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Modeling Headcut Erosion in a Proposed Fuse Plug Auxiliary Spillway Channel at Glendo Dam

Pick-Sloan Missouri Basin Program
Oregon Trail Division – Glendo Unit – Wyoming

U.S. Department of the Interior
Bureau of Reclamation
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14. ABSTRACT
Potential headcut erosion of a proposed unlined spillway channel excavated through Brule siltstone was studied using the SITES water resources site analysis computer program distributed by the USDA. Runs of the SITES model that utilize field-measured values of the detachment rate coefficient and values of headcut erodibility index derived from geologic investigations predict headcut erosion that will threaten to breach the spillway control structure, as presently proposed. Field tests used to determine the detachment rate coefficient exhibited high variability, due to the difficulty of producing measurable erosion and due to the extreme susceptibility of the siltstone to rapid weathering. Predictions of erosion from the SITES model were extremely sensitive to the value of the detachment rate coefficient. Reducing the detachment rate coefficient by what are believed to be plausible amounts caused the SITES model to predict minimal headcut erosion, with no resulting threat to the spillway control structure. Research needs and potential research approaches for improving the ability to model headcut erosion of rock materials are discussed.

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Introduction

Glendo Dam is located on the North Platte River in east-central Wyoming. A Corrective Action Study is underway to investigate and develop designs for a dam raise and fuse plug auxiliary spillway to reduce risk of dam failure due to overtopping during a large hydrologic event. The proposed spillway will be controlled by four fuse plug embankments of varying heights, staged to operate during floods of increasing size, up to an event with a 500,000 year return interval. The maximum discharge expected through the spillway is about 202,000 ft^3/s, during the 500,000-yr return interval flood.

The spillway channel will cross through an existing dike along the southern edge of the reservoir and discharge water into a broad upland area draining back to the North Platte River channel. The proposed spillway channel will be mostly unlined, excavated through a Brule siltstone material. This report describes field studies and computer modeling performed to estimate erosion of the spillway channel during spillway operations. The extent of predicted erosion is compared to the depth of a base slab and cutoff wall at the control structure, to be constructed from roller-compacted concrete (RCC) and conventional reinforced concrete.

The SITES Model

Erosion of the proposed spillway channel was evaluated using the one-dimensional SITES computer model developed by the U.S. Department of Agriculture for analysis of hydrologic and hydraulic issues related to embankment dams and associated features, including free overflow spillways excavated through earthen materials (USDA 1997). The analysis makes significant use of only one component of the SITES model: the earth auxiliary spillway evaluation module.

SITES evaluates the stability and integrity of an earthen spillway using a three-phase simulation of headcut erosion processes. Headcut erosion occurs in a variety of natural materials, especially when cohesion or other internal bonds hold the material together. Headcut erosion is most commonly observed in soil-like materials, but also can occur in rock or in granular materials when the presence of moisture creates apparent cohesion. The headcut erosion process begins when concentrated flow causes local erosion that creates a drop in the channel, or knickpoint. Energy dissipation downstream from this drop then leads to accelerated erosion at the base of the overfall that causes the drop to deepen and advance upstream. The objective of the simulation is to determine whether a headcut will form in the spillway and whether it will become deep enough or advance far enough upstream to cause a breach through the spillway into the reservoir. This would lead to loss of reservoir storage and large outflows, similar to a dam-breach event. Figures 1 and 2 show headcut erosion damage in an earthen spillway, and the aftermath of a spillway breach caused when a headcut advanced into a large reservoir.

Figure 1. — Headcut damage to a vegetated earthen spillway.

