Hydraulic Laboratory Technical Memorandum, PAP-1186

Hyrum Dam – SITES Modeling to Evaluate Spillway Headcutting

Hyrum Project, Utah
Upper Colorado Region

U.S. Department of the Interior
Bureau of Reclamation
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Denver, Colorado

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Background

The following background information is condensed from the 2016 Comprehensive Review of Hyrum Dam.

Hyrum Dam is located on the Little Bear River, approximately 9 miles south of Logan, Utah. It was constructed by the Bureau of Reclamation (Reclamation) in 1934 and 1935 to provide water storage for irrigation and municipal use. The dam and reservoir are the principal water storage features for the Hyrum Project.

The reservoir is impounded by the main embankment dam and a relatively shallow dike embankment. An asphalt-paved road passes over the crests of both embankments. The main dam is a zoned earthfill embankment with a maximum structural height of 116 ft, a crest elevation of 4680.0 ft, and a crest width of 35 ft. The crest length is approximately 500 ft. A concrete parapet with top elevation 4683.0 was constructed along the upstream crest shoulder, a concrete curb with top elevation 4681.0 was constructed along the downstream shoulder, and concrete Jersey barriers have since been placed on top of the downstream curb.

The spillway, which is the focus of this report, is located about 900 ft to the right of the right abutment of the main dam embankment (Figure 1). The spillway consists of a concrete inlet and control structure with three 16-ft-wide by 12-ft-high radial gates, a concrete chute, a concrete stilling basin, and a riprap-lined discharge channel leading from the basin to the Little Bear River. The chute begins with an 85 ft transition from a 53-ft 5-in. wide rectangular channel at the radial gate structure to a trapezoidal channel with 16 ft bottom width and 1H:1V sloping sidewalls. The trapezoidal chute has variable but relatively gentle slopes for approximately 590 ft, then drops at a slope of 0.384 ft/ft for approximately 209 ft to the transition with the stilling basin floor. The stilling basin is trapezoidal, with bottom width of 16 ft and side slopes of 1H:1V and invert elevation 4553.0 at its deepest point; the basin is 80 ft long at this invert elevation. The basin floor then slopes up at 1.5H:1V to the entrance of the riprap-lined discharge channel at invert elevation 4574.0. The discharge channel is trapezoidal, with invert width of 24 ft and side slopes of 1.5H:1V. The discharge channel joins the Little Bear River channel a short distance downstream from the stilling basin. The spillway discharge capacity is 6,000 ft^3/s at reservoir water surface elevation 4672.0 ft.

Figure 1. — Satellite and aerial views of the Hyrum Dam spillway.

Emergency modifications were made to the steeply-sloping segment of the spillway chute in 2004 to address voids detected beneath the lining. The deteriorated chute floor was demolished and

reconstructed with reinforced concrete, and filtered drains were installed beneath the lining. The Wellsville Eastfield Canal crosses under the spillway chute through a siphon a short distance upstream from the stilling basin.

Purpose

One potential failure mode (PFM) leading to uncontrolled release of stored water from Hyrum Dam involves headcutting along the alignment of the spillway chute, initiated by scour undermining the end sill of the stilling basin. Scour at the basin exit has been observed following previous releases, and in a long-duration event, headcutting could progress upstream through the stilling basin and spillway chute, repeatedly undercutting the floor slabs. A similar process could occur if hydraulic jacking were to damage the spillway chute at a point upstream from the stilling basin.

The USDA's SITES (Water Resources Site Analysis Program), ver. 2005.1.8 was used to analyze the headcut erosion process associated with this PFM. (The same technology is also available in the USDA's WinDAM C model which performs both spillway erosion and dam breach analysis, but the user interface for the SITES implementation has advantages for spillway erosion problems.) The model is one-dimensional, simulating flow through a channel of uniform cross section, with a streamwise profile defined by the user. Soil materials underlying the spillway profile are assigned erodibility characteristics, primarily a detachment rate coefficient, k_d, and headcut erodibility index, K_H. The k_d parameter expresses the rate of erosion of exposed surfaces per unit of applied shear stress exceeding a threshold critical shear stress. Units of k_d are ft/hr/psf (psf=lb/ft^2). Values of k_d can be estimated from lab or field-based erosion tests (e.g., the submerged jet erosion test or JET), or by correlation with basic soil properties and knowledge of compaction conditions. The critical shear stress is determined by the program based on other soil properties. The dimensionless K_H parameter determines the hydraulic attack threshold that must be exceeded to initiate headcut advance, and the incremental increase in the rate of advance as the hydraulic attack is increased. The K_H parameter was correlated to observed scour in plunge pools and unlined spillway channels by Annandale (1995) and has been incorporated into Reclamation's *Best Practices in Dam and Levee Safety Risk Analysis* manual (Reclamation 2018). The value of K_H can be estimated as the scalar product of 4 constituent parameters, $K_H = M_s \cdot K_b \cdot K_d \cdot J_s$, where M_s represents the mass strength of intact material, K_b represents the particle or block size, K_d represents the strength of discontinuities and joints between particles of blocks, and J_s represents the effect of joint orientation relative to the flow direction. For this application of the SITES model, detailed geologic information was not available to support estimating these constituent properties, so values of K_H were estimated directly by comparison to simple photographic examples given in the SITES online help document.

