

RECLAMATION

Managing Water in the West

Hydraulic Laboratory Report HL-2009-03

Numerical Modeling of Headcut Erosion in 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
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

November 2009

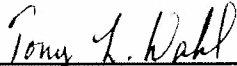
REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) 03-11-2009		2. REPORT TYPE Technical		3. DATES COVERED (From - To) May 2007 – October 2009	
4. TITLE AND SUBTITLE Numerical Modeling of Headcut Erosion in Auxiliary Spillway Channel at Glendo Dam			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Tony L. Wahl			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of the Interior, Bureau of Reclamation Technical Service Center, 86-68460 P.O. Box 25007 Denver, CO 80225			8. PERFORMING ORGANIZATION REPORT NUMBER HL-2009-03		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of the Interior, Bureau of Reclamation Dam Safety Office, 84-44000 P.O. Box 25007 Denver, CO 80225			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161 http://www.ntis.gov					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT A new uncontrolled auxiliary spillway to be excavated through Brule siltstone at Glendo Dam, Wyoming was evaluated to determine the potential for headcut erosion in the unlined spillway channel. The SITES numerical model developed by USDA was used to simulate headcut erosion for the 100,000-yr flood event and for smaller floods likely to occur during the service life of the project. A variety of scenarios were considered ranging from best-case to worst-case combinations of the parameters that describe the erodibility of the materials in the spillway channel. The results were most sensitive to the detachment rate coefficient. Values of this parameter were estimated using field and laboratory jet erosion tests and by comparison to erodibility parameters measured by other investigators on cohesive soils that are likely to be more erodible than the Brule siltstone material. Although very significant headcut erosion was predicted by the SITES model for some scenarios, a complete breach of the spillway was not predicted for any case. As a result of the modeling, the current design of the spillway was deemed to be acceptable from an erosion standpoint.					
15. SUBJECT TERMS hydraulic modeling, hydraulic structure, headcut erosion, erodibility, spillway					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 20	19a. NAME OF RESPONSIBLE PERSON Robert Einhellig
a. REPORT UL	b. ABSTRACT UL	a. THIS PAGE UL			19b. TELEPHONE NUMBER (Include area code) 303-445-2142

Hydraulic Laboratory Report HL-2009-03

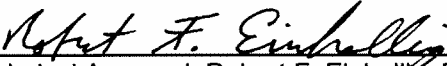
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Pick-Sloan Missouri Basin Project, Wyoming
Great Plains Region

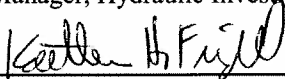
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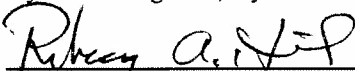
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Bureau of Reclamation
Technical Service Center
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Denver, Colorado

November 2009

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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.

Acknowledgments

This study was carried out as a member of the Glendo Dam Auxiliary Spillway design team. Bill Dressel and Rebecca Heisler provided input data needed to set up the SITES model, and also reviewed the model results and this report. Kathy Frizell also provided helpful comments as a peer reviewer of the report. Zeynep Erdogan assisted with the preparation of jet erosion specimens tested in the laboratory.

Disclaimer

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Introduction

Glendo Dam is located on the North Platte River in east-central Wyoming. To reduce the risk of dam failure due to overtopping during large hydrologic events, a new, uncontrolled ogee crest spillway will be constructed. A dam raise and modifications of the existing service spillway are also being undertaken as part of this Corrective Action. The proposed auxiliary spillway will be 540 ft wide, with an ogee-shaped reinforced concrete crest constructed over a deep roller-compacted concrete (RCC) plug extending approximately 28 feet below the bottom of the newly excavated spillway channel. The spillway is designed to convey a peak discharge of 100,000 ft³/s. With the dam raise and other modifications, this will allow the dam to safely route the 100,000-yr design flood event.