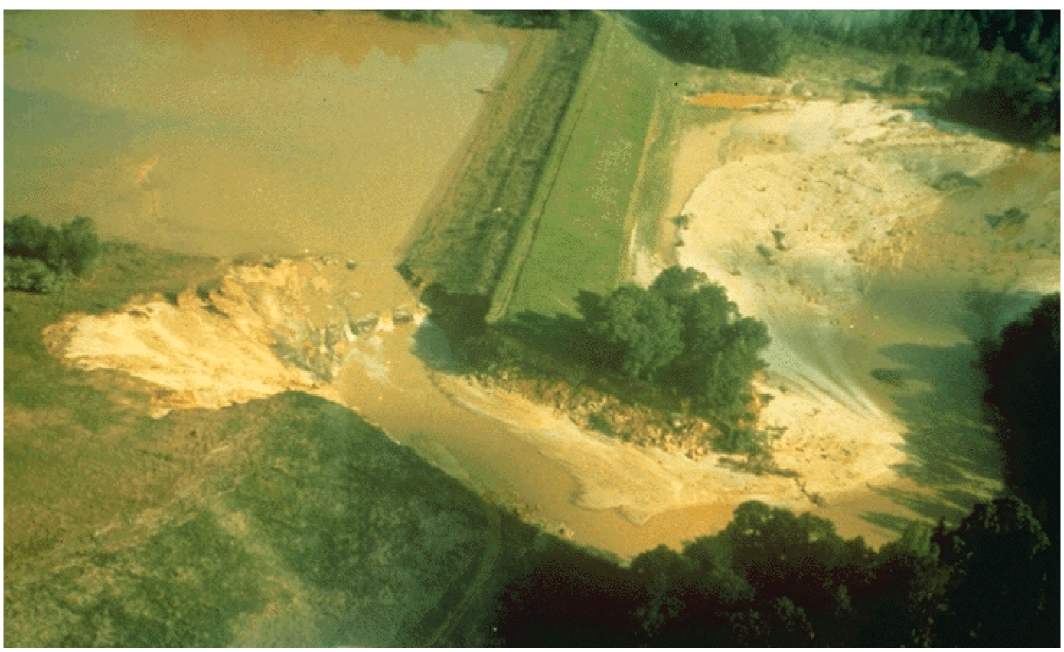

Figure 2. — Spillway breach caused by headcut erosion.

The three-phase model used to simulate headcut erosion in SITES is based on a simplification of the erosion process into the following steps:

1. failure of the vegetal cover in the spillway,
2. concentrated erosion that initiates a headcut, and
3. deepening and upstream advance of the headcut.

In the case of the proposed spillway for Glendo Dam, the local climate and environment are such that vegetal cover is expected to be sparse, discontinuous, or non-existent, so only the last two phases of the erosion process are considered. For spillways that do have good vegetal cover, failure of the vegetation is modeled by comparing instantaneous and time-integrated hydraulic shear stresses to peak and threshold values that the vegetation can withstand, with consideration for the influence of cover uniformity and quality.

Phase 2 of the erosion process compares hydraulic stresses to the critical shear stress (τ_c) required for initiation of erosion, and estimates the rate of material removal to be proportional to the applied excess stress. The modeling equation is one used to simulate erosion processes controlled by the rate of soil detachment (as opposed to erosion limited by the sediment transport capacity of the flow)

$$\dot{\varepsilon} = k_d \left(\tau - \tau_c \right)$$

where $\dot{\varepsilon}$ is the erosion rate (length/time), and τ is the applied shear stress. The detachment rate coefficient (k_d) determines the rate of deepening per unit of applied excess stress. The value of τ_c is determined as a function of the diameter of the particles to be eroded, utilizing Shield's diagram. The inherent assumption is that the particles are loose and free to be transported by the flow.

The value of k_d can be estimated as a function of the dry bulk density of the material and the percentage of clay. Values of τ_c and k_d can also be determined by *in situ* testing with a submerged jet device (Hanson and Cook 2004). The mathematical model of erosion in phase 2 and the submerged jet device were both originally developed for application to soil-like materials; for the Glendo case, we will be applying them to the Brule siltstone, which has characteristics of both soil and rock.

Phase 3 of the erosion process is the deepening and upstream advance of an existing headcut. The SITES model may track the movement of several headcuts during any model run, and it is possible during phase 3 for one headcut to advance quickly enough that it consumes other upstream headcuts. The model focuses its attention on the deepest and most upstream headcuts. Advance of a headcut during phase 3 is modeled by computing the energy dissipation at the base of the headcut and then establishing a threshold for advance and an advance rate coefficient that are each functions of a parameter called the headcut erodibility index, K_h. Values of K_h are determined by considering a number of geologic factors including material strength parameters, spacing and size of joints, properties of joint filling materials, and orientation of joints relative to the primary flow direction. Values of K_h for the Brule siltstone have been estimated for two layers, a weathered upper layer (ground surface to 25 ft depth) and a non-weathered deeper deposit. During phase 3, deepening of the headcut can continue to occur. Deepening is modeled using an equation similar to that used for phase 2.

Modeling Adjustments

SITES offers several simulation alternatives, including two alternate methods for running a simulation of an auxiliary spillway operation event. The **special auxiliary spillway analysis** is meant to be used when flood routing takes places outside of the SITES model. It utilizes a direct input of the flow hydrograph through the spillway, and thus seems at first to be well-suited to this situation.

The **single event** analysis performs a simple level-pool routing of a single inflow flood to the reservoir, and carries out a stability and integrity analysis of the auxiliary spillway that is similar to the special auxiliary spillway analysis option. One additional feature of the single event analysis is the ability to define the location of a barrier wall in the spillway that will stop the upstream advance of any headcut. This option is not available when using the special auxiliary spillway analysis.