Available drill logs, test pit records, and other geotechnical information were reviewed to develop estimates of k_d and K_H. Most of the available information was descriptive and non-quantitative. The soil underlying the spillway alignment seems to generally consist of layers of lean clay and fat clay with thin layers of sandy clays and silts that will probably cause the bulk soil mass to be somewhat more erodible than might be expected for a uniform lean or fat clay. A clayey gravel layer also is present at depth, around elevation 4575 ft (approx. floor of basin), but too little information was available to justify establishing this as a distinct soil layer in the model. Estimates of material parameter values for the soil underlying the spillway chute were based on the review of geotechnical

records, past experience, and guidance offered by the SITES program's documentation (suggested K_H values). To evaluate the sensitivity of model results to the uncertainty of the soil erodibility parameter estimates, four categories of estimates were created: Best Estimate values, Erodible and Erosion Resistant values, and a Very Resistant value. The Best Estimate values reflect an expectation that the weaker layers described in the logs will have a controlling influence on the erodibility. The Erodible category indicates a worst-case estimate. (An even larger value of k_d might have been selected for this category, but SITES limited the maximum value to 10 ft/hr/psf). The Erosion Resistant category takes an optimistic view that the layers of weak soil described in the logs are not extensive enough to impact the overall erodibility of the soil mass. The Very Resistant category is not believed to represent realistic values, but was used primarily to verify that the model would respond appropriately to a significant increase in erosion resistance.

Parameter	Very Resistant	Erosion Resistant	Best Estimate	Erodible
k_d, (ft/hr/psf)	0.2	1	5	10
K_H (dimensionless)	5	1	0.2	0.05

* k_d is often expressed in metric units of $cm^3/(N\text{-}s)$. 1 $cm^3/(N\text{-}s)$ = 0.5655 ft/hr/psf.

Estimates of k_d were made primarily on the basis of Table 3 in Hanson et al. (2010), which indicates the effect of compaction energy, soil type, and moisture content at time of compaction on the erodibility of constructed earthworks. Because the soils beneath the Hyrum Dam spillway are naturally occurring (except perhaps immediately beneath the chute slab), this table provides only a rough guide, since compaction of the soils has occurred through natural processes. Estimates of K_H were made primarily using the pictorial guidance provided in the SITES program's online help (see Appendix). It should be noted that the soils beneath the Hyrum spillway are known to exhibit some light cementation, and this factor is not accounted for by Table 3, so values of k_d for the Hyrum case might tend to be slightly lower than indicated by the table.

Table 3. Approximate values of k_d (cm^3/N-s) relative to compaction and % clay.

Clay %	Modified Compaction (27.5 kg-cm/cm^3)		Standard Compaction (6.0 kg-cm/cm^3)		Low Compaction (1.2 kg-cm/cm^3)	
	≥Opt WC%	<Opt WC%	≥Opt WC%	<Opt WC%	≥Opt WC%	<Opt WC%
	Erodibility, k_d (cm^3/N·s)					
>25	0.05	0.5	0.1	1	0.2	2
14-25	0.5	5	1	10	2	20
8-13	5	50	10	100	20	200
0-7	50	200	100	400	200	800

Hanson et al. (2010) Table 3.

A vertical profile of the spillway alignment was created using available drawings of the spillway chute and stilling basin. The SITES program is unable to calculate the flow profile through a hydraulic jump, so the stilling basin itself was omitted from the profile and replaced by a channel section with a slope of about 3%, connected to a steeper section representing the end sill and exit of the basin. In the model, the spillway chute and the artificial "lid" over the basin were defined to have a 1-ft

thick top layer of nonerodible material (i.e., concrete), with a very small k_d and very large K_H value. The intent was to force initial erosion and headcut development to start at the basin exit, which was defined in the model to have bare soil. Headcutting should still be able to take place through the basin despite the nonerodible lid, since the headcutting process is driven by erosion of the weaker underlying layers of soil, which undercuts the upper soil zones.

A key input for the model is the elevation of the valley floor. SITES does not allow any erosion to occur below the valley floor elevation. As erosion occurs in the model, headcuts are developed when the localized depth of erosion exceeds the critical depth of the flow. Once this occurs, each headcut is represented by a vertical step in the spillway profile, and the rate of headcut advance is driven by the height of the overfall and the resistance of the soil expressed by K_H. The lower limit for any overfall is the valley floor. Erosion that occurs very near the valley floor elevation cannot produce a headcut of sufficient height to activate the headcut advance model. The valley floor elevation was set to elev. 4572.3 ft based on a note on drawing 188-D-55 that states that the exit channel was extended at a constant slope of 0.004 ft/ft from the basin end sill (sta. 1215.67, elev. 4574.0) to the river at sta. 1640.3. Early runs of the model were made with the initial erosion forced to occur at the end sill elev. 4574.0, and they exhibited the behavior just described, with no headcut advance occurring.

Because scour has been observed in the field downstream from the stilling basin end sill even for relatively small flows, this behavior of the model did not seem realistic. To enable the model to begin calculating advance of a headcut, the profile was artificially modified to raise the basin end sill (and the point of initial erosion) by 10 ft, to elevation 4584.0 ft, and then later by greater distances, eventually as much as 20 to 30 ft. Rates of headcut advance increased as the initiation elevation was raised, and became relatively stable when erosion was initiated at or above elev. 4589. On the basis of these test runs, elevation 4595 was selected as the initial erosion elevation for all subsequent runs of the model. A similar outcome probably could have been achieved by lowering the valley floor elevation, but raising the initiation point was chosen because it could also represent a hydraulic jacking failure initiating in the spillway chute, upstream from the stilling basin. Testing to establish the threshold for the change in erosion behavior was performed with only the 100,000-yr general event (rain-on-snow) hydrograph and the Erosion Resistant soil properties.