The spillway will be constructed through a sharp natural ridge on the southern rim of the reservoir, about 1 mile west from the dam. The spillway cut will be through Brule siltstone material, and the spillway channel will be unlined, except for the concrete used in the vicinity of the crest control structure and a thin top-soil lining that will provide some protection against weathering for the surface material. The Brule siltstone is a sedimentary rock of moderate strength, subject to rapid weathering by drying and slaking processes [1]. When pulverized, the material exhibits soil-like properties and over the depths of interest is classified as a Sandy Silt, ML, or Silty Sand, SM, with 40 to 60 percent sand and the remainder fines. Samples exhibiting plasticity have Liquid Limits ranging from 33 to 45 and Plasticity Index values of 8 to 14. The material has a specific gravity ranging from 2.38 to 2.61.

This report describes and provides results of numerical modeling undertaken to evaluate the potential for headcut erosion in the unlined spillway channel. Field and laboratory tests performed to develop quantitative erodibility parameters for the Brule siltstone material in support of this modeling effort are also discussed. A physical hydraulic model study of the new spillway was also performed during the summer of 2009, but that study did not specifically address the headcut erosion issue [2].

Headcut Erosion Modeling

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 [3]). The analysis makes significant use

of only one component of the SITES model: the earth auxiliary spillway evaluation module. A detailed description of SITES and its approach to the modeling of headcut erosion are contained in Hydraulic Laboratory Report HL-2008-05 [4], which provides results of an earlier effort to model headcut erosion in a fuse plug auxiliary spillway proposed for this same site.

To briefly review, the SITES model allows the user to define the materials in and underlying the spillway excavation and to specify the flood hydrograph that will flow through the spillway. The model simulates flow in the spillway channel using steady uniform-flow equations and erosion as a three-phase process consisting of (1) vegetation removal, (2) concentrated erosion to develop knickpoints in the channel, and (3) the deepening and upstream migration of headcuts. In the Glendo application, vegetation in the spillway is expected to be of no value in preventing or delaying erosion, and the expected weathering of the excavated spillway channel surface (despite topsoil protection) will allow for rapid progression into the third phase of the process. During the third phase, the model tracks the upstream advance and deepening of individual headcuts that have initiated at sections of high velocity flow and changes in channel slope (natural triggers for concentrated erosion). The model allows for the combination of multiple small headcuts into one larger headcut and eventually reports the estimated location and depth of the most upstream and deepest headcuts following the passage of the flood hydrograph through the spillway.

The thresholds and rate for headcut formation and advance are controlled in the model primarily by three parameters describing the materials in the spillway channel. These parameters are the representative diameter of the material, a detachment rate coefficient (k_d), and a headcut erodibility index (K_h). The first two parameters primarily control the rate of downward erosion, while the last parameter controls the rate of upstream headcut advance.

The representative diameter is determined by an evaluation of the geology and examination of drill hole data obtained from the site. The diameter parameter is used by the SITES model to compute a critical shear stress, τ_c , (via Shield's diagram) needed to initiate downward erosion of the material. An inherent assumption in the use of Shield's diagram is that the particles whose diameter are specified are loose and free to be transported by the flow, not integrated into a larger rock mass.

The detachment rate coefficient k_d expresses the rate of downward erosion per unit of applied stress in excess of the computed critical shear stress. For soil materials, k_d can be estimated as a function of the dry bulk density of the material and the percentage of clay. Values of both τ_c and k_d can also be determined by *in situ* (field) or laboratory testing with a submerged jet device (Hanson and Cook 2004 [5]). Field or laboratory testing are generally preferred when possible. The mathematical model of downward erosion used by SITES and the submerged jet device were both originally developed for application to soil-like materials; for

the Glendo case, we are applying them to the Brule siltstone, which has some characteristics of both soil and rock.

The headcut erodibility index establishes the threshold for headcut advance and the rate of advance as a function of the energy dissipation that takes place at a specific headcut. 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 were estimated by Rebecca Heisler, Geologist, Engineering Geology Group, for three layers: a weathered upper layer (ground surface to 40 ft depth), a second layer from 40 to 90 ft below original ground surface, and a third layer more than 90 ft below the original ground surface.