The SITES model was designed for application to dams constructed by the USDA Natural Resources Conservation Service (formerly Soil Conservation Service). These dams typically have simple free overflow spillways excavated through natural materials, protected by vegetation that is established and maintained in the spillway channel. SITES was not designed for use with fuse plug spillways and thus does not have the capability to directly simulate the dynamic changes in spillway rating that occur as fuse plug embankments breach to open up the spillway channel.

To take advantage of the barrier wall analysis option while avoiding the problems of routing an inflow flood through a fuse plug spillway, a hybrid modeling option was used. The single event option was selected, but the reservoir inflow given to the model was the outflow hydrograph through the fuse plug spillway, determined separately in routings performed by spreadsheet analysis. To obtain the correct outflow hydrograph in the simulation, the reservoir was defined to be of miniscule volume, causing the provided inflow hydrograph to become the outflow hydrograph with minimal attenuation. This method of model operation was tested and it was verified that the model correctly translated the inflow directly to outflow with reasonable simulated reservoir water surfaces and was stable in its operation.

A further adjustment was made to account for the staged operation of the fuse plug embankments. The embankments are staged to operate in sequence from left to right as reservoir levels increase. The exit channel downstream from each embankment is excavated with a 5% slope and extends downstream until it daylights at about elevation 4644.50 ft. The distance from the end of concrete to the daylight point is about 100 ft for fuse plug 1, and about 70 ft for fuse plugs 2 through 4. Trial runs of the model showed that the controlling headcut was always one which initiated around the daylight position and then advanced upstream toward the control structure. Thus, the length of the excavated portion of the spillway channel was of prime importance.

The staged operations will cause different parts of the spillway channel to experience different flow durations, but the SITES model is incapable of simulating two-dimensional aspects or the staged operation of the fuse plugs. It assumes that any flow through the spillway is distributed across the full spillway width. This required an adjustment of the spillway description in the model. Since fuse plug 1 will operate for the longest period of time, a run was made specifically to analyze erosion on the left side of the spillway. For this run, the spillway was defined to be 120 ft wide and the hydrograph provided to SITES consisted of just the flow through the first fuse plug bay. Thus, the unit discharge in bay 1 was correctly simulated throughout the run.

A second run was made to analyze erosion downstream from fuse plug 2, where the distance to the daylight location was shorter. For this run, the inflow hydrograph provided to the model was the routed outflow hydrograph for fuse plug 2 and the spillway width was entered as 150 ft, the width of bay 2. Runs to examine erosion in bays 3 and 4 were not specifically made. The length of the excavated channel downstream from these fuse plugs is similar to bay 2 and unit discharges in these bays would be similar to those in bays 1 and 2, but the flow duration would be less, since fuse plugs 3 and 4 do not breach until the later stages of any flood event. Thus, erosion downstream from these fuse plugs should be less severe than that in bay 1 or 2.

The runs just described were made for the 500,000-yr return interval flood. In addition, a set of runs was made for the 5,000-yr return interval flood, the smallest flood analyzed that causes operation of the fuse plug spillway. During this flood, only fuse plug 1 operates, so a simulation of flow through bay 2 was not needed.

Material Parameters

The Brule siltstone is an unusual material which weathers very rapidly when exposed to air and allowed to dry. The ground surface is a very dusty, soil-like material, but within inches of the surface the material becomes rock-like, and at depth the material is believed to be very massive.

Figure 3. — Brule siltstone material exposed in test trench TT-06-1. This material has weathered for about 4-5 months.

Three material parameters are needed for input to the SITES model.

- headcut erodibility index, K_h
- representative diameter of material
- detachment rate coefficient, k_d

The critical shear stress, τ_c, is determined internally in the SITES model from the material diameter input.

Two material layers were defined in the SITES model, an upper weathered layer from the original ground surface to 25 ft depth, and a deeper, unweathered layer beneath 25 ft depth. In the spillway cut, the weathered layer was assumed to begin about 35 ft downstream from the end of concrete in fuse plug bay 1, and about 30 ft downstream in fuse plug bay 2. In addition to the “weathered” and “unweathered” layers entered into the model, there will also be a highly weathered near-surface layer (top few inches) that is neglected in the analysis, since it will be quickly eroded, thus exposing material that has not undergone extreme surface weathering.

Values of k_d and τ_c were obtained from a set of two *in situ* jet tests conducted at the site on May 3, 2007 by Engineering & Hydrosystems of Littleton, Colorado. The tests were performed with assistance from the Bureau of Reclamation, Technical Service Center, and utilized a jet test device belonging to Reclamation.