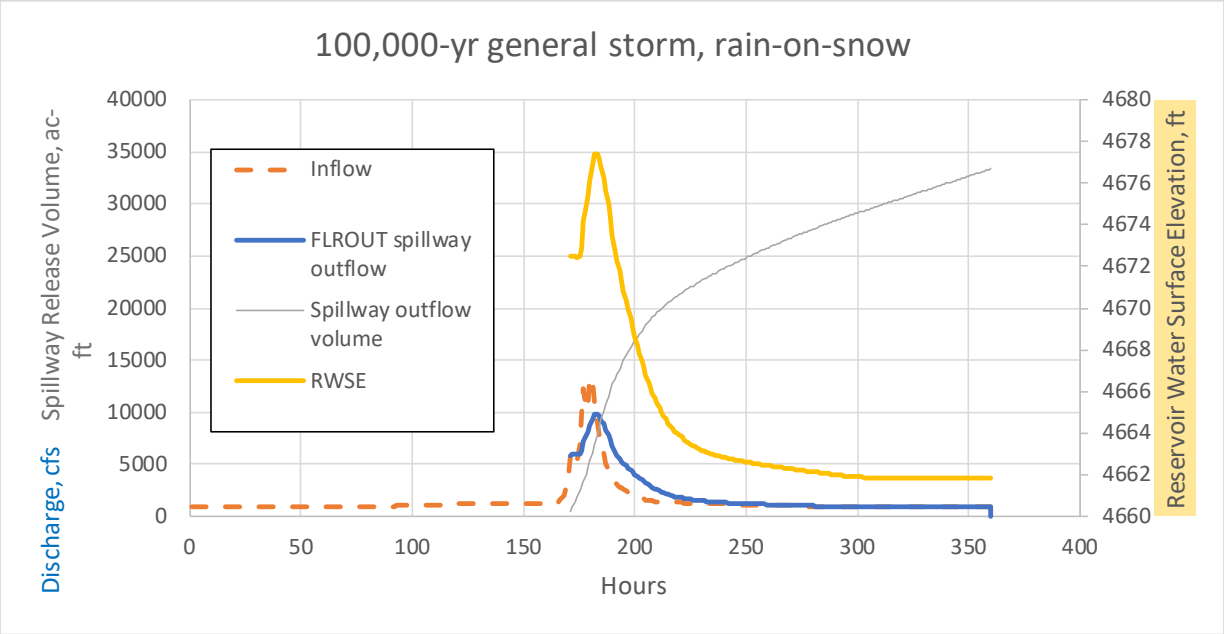
Testing was also conducted using reduced amplitude hydrographs (e.g., 50% of the 100,000-yr general storm outflow), and this showed that when the initial erosion elevation was low, there was an unusual sensitivity to the flood amplitude, with smaller floods sometimes causing more rapid erosion. Experimentation and discussions with the model developers seemed to confirm that this was due to a tailwater effect. Although the user of the model does not provide a specific tailwater boundary condition or tailwater rating curve, the model internally computes a water level elevation at the downstream end of the model, constrained by the valley floor elevation and the width of the spillway channel. (The model does not allow one to define a wider valley cross section downstream from the spillway itself.) If the tailwater is sufficient to partially submerge an active headcut, it will reduce the rate of advance of that headcut. Tailwater probably does affect headcut advance rates in the real world, but the effect may be exaggerated in the model, with headcut advance being effectively halted when tailwater exceeds a certain elevation. After the initial erosion elevation was increased to 4595, this tailwater effect vanished, and smaller hydrographs then produced slower erosion, as expected.

Production Runs

Once the basic setup of the model had been determined using the previously described trial runs, production runs of the model were made using a range of hydrographs and soil properties. For these runs, the geometry of the spillway profile and the elevation of initial erosion were held constant. Spillway outflow hydrographs were obtained from routing studies performed by the design team using program FLROUT. In these routing studies, spillway releases were started when reservoir elevation 4672.5 ft was exceeded. Scenarios were run as follows:

- General storms (100,000-yr, 10,000-yr, and 2,000-yr frequency floods for rain-on-snow events) with Erodible, Best Estimate, Resistant, and Very Resistant soil properties;
- Local storms (100,000-yr, 10,000-yr, and 1,000-yr frequency floods for thunderstorm events) with Erodible, Best Estimate, and Resistant soil properties.

Routed spillway outflow hydrographs were not available for the 1,000-yr or smaller general storm event. The Very Resistant soil properties were not used with the local storms because they did not produce a breach, even for the 100,000-yr event.



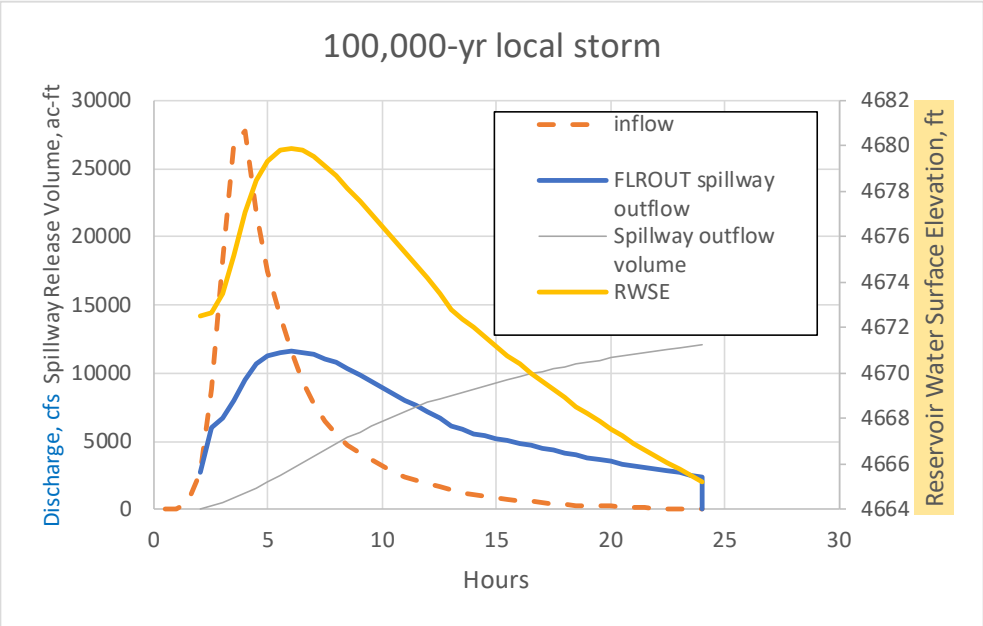


Figure 2. — General and local storm spillway outflow hydrographs for the 100,000-yr frequency flood.