Material Parameters

For each of the three material layers previously described, estimates of “most likely”, “best case”, and “worst case” erodibility parameters were made. These estimates were made using geologic data obtained through the field exploration program (drill holes and test trench), results of field and lab erodibility testing, comparison to reported values in the literature, and engineering judgment. Details for each parameter follow.

Submerged Jet Erosion Tests

A total of four submerged jet erosion tests were performed, two on May 3, 2007 in the field in test trench TT-06-1, and two in the laboratory from September 8-10, 2009 utilizing core samples from drill hole DH-07-5. The objective of these tests was to evaluate the erodibility of the material in its moist, *in situ* condition. Since the material is known to weather rapidly, we expect that in the first minutes of any future spillway operations, highly erodible material from the weathered surface layer would be removed, and the flow would then begin attacking the non-weathered material below. To answer the question of whether the spillway integrity can be maintained during design-flood operations, we need to know the erodibility of the non-weathered material.

The submerged jet erosion test is performed by subjecting a material sample to flow from an impinging hydraulic jet issuing from a ¼-inch diameter nozzle positioned initially about 1.5 inches from the surface of interest. The measured depth of scour produced by the jet over time is used to compute the critical shear stress and detachment rate coefficient for the material. The material sample and the jet are completely submerged throughout the test. This is accomplished in the field by installing a bottomless tank over the test site and sealing it to the ground surface with bentonite clay; in the laboratory a core sample can be placed into a

submergence tank. The same jet device may be attached to the top of either the field or laboratory tank. The pressure used to generate the jet flow is held constant throughout the test. For these tests, that pressure was approximately 22 to 24 psi, or about 50 to 55 ft of hydraulic head. For jet erosion tests of soil materials, a jet pressure of 1.5 to 6 ft of head is typical and scour depths of 0.25 to 2 inches are produced in tests lasting up to 2 hours. Table 1 summarizes the jet tests that were performed.

Table 1. — Results of submerged jet erosion tests.

Test No.	Date	Sample and depth below original ground surface	Applied stress psf	Duration min	Observed Scour ft	Results	
						k_d ft/hr/psf	τ_c psf
1	5/3/07	TT-06-1 (approx. 5' depth)	8.32	38	0.020	0.041	5.3
2	5/3/07	TT-06-1 (approx. 5' depth)	18.61	60	0.002	0.0037	20.7
3	9/8/09	DH-07-5 at 50.1-ft depth	26.1	1207	0.000	---	≥ 26.1
4	9/9/09	DH-07-5 at 13.6-ft depth	26.1	1488	0.000	---	≥ 26.1

Tests 1 and 2 were performed on site in the test trench, jointly by the Bureau of Reclamation and a contractor, Engineering & Hydrosystems (E&H). The results reported here are from a reanalysis of the data by Reclamation, as the results provided by E&H [6] were in S.I. units and lacked sufficient precision to be accurately reported when converted to customary English units. Test 1 produced the lowest critical shear stress and highest erodibility rate coefficient of any of the tests, but this is believed to be due to the fact that the site was not sufficiently protected from weathering (drying and subsequent slaking) during site preparation, which took about 90 minutes. Test 2 is believed to be more representative of the erodibility of the material in the *in situ* condition, as this site was very carefully protected from drying during test setup. It should be noted that even for this test, the surface that was tested had been within about 2-3 inches of the surface for several weeks prior to the test, so some weathering could have occurred during that time. Also, it should be noted that only 0.002 ft of scour was observed, and the first 0.001 ft occurred in the first minute of the test, so this may have been due to removal of previously weathered material from the surface. (The second 0.001 ft erosion increment was observed between 3 and 5 minutes into the test, after which there was no more erosion for 55 minutes). If this test were to be reanalyzed with the first minute of erosion ignored, the value of k_d would drop by a factor of about 2 to 0.0019 ft/hr/psf. It is probable that even the second increment of erosion may have been due to removal of somewhat weathered material, which would suggest that k_d could be even lower, and τ_c higher.

