gate was utilized to control the reservoir level, less control of the reservoir was possible due to the size of the lower gate and the reduced storage volume per vertical distance within the remaining reservoir. Ideally the drain gate could have been opened slightly the first time and subsequent gate manipulations could have been made to obtain more reservoir level control; however, based on the real time information collected by NRCS and GF and reviewed and interpreted by GF Engineers, the group determined that fewer trips and less gate manipulations were acceptable. Part of the decision making process included safety concerns when accessing the top of the intake riser structure during the winter months for gate manipulations. During this process the reservoir level, stage storage curve, watershed inflow, and the Gannett Fleming modeling and instrumentation data were utilized to assess real time site conditions and adjust the controlled drawdown plan.

The surface monitoring pins showed very little movement throughout the drawdown period. Surface monument elevation plots showed that several monuments settled vertically a relatively small amount (less than 0.42 inches) during the drawdown of the reservoir.

One of two embankment inclinometer readings indicated a relatively small displacement of less than 0.3 inches in the down-slope direction within six feet of the ground surface. The movement is within the error cone and could be an indication of shall sloughing. Additional review of the same inclinometer data revealed displacement of less than 0.1 inch at a depth of 42 feet. A similar displacement of lower magnitude was also observed in the other embankment inclinometer at 35 feet in depth.

A small, shallow scarp indicating a surface sloughing failure was observed during drawdown near one of the surface monuments at the left limit of the upstream slope near the abutment near Elevation 1627. The scarp was approximately six inches deep, and the slip surface also appeared to be six inches deep and roughly parallel to the slope face. Observation of the surface soils in the area indicate significant organic material at the embankment slope surface. No other scarps or significant sloughs were identified.

During the controlled reservoir drawdown stability was analyzed at two sections on five discreet dates. The ten analyses were performed using actual piezometer data. The analyses used SLOPE/W by GEO-SLOPE International. Spencer’s Method of calculating factor of safety was utilized as recommended by the US Army Corps of Engineers EM-1110-2-1902, Slope Stability. Factors of safety in the analyses varied from 0.9 to 1.4 and the critical failure circle in all cases was relatively deep, with the upslope entry located at or near the crest and the down-slope exit typically at or beyond the toe.

Data from the instrumentation monitoring on the upstream slope conducted concurrently with the reservoir drawdown were utilized to perform the upstream slope rapid drawdown stability analysis. The rapid drawdown analysis revealed that some treatment option was required to meet NRCS and WVDEP Dam Safety requirements. Gannett Fleming and NRCS discussed treatment options and concluded it was in the best interest of the project to utilize the rock excavated for construction of the ASW structural measures. Since the majority of the excavation required for the ASW was originally intended to be placed in a random fill section downstream of the dam, it made the most sense to attempt to utilize the courser material from this excavation on the upstream slope to address the rapid drawdown condition.

![Figure 2: Rehabilitated Dam Zoning](image-url)
The recommended rehabilitation design for the upstream slope at NC14 dam included a triangle-shaped wedge of rockfill (Zone V) with a bottom width of approximately 50 feet, measured horizontally from the existing toe of dam. See Figure 2. This Zone V material decreases in width as the elevation increases, to a minimum width of eight feet at Elevation 1645.5. The outside slope of the constructed rockfill is 4.8 to 1. The Zone IV material, or transition material, would be placed between the existing embankment and the Zone V material up to Elevation 1620. Above Elevation 1620 the existing embankment surface material was Zone II-A, which consists of rocks that had been removed from the adjacent Zone II; therefore, a transition from rock to rock was not needed at this location. Approximately 26,000 CY of material was required for the upstream slope rehabilitation.

There were a few concerns related to using the material excavated from the auxiliary spillway. One concern was the gradation of the transition material to be placed between the existing embankment and the rockfill material from the ASW excavation. Since the gradation of the excavated rock material was an unknown, the material would most likely require some sort of on-site processing. Additionally the effects resulting from the excavation and subsequent handling and compaction of the transition material were unknown as well. The gradation requirements for the transition material for compatibility between the in-situ embankment material and Zone V were determined to be the following: D100< 3 inches, D50<1.5 inches, and D5<#200 sieve. The Zone V gradation requirements D100< 18 inches with a maximum layer thickness before compaction of 24 inches.

During original discussions with the construction contractor it was the intent to require the on-site material to be screened so that acceptable material could be used for the Zone IV or transition material. The construction contractor was concerned about the costs associated with setup of equipment necessary to process a relatively small amount of material. Based on the discussions with the construction contractor regarding the proposed upstream slope rehabilitation it was decided that the transition material would be constructed from readily available material from a nearby quarry instead of setting up large screens to separate a relatively small amount of material. Additionally, the Zone IV was changed from one gradation requirement, stated above, to two different standard gradations, West Virginia Department of Highways (WVDOT) Class 9 aggregate and No. 24 coarse aggregate. Each of the WVDOT aggregates would be one foot lifts on the slope, for a total transition thickness of two feet normal to the slope.

D. SUMMARY

Although the source for the “safe” reservoir drawdown rule of thumb (1 foot/day) cannot be located, the authors question its validity. The rule of thumb drawdown rate should not be considered to provide adequate margin of safety for all earth embankments, especially those constructed of fine grain soils on the upstream slope. A review of state dam safety law revealed that some states specify acceptable rates of drawdown unless studies provide alternative drawdown rates. These rates typically range from 6 inches to one foot per day.