Figure 1 shows the characteristics of the inflow and spillway outflow hydrographs for the 100,000-yr general and local storms. Frequency floods for smaller return periods were similar in shape and duration, but lower in amplitude. Several things are notable:

- Although the total duration of the general storm is about 15 days, over 50% of the volume of water passing through the spillway does so in a period of about 2 days (48 hrs).
- When these spillway outflow hydrographs were supplied to the SITES model, they were run for the full period shown in the spillway outflow hydrograph, but they were truncated at the end of the routing period with a zero flow condition. (SITES will continue the flow indefinitely at the last specified flow value, so if a zero flow is not specified, flow continues forever, causing continued headcut advance and a spillway breach at some future time.)

- The routings were continued well past the point in time at which the reservoir water surface elevation had dropped back to 4672.5 ft, producing a long duration of spillway flows. It seems likely during a real event that spillway outflows could be or would be reduced more quickly if erosion damage was taking place in the spillway.

Figure 2 shows all of the spillway outflow hydrographs used for the SITES model runs. Table 1 provides the duration for which the reservoir was above elevation 4672.5 ft for each frequency flood event. Table 2 presents the SITES model results for all scenarios. Note the cases for which breach occurs after the time indicated in Table 1.

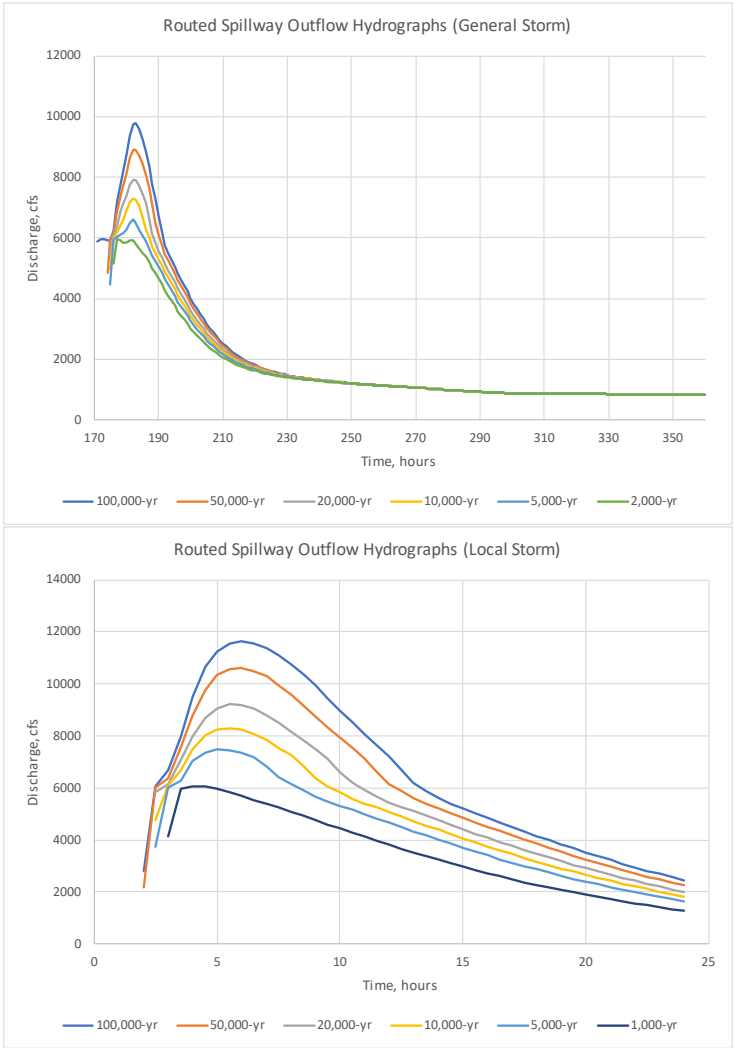


Figure 3. — Spillway outflow hydrographs used as input for the SITES model runs.

Table 1. — Duration of spillway flows while reservoir is above starting elevation.

Storm Event	Frequency, years	Duration of reservoir above starting elevation, hours
General Storm	100,000	21
	50,000	17
	20,000	14
	10,000	13
	5,000	11
	2,000	7
Local Storm	100,000	11.5
	50,000	10.5
	20,000	8.5
	10,000	7.5
	5,000	6.0
	1,000	2.5

Table 2. — Results of spillway headcut advance simulations using the SITES model.

Flood	Soil Properties	Time of Breach, hr*	Furthest upstream station of headcut advance**, ft	% advance (100% needed to breach)
100,000-yr General	Very Resistant	36 [a]		
10,000-yr General	Very Resistant	42 [a]		
2,000-yr General	Very Resistant	46 [a]		
100,000-yr General	Resistant	18		
10,000-yr General	Resistant	20 [a]		
2,000-yr General	Resistant	21 [a]		
100,000-yr General	Best Estimate	13		
10,000-yr General	Best Estimate	13		
2,000-yr General	Best Estimate	14 [a]		
100,000-yr General	Erodible	10		
10,000-yr General	Erodible	10		
2,000-yr General	Erodible	11		
100,000-yr Local	Very Resistant	no breach	674	53%
10,000-yr Local	Very Resistant	no breach	780	43%
1,000-yr Local	Very Resistant	no breach	879	33%
100,000-yr Local	Resistant	18 [a]		
10,000-yr Local	Resistant	20.5 [a]		
1,000-yr Local	Resistant	no breach	303	89%
100,000-yr Local	Best Estimate	11		
10,000-yr Local	Best Estimate	12.5 [a]		
1,000-yr Local	Best Estimate	14 [a]		
100,000-yr Local	Erodible	8.5		
10,000-yr Local	Erodible	9.5 [a]		
1,000-yr Local	Erodible	10 [a]		

** Spillway flow begins at t = 1 hr.*

*** Spillway control structure crest station = 192 ft. Erosion initiated at station = 1216 ft (1024 ft downstream from crest).*

[a] *Breach occurs after the reservoir has receded below initial elevation of spillway operations (4672.5 ft).*

In the majority of the scenarios analyzed, headcutting advanced to the crest structure at station 1+92 ft, causing a breach into the reservoir, although in some cases the breach occurred long after the peak flow had been passed, and after the reservoir had been lowered to below its initial elevation (4672.5 ft). The SITES model does not simulate the development of a breach beyond its initiation, so the model does not provide a breach outflow hydrograph. The primary output is a report of the

time at which breach is initiated. In cases where breach does not occur, the model reports the distance of upstream headcut advance and the height of the overfall at the most upstream headcut.