Tests 3 and 4 were performed in the hydraulics laboratory in September of 2009. The drill core samples used for these tests had been stored in 75% humidity, 73°F conditions for more than two years, but showed no effects of weathering. Table 1 shows that the tests were conducted at higher stress conditions than the two field

tests and for durations far exceeding those of the field tests, but no measurable erosion occurred. The lack of measurable erosion makes it impossible to determine a value for k_d , but we can state that the critical shear stress is greater than the stress applied during the tests and we would expect a commensurately low value for k_d .

Figure 1 shows the results of submerged jet tests performed on a broad range of cohesive soils from streambeds in loess regions of the United States (Hanson and Simon 2001 [7]). Overlaid on this chart, the dashed line is a visually fitted relation between the detachment rate coefficient and the critical shear stress. (Conversions to English customary units are $0.5655 \text{ ft/hr/psf} = 1 \text{ cm}^3/(\text{N}\cdot\text{s})$, and $47.9 \text{ Pa} = 1 \text{ psf}$). On the basis of this chart, we can speculate that materials with a critical shear stress in excess of 26.1 psf (1250 Pa) would have an expected k_d value less than or equal to $0.002 \text{ cm}^3/(\text{N}\cdot\text{s})$, or 0.0011 ft/hr/psf . The lowest value of k_d on the chart is $0.001 \text{ cm}^3/(\text{N}\cdot\text{s})$ or $0.00057 \text{ ft/hr/psf}$, and the highest value of k_d within the “very resistant” erodibility class is about $0.03 \text{ cm}^3/(\text{N}\cdot\text{s})$ or 0.017 ft/hr/psf . These will serve as bracketing values for best and worst-case scenarios.

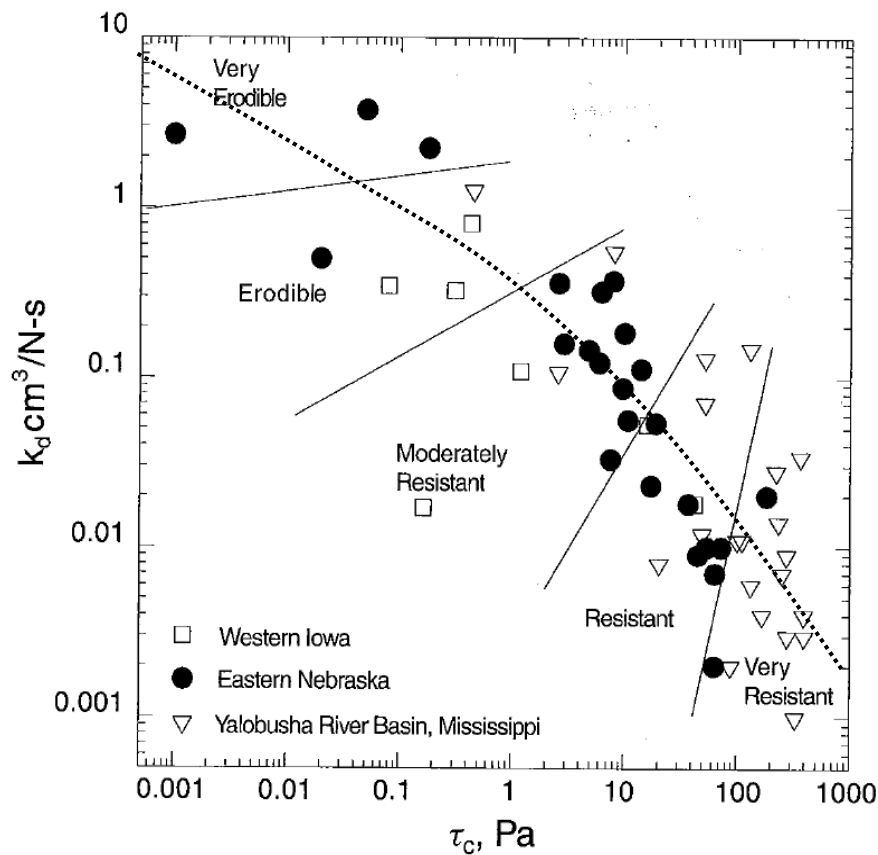


Figure 1. — Submerged jet test results for cohesive streambed sediments in loess areas of the midwestern United States (Hanson and Simon 2001 [7]). The dashed line overlaid on this chart is a visual curve fit to these data (proposed for this study, not by Hanson and Simon).