Two jet tests were performed at sites located within test trench TT-06-1, at a depth that is within 25 ft of the original ground surface. In the first of the two tests, some weathering occurred while the test site was being prepared and this test was believed to be somewhat indicative of the material that would be found in the highly weathered surface layer. For the second test, the site was more carefully preserved in an unweathered state during site preparation, and these results were believed to be representative of both the weathered layer (0 to 25 ft) and the deep, unweathered layer, neither of which has experienced the extreme surface weathering. Material below the 25 ft depth level may be even more erosion resistant than the test indicated.

The jet test consists of directing a ¼-inch diameter submerged hydraulic jet at the surface of the material, with the jet initially positioned about 6 to 30 jet diameters from the surface. Erosion depth beneath the jet is measured periodically over a time period of about 1 to 2 hours. Through analysis of the test data, values of k_d and τ_c can be determined. The test typically is used in soil-like materials and uses a pressure head of 1 to 8 ft to drive the jet. Due to the low erodibility of this material, we used jet pressures as high as 24 psi (55 ft of head), and positioned the jet at the minimum distance from the surface, 1.5 inches (6 jet diameters). The first test produced 0.020 ft of scour in 38 minutes. The test was terminated early because the seal between the submergence tank and the ground surface was lost, making it impossible to maintain submergence of the jet, but the scour beneath the jet appeared to have already reached a near-equilibrium condition. The second test was run for 60 minutes and produced only 0.002 ft of scour.

The second test yielded a detachment rate coefficient of 0.0057 (ft/hr)/(lb/ft^2), and a critical shear stress of 17.9 lb/ft^2. The detachment rate coefficient from the first test was 12.4 times higher, and the critical shear stress was 5.7 times smaller, indicating the large variability of the material due to weathering differences and other factors.

Table 1. — Material properties used for SITES analysis.

Layer	K_h	**Representative diameter** (inches)	k_d (ft/hr)/(lb/ft^2)	**Dry density** (lb/ft^3)
Concrete	12000	240	-	150
Weathered, top 25 ft	0.847	32	0.0057	130
Unweathered, deeper than 25 ft	75.2	165	0.0057	130

Values of the representative diameter for input into SITES were obtained in two ways. First, for the deeper layer (below 25 ft depth), the representative block sizes were based on joint spacings estimated from geologic investigations to be 0.33 m x 15 m x 15 m. This yielded a block volume of 74 m^3, or an effective diameter of 4.2 m (165 inches). Such a material would have an approximate critical shear stress of τ_c=100 lb/ft^2. Geologic investigations suggested an estimate of 9.4 inch diameter material in the upper 25 ft layer, but the jet test indicated a critical shear stress of 17.9 lb/ft^2, which equates to a 32 inch diameter material on Shield's diagram for incipient motion. Since the diameter input is used in the SITES model to determine the critical shear stress, τ_c, a diameter of 32 inches was used so that a critical shear matching the jet test result would be used in the model.

Some other geometric simplifications were made in setting up the model. The crest of the control structure was made flat and level at elevation 4653 ft, and a thin layer of upper Brule material was included in the model which is not actually present in the proposed design. This was done because the model has been internally programmed to try to initiate the headcutting process at the first break in slope downstream from the point of hydraulic control; if the actual top-of-concrete surface had been entered, the model would have tried to initiate headcutting on the concrete apron. It is important to keep in mind that the SITES model is not simulating details such as the effect of the sill block and small concrete flip at the downstream end of the concrete apron. Experimentation with the model showed that minor changes in the geometry of the concrete crest had no significant effect on the results, and the inclusion of this small extra amount of weaker Brule material is believed to be inconsequential.

Erosion Modeling Results

Three base-condition runs of the SITES model were made:

1. Spillway flows occurring downstream from fuse plug bay 1 during 500,000-yr return interval event,
2. Spillway flows occurring downstream from fuse plug bay 2 during 500,000-yr return interval event, and
3. Spillway flows occurring downstream from fuse plug bay 1 during 5,000-yr return interval event.

The spillway hydrographs for these three events, shown in Figure 4, are surprisingly quite similar. The hydrographs through fuse plug bays 1 and 2 are almost identical during the 500,000-yr event. The hydrograph through fuse plug bay 1 during the 5,000-yr event has about 75% of the peak discharge of the hydrograph during the 500,000-yr event, but a longer duration, presumably because the reservoir drains more slowly with only one fuse plug bay opened. The volumes of water discharged in each case are approximately the same.

Figure 5 shows the predicted erosion in the first case. Table 2 summarizes results for the other cases.