It is the authors’ opinion that there cannot be a single rule of thumb of safe drawdown rates for “an embankment dam”. This is primarily due to the variable time to dissipate pore pressure which is highly dependent on embankment soil permeability, as well as the length of the drainage path which provides for pore pressure dissipation. The rate of drawdown that can safely occur while pore pressures dissipate for a dam with a large rockfill or highly permeable zone on the upstream face is significantly higher than for a homogenous embankment of relatively low permeability material.

How should total drawdown of the reservoir be completed when the rule of thumb results in upstream slope stability safety factor of less than 1? The authors contend that an evaluation should be completed where appropriate. In the case of NC14 we had the opportunity to evaluate and monitor the upstream slope embankment during a controlled drawdown and reassess the drawdown evaluation as it proceeded. Others may not be afforded this opportunity. As the reservoir is lowered the storage per vertical distance is reduced and the ability to manage the drawdown rate is lessened. Other considerations should be made to allow greater control of the drawdown in the case where drawdown gate manipulation is difficult, as the case was during the winter months at NC14.

The authors also believe that the engineering profession would benefit from a departure of “rapid drawdown” definition for an “earth dam” in terms of feet per day due to the variability of pore pressure dissipation in embankment dam construction, i.e. the maximum safe rate of drawdown will be different for different materials.

The authors contend that the definition of rapid drawdown condition should be the rate of reservoir drawdown from normal pool to the lowest gated outlet, assuming that the lowest gated outlet is completely open without restriction. A review of several state dam safety law revealed many different requirements for design of embankment dams for the rapid drawdown condition. The majority specifies a minimum safety factor of 1.2 for rapid drawdown; but, little to no guidance is provided beyond that. Some states require a specific reservoir pool elevation. Others differentiate between instantaneous and actual drawdown rates and provide minimum required safety factors for each type of drawdown. Typically the rapid drawdown analysis is performed from the highest normal pool elevation to the lowest gated outlet. Therefore, it would be reasonable to
evaluate the rapid drawdown rate to be the rate of reservoir drawdown assuming that the lowest gated outlet is completely open without restrictions. Then that rate of reservoir discharge would be used to evaluate the stability of the embankment for that condition. This rate may or may not be significant during the evaluation; however, it provides a reasonable rate for analysis in the absence of other criteria. Regulators should consider specifying required safety factors for the instantaneous verses actual drawdown.

The profession would do well to remember: It is not appropriate to “look” at a dam and say the safe rate of drawdown is X feet per day. As professionals, we should either perform calculations recommended by Duncan, Wright and Wong or complete a detailed analysis similar to those completed for NC14. If the safe rate of drawdown is slower than can be accommodated by the outlet works controls, then consideration should be given to evaluate the consequences, risks and consider alternate drawdown options, including pumps, siphons and monitoring.

E. RISK OF SLOPE INSTABILITY and FAILURE…Is rapid drawdown a “real” concern?

Loss of upstream slope stability due to rapid lowering of the reservoir has occurred based on the number of examples that can be found in the literature (over 30). However, it does not appear that any dams have experienced a loss of reservoir due to upstream slope failure caused by a rapid drawdown incident. One case (Bouldin Dam), experienced a loss of reservoir. However, the literature is unclear if the reservoir loss was the result of a piping incident or purely a rapid drawdown incident. Published professional opinion leans towards loss of water primarily due to internal erosion and piping failure of the earth embankment dam. There is the potential for the outlet structure blockage or damage which could impact ability to safely operate the reservoir. It appears from the case histories that the incidences have resulted in upstream slope movement, but not dam failure resulting is risk to downstream population.

Rapid drawdown slope instability may be a concern where the outlet pipe and auxiliary spillway are combined, like in the case of riser structures through which design flood is routed. In these instances, movement of upstream slope may cause failure of the riser structure and/or plugging of the outlet pipe. Assuming the riser structure provides adequate capacity and safe routing of the design flood, failure of the riser structure’s operation may lead to dam overtopping and failure of the downstream earth embankment causing rapid release of full pool and hazard to downstream population at risk.

However, where the auxiliary spillway is separate from the outlet pipe, like in case of abutment located non-erodible auxiliary spillway, upstream movement which leads to plugging of the outlet pipe may not be an immediate dam safety concern since the auxiliary spillway provides safe routing of the design precipitation event. The authors contend that an additional failure mode would need to manifest itself assuming the upstream slope movement is such that full reservoir load can be safely withstood. The additional failure mode could be a piping failure initiated at clogged / failed low level outlet pipe. With this in mind, perhaps the design case to analyze is evaluation of depth and extent of slope movement during a rapid drawdown event, i.e. determine if the dam can safely support reservoir design loads after the upstream slope movement has occurred. As a profession, this design scenario should be considered in evaluation and regulation development for the future of dam safety.

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Robert Saber, PE is a Chief Geotechnical Engineer with Gannett Fleming, Inc. He provides oversight and review for the company’s design & rehabilitation efforts to address geotechnical concerns for projects related to earth embankment dams, concrete and masonry gravity dams, roller compacted concrete (RCC) dams, levees and other flood risk reduction features. Mr. Saber has a MS in Civil Engineering from Clarkson University and is a registered Professional Engineer in the States of Pennsylvania, Virginia and West Virginia.