Representative Diameters

Representative particle diameter values for the three material layers were assigned as shown in Table 2.

Table 2. — Representative diameters of materials in spillway channel.

Layer	Best case	Most likely	Worst case
0-40 ft below original ground surface	40.4 inches	34	27
	Particle requiring a shear stress of 20.7 psf to initiate erosion (result from jet test 2)	Mean of best and worst cases	Round particle with volume equivalent to a block measuring 1x2x3 ft
40 - 90 ft	75	58	34
	Cubic particle equivalent to a block that is 1x15x15 ft	Round particle with volume equivalent to a block measuring 2x5x6 ft	Particle equivalent to a block that is 1x3x3 ft (presumes that 1-ft thick beds with joints on 15 ft spacing may break up into blocks with a 1:3:3 aspect ratio)
> 90 ft	93	58	34
	Spherical particle equivalent to a block that is 1x15x15 ft	Round particle with volume equivalent to a block measuring 2x5x6 ft	Particle equivalent to a block that is 1x3x3 ft

Detachment Rate Coefficients, k_d

Detachment rate coefficients were assigned as shown in Table 3.

Table 3. — Values of the detachment rate coefficient.

Note: $0.5655 \text{ ft/hr/psf} = 1 \text{ cm}^3/(\text{N-s})$.

Layer	Best case	Most likely	Worst case
0-40 ft below original ground surface	0.00057 ft/hr/psf (0.001 cm³/(N-s))	0.0011 ft/hr/psf (0.002 cm³/(N-s))	0.0037 ft/hr/psf (0.0065 cm³/(N-s))
	Lowest value of k_d on Hanson and Simon chart (Fig. 1)	Projected value of k_d for a material with critical shear stress of at least 26.1 psf	Result of field jet test #2
40 - 90 ft	0.00057 ft/hr/psf	0.00057 ft/hr/psf	0.0037 ft/hr/psf
	See above	Lowest value of k_d on Hanson and Simon chart (Fig. 1). Reflects belief that deeper layers will be more erosion resistant.	See above
> 90 ft	0.00057 ft/hr/psf	0.00057 ft/hr/psf	0.0037 ft/hr/psf
	See above	See above	See above

The jet tests performed in the field and in the laboratory established that the Brule siltstone material is at least as erosion resistant as the most resistant soil materials previously tested by this method. Thus, the values shown in the table above are still believed to represent conservative estimates of the bulk rate of detachment-driven downward erosion.

Headcut Erodibility Indexes, K_h

Headcut erodibility index values are determined through an analysis that combines geologic parameters relating to material strength, spacing and size of joints, properties of joints and joint-filling materials, and orientation of joints relative to the primary flow direction. The primary source of uncertainty used to establish the best-case and worst-case ranges of K_h values was the strength of the rock itself. Strength parameters were obtained primarily from the testing of drill core samples (see [1]). To be most conservative, for the upper layer the “most likely” value and “worst-case” value were assumed to be the same.

Table 4. — Values of the headcut erodibility index, K_h .

Layer	Best case	Most likely	Worst case
0-40 ft below original ground surface	11.2	7.2	7.2
40 - 90 ft	148	117	62
> 90 ft	164	130	65

Erosion Modeling Results

Erosion modeling was performed with the auxiliary spillway outflow hydrograph shown in Figure 2. This hydrograph represents a total volume of 957,000 ac-ft passing through the spillway during a 14-day period.