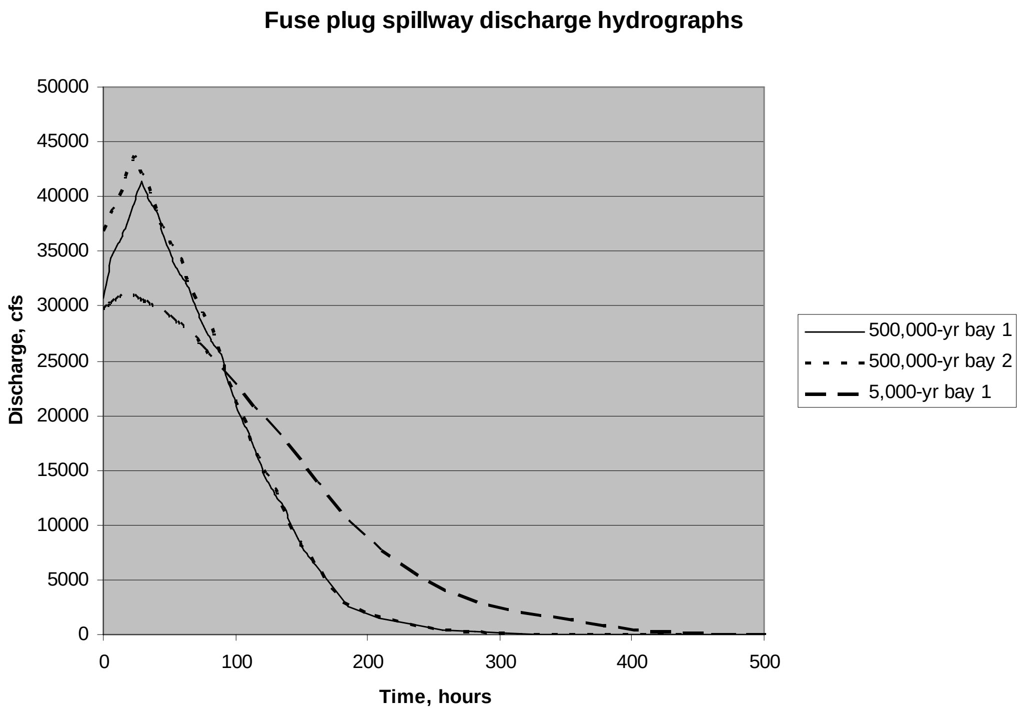

Figure 4. — Discharge hydrographs through fuse plug spillway bays, normalized to a common time base for comparison.

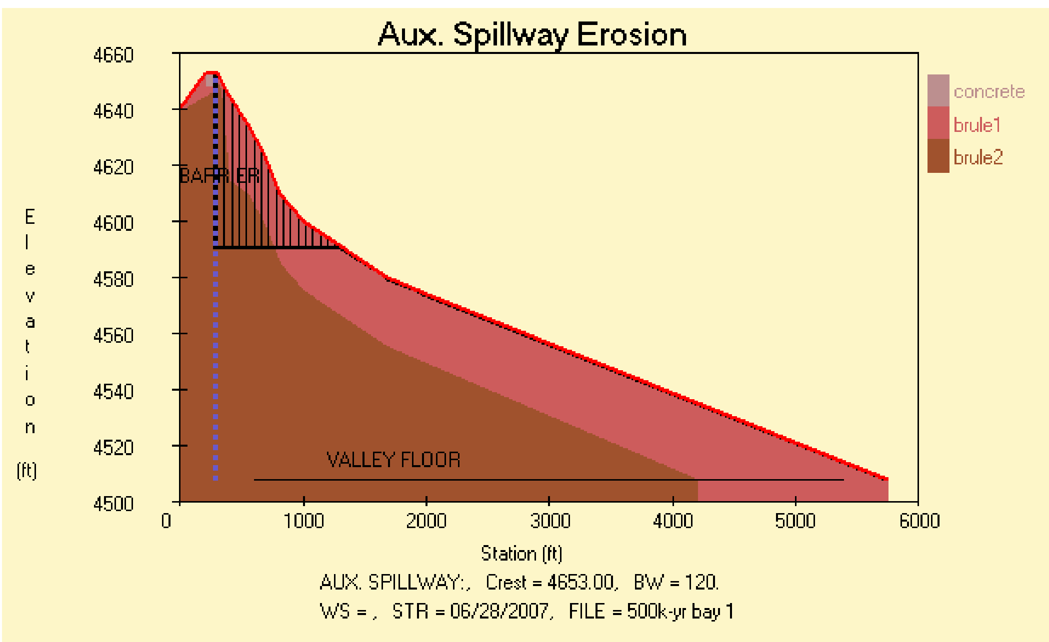

Figure 5. — Predicted headcut erosion for base case, 500,000-yr event through fuse plug bay 1. Black vertically-hatched area indicates removal of material by headcut erosion. The vertical dashed line is the barrier wall.