Figures 3 and 4 show the times of breach initiation predicted in simulations of the 100,000-yr events. With more erodible soils, breach occurs earlier in the hydrograph, even on the rising limb in some cases. With more resistant soils, breach occurs later, in some cases after the reservoir has receded below the initial elevation at which spillway flows began. Recall that the Very Resistant soil properties category was included primarily to validate appropriate model behavior, but is not believed to represent realistic soil properties for the Hyrum Dam spillway site.

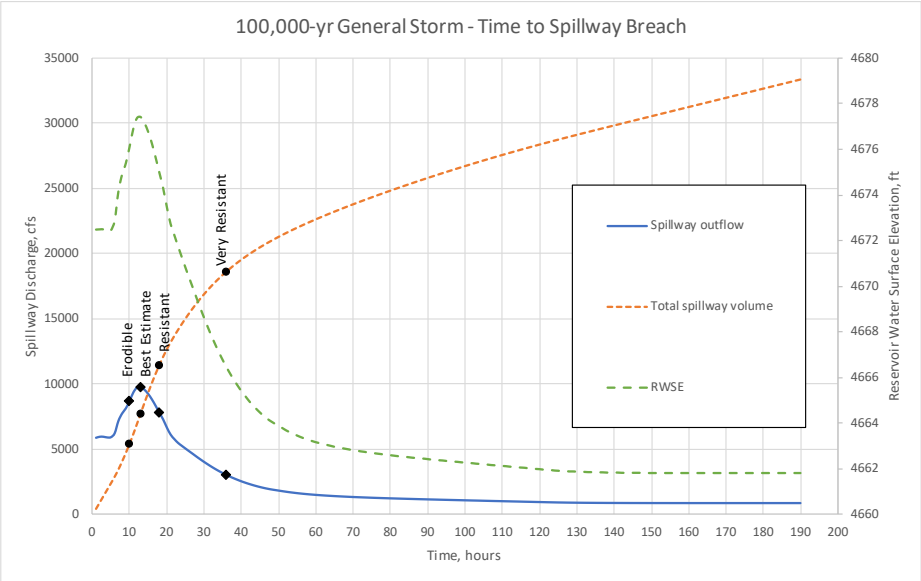


Figure 4. — Results of SITES model runs for the 100,000-yr general storm event, with four different levels of soil erodibility. Symbols indicate the time at which a headcut advanced through the station of the spillway control structure.

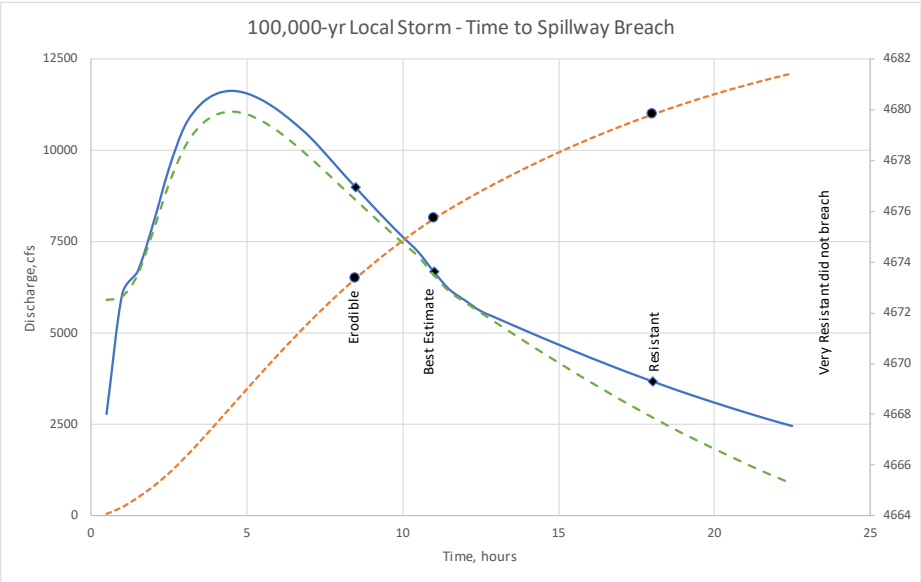


Figure 5. — Results of SITES model runs for the 100,000-yr local storm event, with four different levels of soil erodibility. Symbols indicate the time at which a headcut advanced through the station of the spillway control structure. When Very Resistant soil properties were assumed, headcutting did not reach the control structure.

Figure 5 shows the times of breach initiation for lesser flood events. Trends are as expected, with smaller floods exhibiting slower headcut advance and later breach initiation. Breach occurs a little more rapidly for the local storm events (vs. general storm events) when more erodible soil properties are assumed, and later when more erosion resistant soil properties are assumed. This difference is related to the different shapes of the hydrographs and different distributions of flow volume in time.

Summary and Conclusions

Simulations made with the USDA SITES model showed that headcut erosion could develop and rapidly advance upstream along the alignment of the existing spillway channel at a rate that could lead to an uncontrolled release of the reservoir. It should be emphasized that a sequence of multiple events would be required to progress from spillway releases to uncontrolled release of reservoir water, and these simulations examined only the erosion progression stage of the process. Each simulation started with the assumption of an initiating failure taking place in the spillway chute lining or in the exit channel downstream from the stilling basin exit, and this failure was assumed to occur shortly after the beginning of spillway releases. Although the assumed failure location was at an elevation most consistent with a possible hydraulic jacking failure in the chute, the resulting erosion process was believed to also be indicative of what could occur following a failure at the stilling basin exit.