The spillway channel was modeled as 540 ft wide with 2:1 side slopes throughout its length from the control structure down to the point at which flow will be intercepted by the existing railroad line that is located south of the spillway. The profile of the spillway channel was defined by the use of topographic maps of the site. Beyond the end of the excavated channel, flow over the natural slope was assumed to still be contained within a 540-ft wide channel. In reality there will be both some spreading of the flow over the natural terrain and some concentration of flow within existing natural drainage channels, but these details cannot be modeled in the SITES software. To introduce some conservatism on this issue, the profile of the channel (i.e., channel slope) was estimated by following the steepest lines through natural drainage gullies existing at the site.

Auxiliary spillway outflow hydrograph

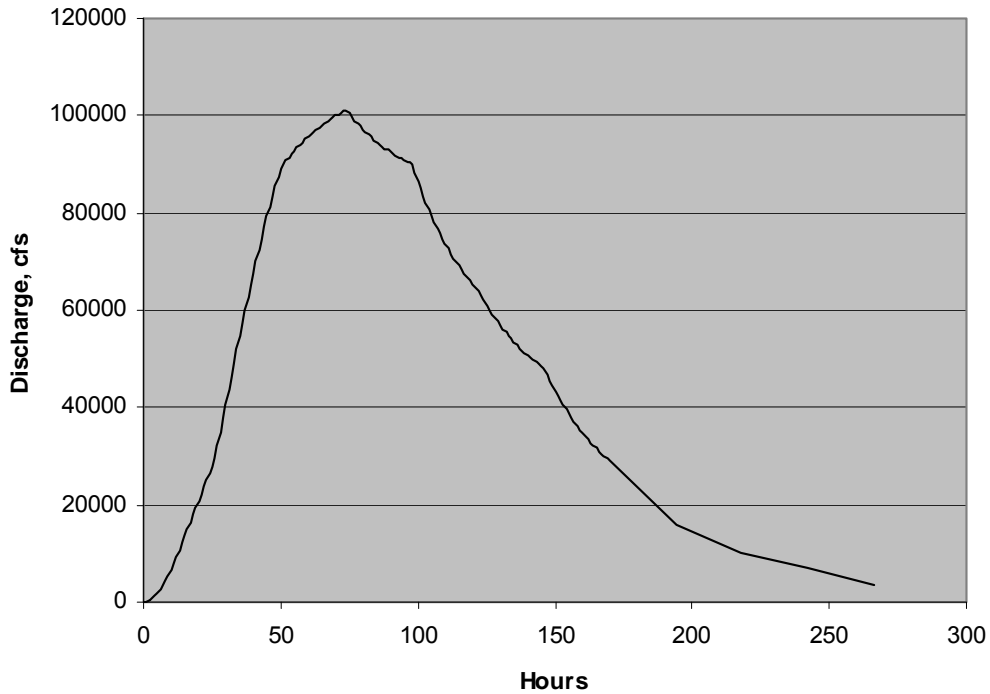


Figure 2. — Auxiliary spillway outflow hydrograph for the 100,000-yr event.

The concrete ogee-crest control structure, the downstream apron, and the underlying RCC block were included in the model. The concrete in the RCC plug was assigned a particle diameter of 240 inches and a headcut erodibility index of 12,000. No detachment rate coefficient was assigned, as the concrete was considered to be absolutely non-erodible by detachment of individual particles. A thin cutoff wall extending an additional 20 ft below the RCC plug was also included in the model, but this feature was subsequently eliminated from the design following a value engineering study of the project. The cutoff wall had no effect on the modeling results, and is not visible in the charts that appear on following pages because it was too narrow to be seen in the plots that are generated by SITES.

Table 5 presents the results of the SITES computer runs. The initial run, or “base case”, used the most likely values of all of the input parameters. Parameters were then varied one at a time (with values for all three layers changed simultaneously) to consider best- and worst-case scenarios for each of the three key parameters. A combined worst-case diameter and K_h case was also considered, since these parameters on their own seemed to have a relatively small effect on the results. Finally, combined best- and worst-case scenarios were considered in which all three parameters in all three material layers were set together to their best- and worst-case values.