Table 2. — Summary of results for initial runs of the SITES model.

Case	Bottom elevation of most upstream headcut (ft)	Maximum upstream headcut advance, distance from barrier (ft)
500,000-yr, bay 1	4590.7	0
500,000-yr, bay 2	4591.4	0
5,000-yr bay 1	4590.9	0
500,000-yr, bay 1 *** No cutoff wall	Spillway breached after 69 hours	

In all three cases, the headcut advanced to the cutoff wall (barrier), which is assumed by the SITES model to be of infinite depth. In the simulation, the headcut reached a depth below the bottom of the currently proposed cutoff wall, which reaches elev. 4607.0 ft. To demonstrate the influence of the cutoff wall, one additional run was made in which no cutoff wall was included; this run indicated that the spillway would breach after 69 hours of operation.

The surprising result that headcutting is nearly as severe in the 5,000-yr case as the 500,000-yr case is due to the fact that the unit discharges are similar in both cases, and the flow duration is actually longer in the 5,000-yr case due to the time required to drain the flood surcharge volume through only one open fuse plug bay.

Sensitivity Testing

To test the sensitivity of the results to material parameter inputs, a series of runs were made with varying representative diameters and with different detachment rate coefficients (k_d) and headcut indices (K_h). These runs were all variations of the first case (500,000-yr hydrograph through fuse plug bay 1). The three parameters were each varied by amounts representative of the range of uncertainty in our knowledge of the true values.

Table 3 summarizes the results. The model proves to be extremely sensitive to the k_d parameter within a narrow range of values. This is believed to be due to an interaction between k_d and K_h during the phase 3 headcut advance process. Small changes in the value of k_d are believed to change the rate of deepening of headcuts that have already initiated. When a headcut continues to deepen, this in turn leads to greater energy dissipation at the headcut, which allows the headcut advance rate to also increase. As headcuts advance and grow deeper, the headcut height is further increased, accelerating the process. This is a result of conservative assumptions made in the development of the model, specifically the decision to model the deepening of headcuts in rock materials using a model based on shear stress, τ_c, and k_d, and an assumption (since τ_c comes from the particle diameter and Shield’s diagram) that the materials at the base of the headcut are loose and ready to be transported, rather than being part of a coherent rock mass. An alternative approach in the development of SITES that might have made the model more applicable to rock channel applications would have been to relate the deepening of existing headcuts to energy dissipation and the value of K_h (similar to the headcut advance model), since rock mass integrity is incorporated into the K_h value. This was not done because USDA envisioned very few applications to rock channels in their dam inventory, and preferred to develop a model best suited to channels composed of soil-like materials (personal communication, Darrel Temple, retired USDA-ARS).

Table 3. — Summary of runs made to evaluate sensitivity and uncertainty of SITES model results.

Description of change from 500,000-yr, bay 1 base case	**Bottom elevation of headcut at barrier (ft)**	**Maximum upstream advance of deepest headcut, distance from barrier (ft)**
BASE CASE: 500,000-yr event, bay 1	4590.7	0
Hydrograph magnitude reduced by half	4601.6	0
Hydrograph duration reduced by half	4598.8	0
Upper layer of Brule representative diameter doubled to 64 inches	4598.2	0
Lower layer of Brule representative diameter doubled to 330 inches	4590.7	0
Divide k_d of both Brule layers by 2	4599.2	0
Divide k_d of both Brule layers by 2 *** No cutoff wall	Spillway breached after 122 hours	
Divide k_d of both Brule layers by 5 **(*see Fig. 6*)**	—	48
Divide k_d of both Brule layers by 8	—	217
Divide k_d of both Brule layers by 8.25 **(*see Fig. 7*)**	—	268
Divide k_d of both Brule layers by 8.5 **(*see Fig. 8*)**	—	503
Multiply K_h of both Brule layers by 2	4590.7	0
Multiply K_h of both Brule layers by 10	4596.2	0