Simulations were made with four different levels of soil erodibility parameters, three of which were believed to within a realistic range for the site. In many cases the breach of the spillway occurred late in the simulation, on the receding limb of the spillway outflow hydrograph at a time after the reservoir had already receded below the reservoir elevation used to start the simulations (see Table 2). These late breaches are possibly avoidable with operational intervention to reduce spillway flows after the reservoir has receded below elevation 4672.5 ft. For the long-duration General Storm events, early breaches occurred for all storm levels (2,000- to 100,000-yr) when Erodible materials were assumed; for 10,000-yr and greater storms with Best Estimate materials assumed; and for only the 100,000-yr storm with Resistant materials assumed. For the shorter Local Storm events, early breaches occurred for the 100,000-yr event with Best Estimate or Erodible materials assumed, but not for any simulations with Resistant materials or smaller flood magnitudes.

Material properties are a great source of uncertainty for this analysis. Estimates of detachment rate coefficients (k_d) and headcut erosion index values (K_H) were made with limited descriptive information drawn from a handful of field geologic investigations that took place primarily along the alignment of a proposed new spillway, not within the existing spillway chute footprint. The SITES simulations also do not consider any possible protection of the eroding headcut face that might be provided as portions of the spillway chute slab fall into the developing scour hole.

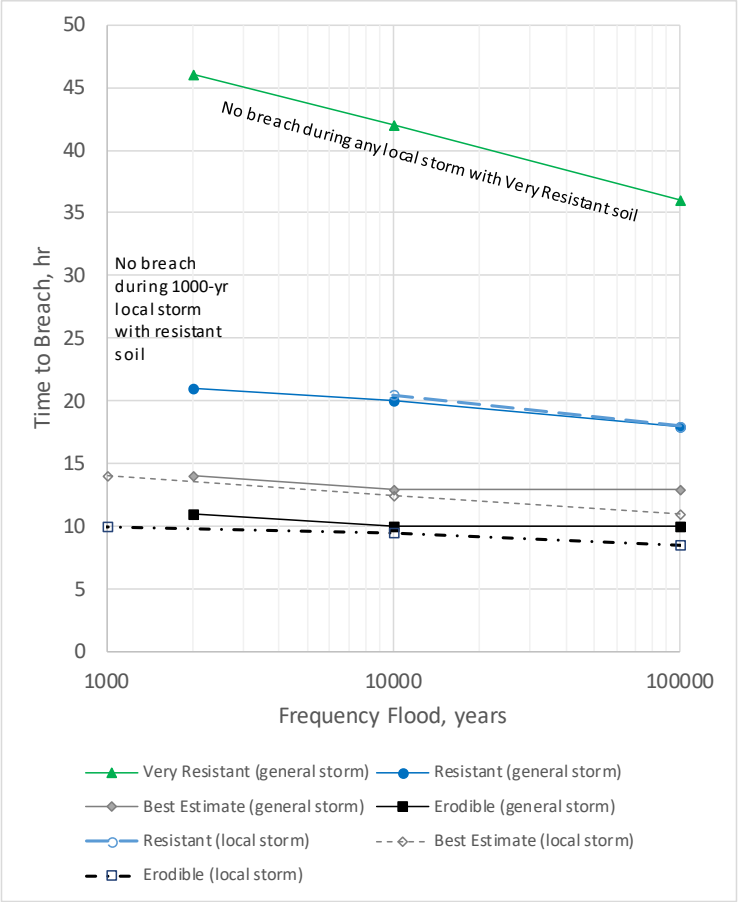


Figure 6 .—Time of breach initiation for the full range of frequency floods and soil properties.

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Appendix

Photographic guidance for estimating headcut erodibility index values. From SITES help file.

Kh = 0.02

DESCRIPTION : ML, cohesionless
SITE: Rush Creek 45, Oklahoma
COMMENT: Eroding material in headcut face
Index value based on lab. strength test

Kh = 0.03

DESCRIPTION : ML, some apparent bonding
SITE: Big Sand 3, Mississippi
COMMENT: Eroding material in headcut

Kh = 0.05

DESCRIPTION : Soil debri fill
SITE: East Fork Pond River, Kentucky
COMMENT: Eroding material in gully bank at spillway exit

Kh = 0.05

DESCRIPTION : CL, firm, soil fill
SITE: Twin Caney 17-34, Kansas
COMMENT: Eroding material in headcut face

<u>NOTE:</u> K_H = 0.05 was used for the "Erodible" model runs for the Hyrum Dam spillway study.

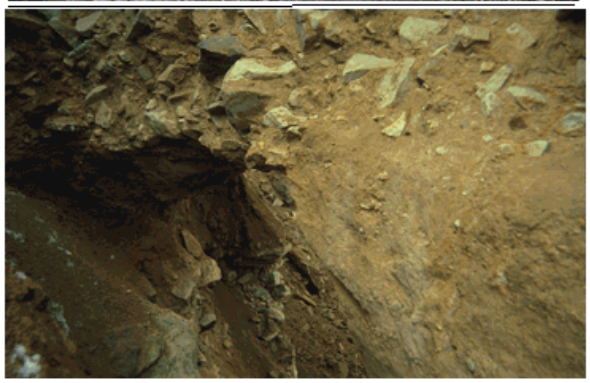
Kh = 0.1

DESCRIPTION : CL, firm soil
SITE: East Fork Pond River 9A, Kentucky
COMMENT: Eroding material in headcut

Kh = 0.12

DESCRIPTION : ML, medium dense loess
SITE: Black Creek 53, Mississippi
COMMENT: Eroding material in breached spillway gully wall

Kh = 0.12



DESCRIPTION: GM, dense, some apparent bonding
SITE: Lower North River 78, Virginia
COMMENT: Eroding material on headcut face: no lab tests available

Kh = 0.16

DESCRIPTION: CL, stiff, glacial till
SITE: Misteguay 4, Michigan
COMMENT: Eroding material on headcut face