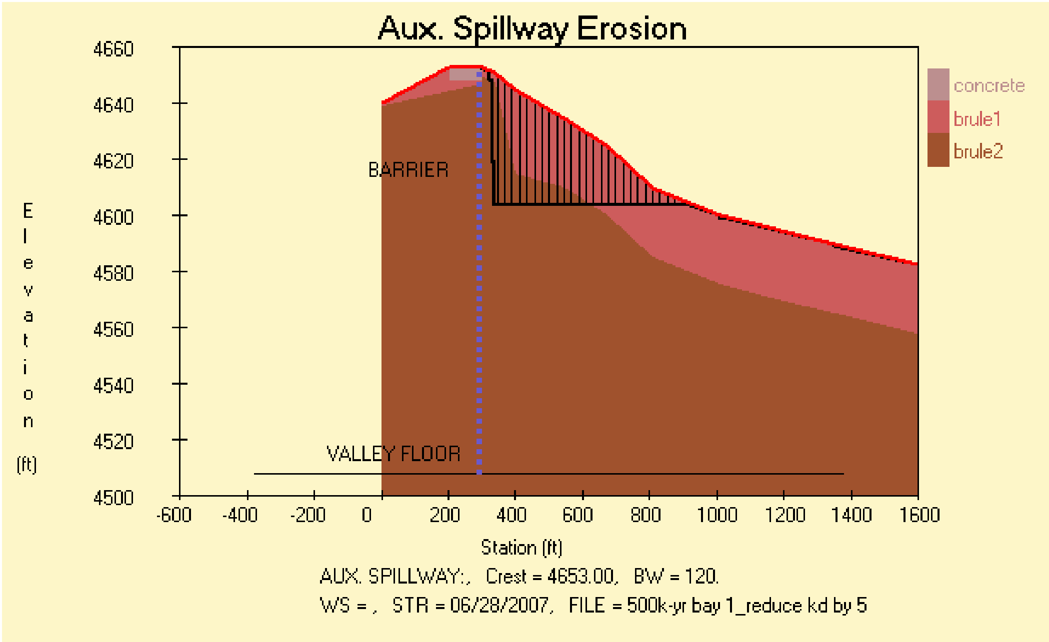

Figure 6. — Effect of reducing k_d values by factor of 5.

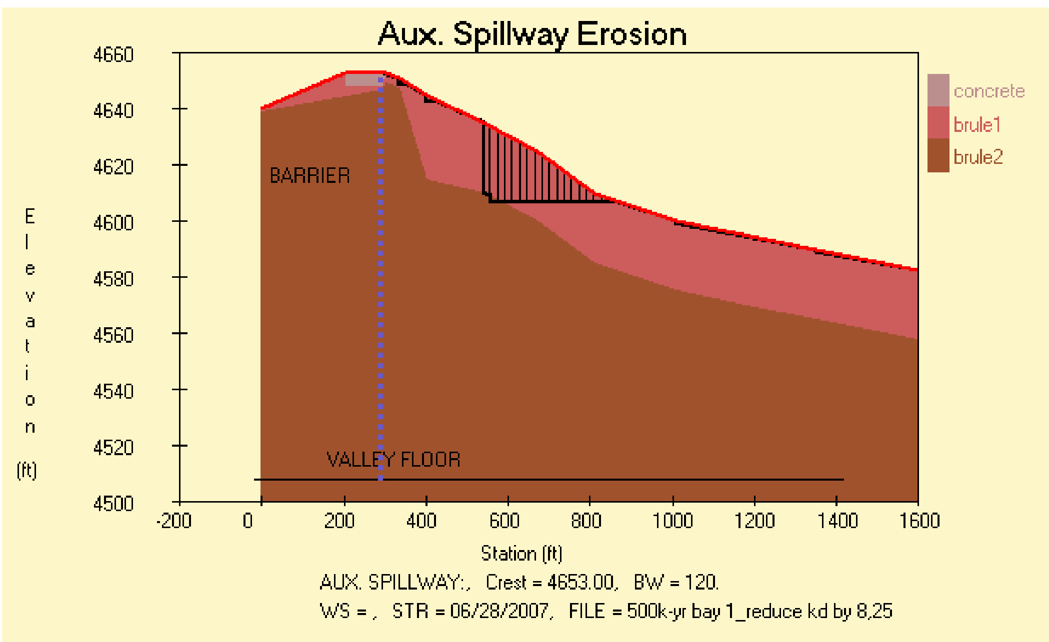

Figure 7. — Effect of reducing k_d values by a factor of 8.25.