Kh = 0.17

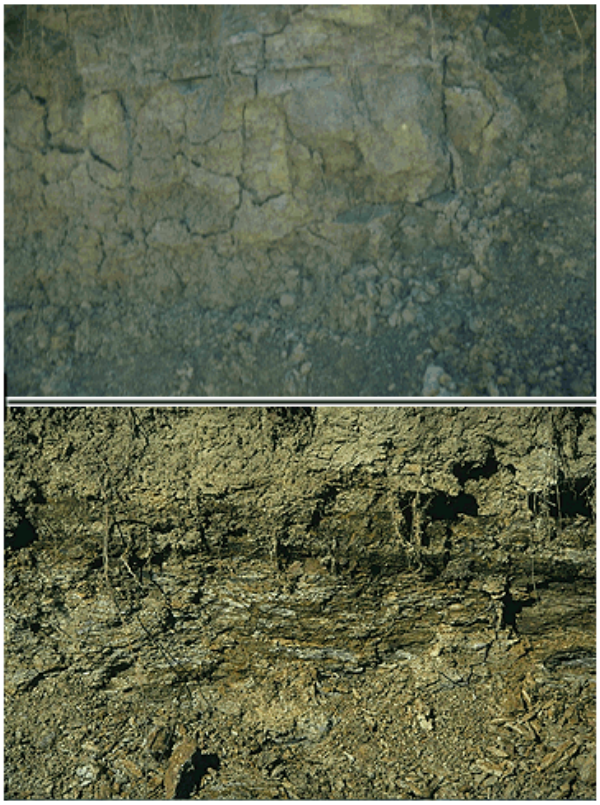
DESCRIPTION: CL, stiff
SITE: Rush Creek 12R, Oklahoma
COMMENT: Eroding material in headcut face

Kh = 0.2

DESCRIPTION: Decomposed shale
SITE: Bee Creek B-1-17, Kansas
COMMENT: Eroding material in headcut face
Est. representative diameter of 1 in

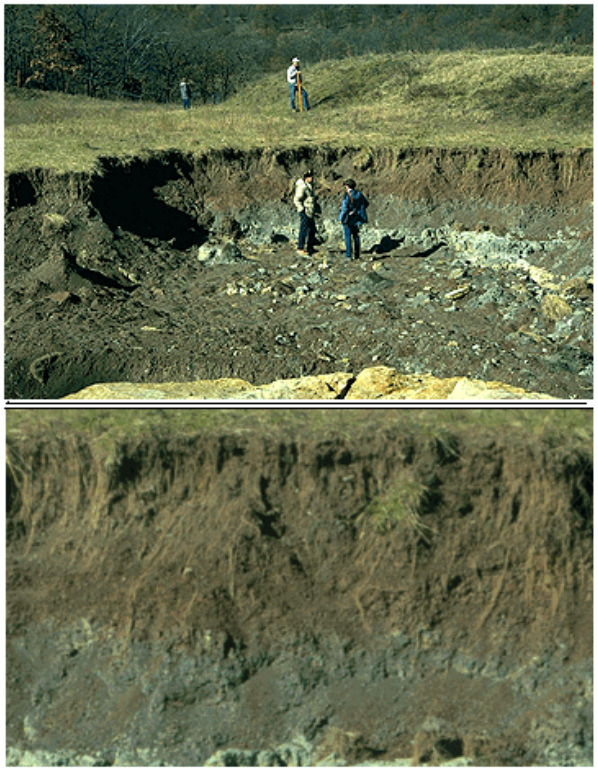
<u>NOTE:</u> K_H = 0.2 was used for the "Best Estimate" model runs for the Hyrum Dam spillway study.

Kh = 0.2



DESCRIPTION: Decomposed shale
SITE: Twin Caney 17-3, Kansas
COMMENT: Eroding material in gully wall
Est. representative diameter 0.8 in

Kh = 0.27



DESCRIPTION: Decomposed shale
SITE: Twin Caney 17-34, Kansas
COMMENT: Eroding material in headcut face.
Est. representative diameter of 1 in.

<u>NOTE:</u> K_H = 0.2 was used for the "Best Estimate" model runs for the Hyrum Dam spillway study.

Kh = 0.5

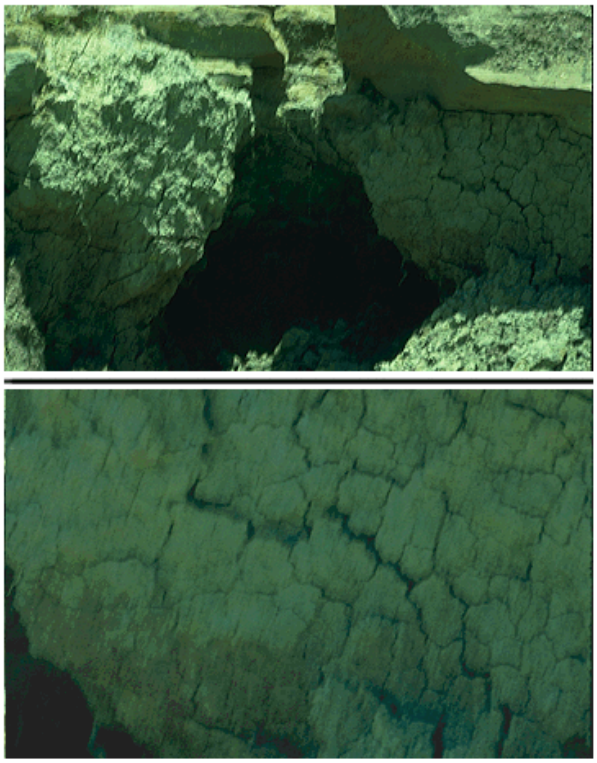
DESCRIPTION: Disintegrated shale
SITE: West Fork Point Remove 5, Arkansas
COMMENT: Eroding material in gully bank
Est. representative diameter of 3 in

Kh = 0.3

DESCRIPTION: Hillside overburden (saprolite/colluvium)
SITE: West Fork Point Remove 11, Arkansas
COMMENT: Eroding material remaining in island area
in spillway exit

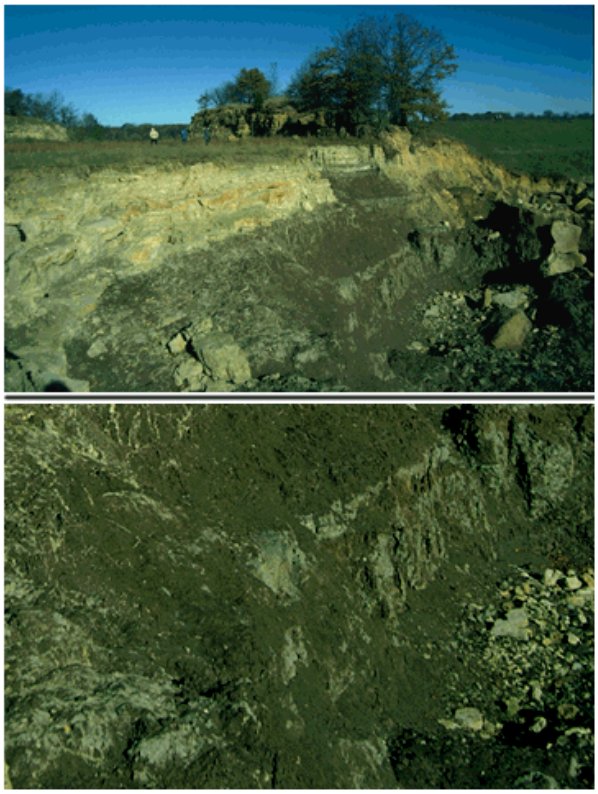
<u>NOTE:</u> K_H = 1.0 was used for the "Erosion Resistant" model runs for the Hyrum Dam spillway study.

Kh = 2



DESCRIPTION : Shale
SITE: Big Sandy 10, Texas
COMMENT: Eroding material below sandstone
Est. representative diameter of 6 in

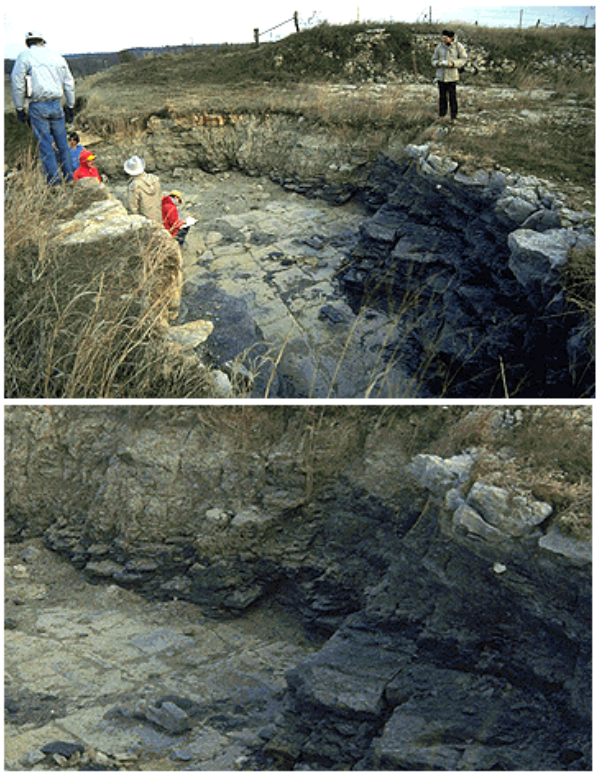
Kh = 10



DESCRIPTION : Shale below sandstone cap
SITE: Twin Caney 18-26, Kansas
COMMENT: Eroding material in lower part of headcut
Est. representative diameter of 12 in

<u>NOTE:</u> K_H = 5.0 was used for the "Very Resistant" model runs for the Hyrum Dam spillway study.

Kh = 13



DESCRIPTION: Shaley limestone
SITE: Lower Elk 18, Kansas
COMMENT: Eroding material in headcut face
Est. representative diameter of 8 in

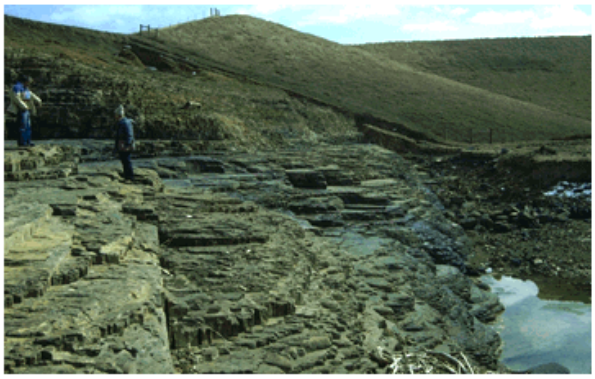
Kh = 20

DESCRIPTION: Jointed sandstone
SITE: West Fork Point Remove 5, Arkansas
COMMENT: Material remaining below surface erosion
Some minor detachment by flow

Kh = 50

DESCRIPTION : Black shale
SITE: West Fork Point Remove 3, Arkansas
COMMENT: Material remaining below erosion

Kh = 200



DESCRIPTION : Shale
SITE: South Fork Branch Potomac 19, West Virginia
COMMENT: Foreground material; negligable detachment during flow

Kh = 550

DESCRIPTION : Sandstone
SITE: West Fork Point Remove 11, Arkansas
COMMENT: Material remaining below eroded surface

Kh = 2000

DESCRIPTION : Limestone
SITE: East fork Pond River 7B, Kentucky
COMMENT: At spillway grade

Kh = 35000

DESCRIPTION : Massive rock (ryolite)
SITE: Painted Rock Dam, Arizona
COMMENT: Spillway outlet; negligable erosion