Conclusions

Runs of the SITES model that utilize field-measured values of the detachment rate coefficient and critical shear stress parameter and values of headcut erodibility

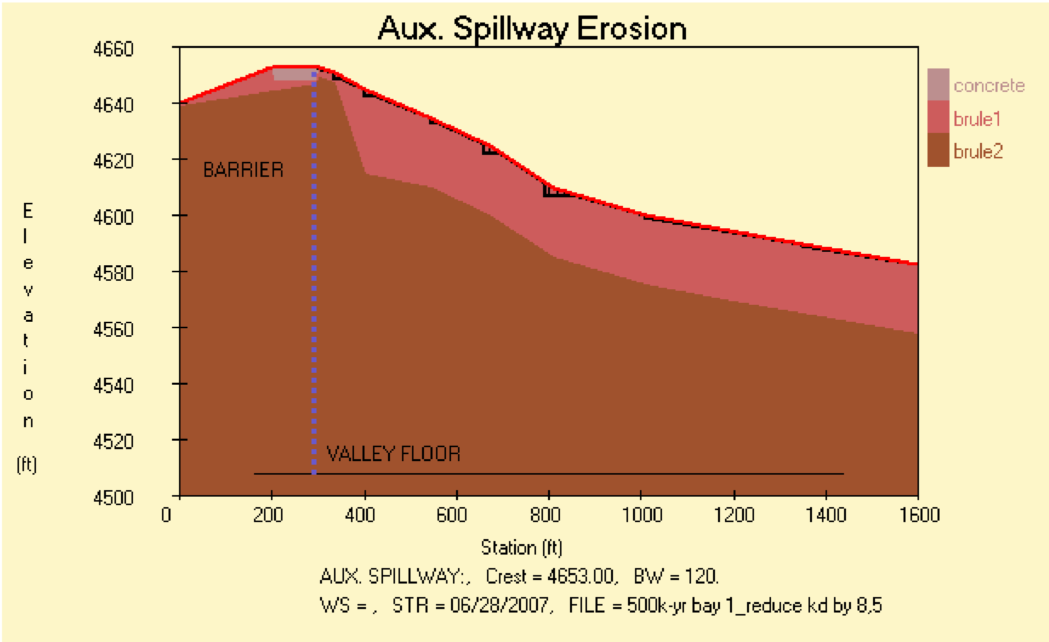

Figure 8. — Effect of reducing k_d values by a factor of 8.5.

index derived from geologic investigations predict headcut erosion that will threaten to breach the spillway control structure, as presently proposed.

Field tests used to determine the detachment rate coefficient and critical shear stress exhibited high variability. Although the tests were carried out at the highest possible stress ranges that could be produced with available equipment, they produced only slight erosion of the Brule siltstone material. Inferring values of erodibility parameters from tests that produce only slight erosion implies significant uncertainty. Since the Brule siltstone was very easily affected by weathering, any weathering or damage to the tested materials that took place during test equipment setup may have significantly affected the results. Thus, it is quite possible that the material in its unweathered state is even less erodible than indicated by the parameter values obtained in the tests.

Predictions of erosion from the SITES model are extremely sensitive to the value of the detachment rate coefficient. Given the uncertainty of the field tests used to determine this coefficient, the uncertainty of the SITES model results is also quite large. Reducing the detachment rate coefficient by a factor of 5 or more leads the SITES model to predict some erosion, but no breach of the spillway channel. The uncertainty in the true value of k_d is probably at least one order of magnitude (factor of 10), based on Reclamation experience with jet erosion testing of a variety of materials. We should also keep in mind that we conservatively assumed no spreading of the flow downstream from the control structure. Spreading of the flow will reduce unit discharges and flow velocities and should thus reduce erosion.

Strengthening and deepening of the cutoff wall could increase stability of the structure and protect against an unintended breach, thus reducing uncertainty in the performance of this design. Some details of the design that may affect erosion of the spillway channel (e.g., effect of a small flip at the end of the concrete apron) could not be evaluated using the SITES model.

Research Needs

There is presently a lack of good computational modeling tools for analyzing headcut erosion of rock-like materials. SITES, having been proven as a useful tool for modeling headcut erosion of soil-like materials, seemed like a tool that could potentially be applied also to rock-like materials. Unfortunately, this study has illustrated the limitations of the SITES model in this arena. The fundamental problem is an extreme sensitivity to the detachment rate coefficient, k_d, which controls the rate of headcut deepening. Rapid headcut deepening can lead to rapid headcut advancement, even in resistant materials. The k_d parameter is clearly the most important input to SITES in its current configuration, but the state-of-the-art erosion testing equipment designed for determining k_d is better-suited to the evaluation of soil-like materials.

Two potential avenues of research seem to have potential for improving the situation. The first would be to relate k_d and K_h, the headcut erodibility index. Values of K_h are determined on the basis of tests that are relevant to rock-like materials, so a k_d-K_h relationship might offer a better way to estimate values of k_d for rock-like materials. The second approach would be to develop a model for the rate of headcut deepening as a function of K_h, rather than k_d. The two approaches might give similar results, depending on the degree of scatter in a potential k_d-K_h relationship.

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