Figure 3 shows the result of the base-case run. Headcutting back to nearly the edge of the RCC plug is predicted, with a depth approximately equal to the base of the RCC plug. Note that the SITES model does not attempt to simulate potential overturning of the RCC plug, but this was evaluated separately by the design team and the plug was found to be stable for the modeled condition. The best- and worst-case scenarios for particle diameter and headcut index show very little change from the base-case result (see Appendix for output charts from all runs). However, the sensitivity to variation of the detachment rate coefficient, k_d , is much more significant. In the best-case scenario for k_d (Figure 4), headcut advance stops at about the location where the 40-90 ft deep material layer is exposed in the spillway cut. The valley floor depicted in the figures effectively establishes a lower limit for headcut deepening. In these runs the valley floor elevation was set equal to the elevation of the existing land surface where a railroad embankment crosses the site downstream from the spillway crest. Flow will be turned at the embankment and then proceed more than 1 mile to the southeast before rejoining the North Platte River.

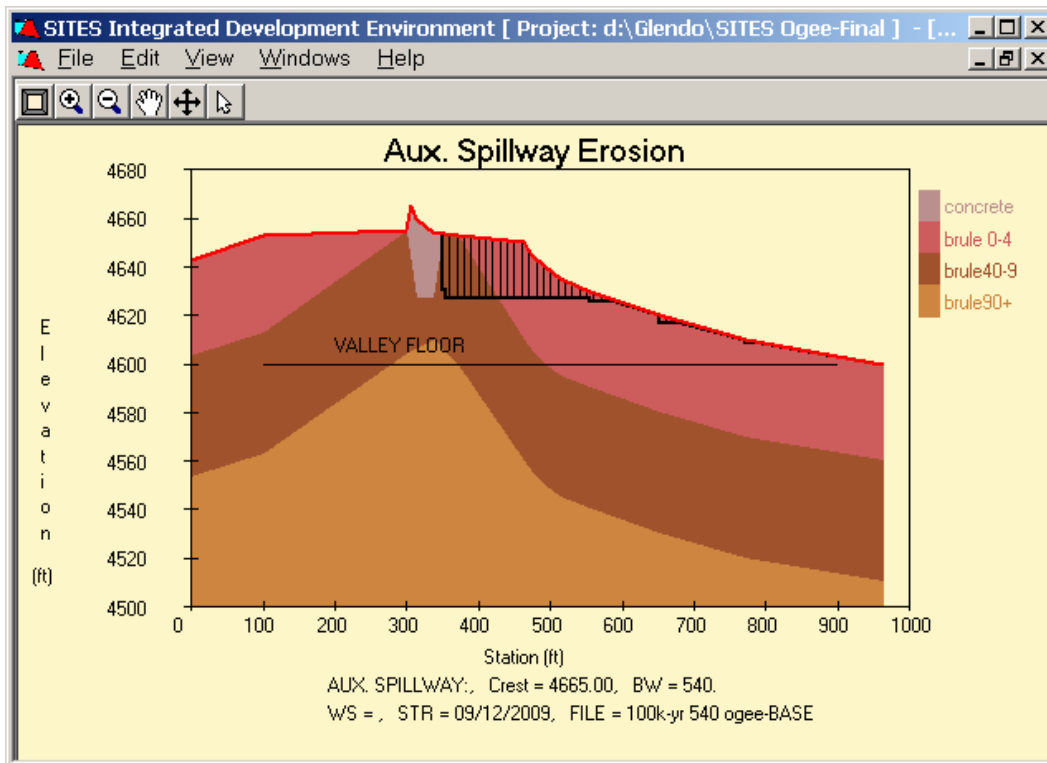


Figure 3. — Auxiliary spillway erosion predicted by SITES for the base-case condition. Note that the legend key labels for the “brule 0-40” and “brule 40-90” layers are cut off in the legend.

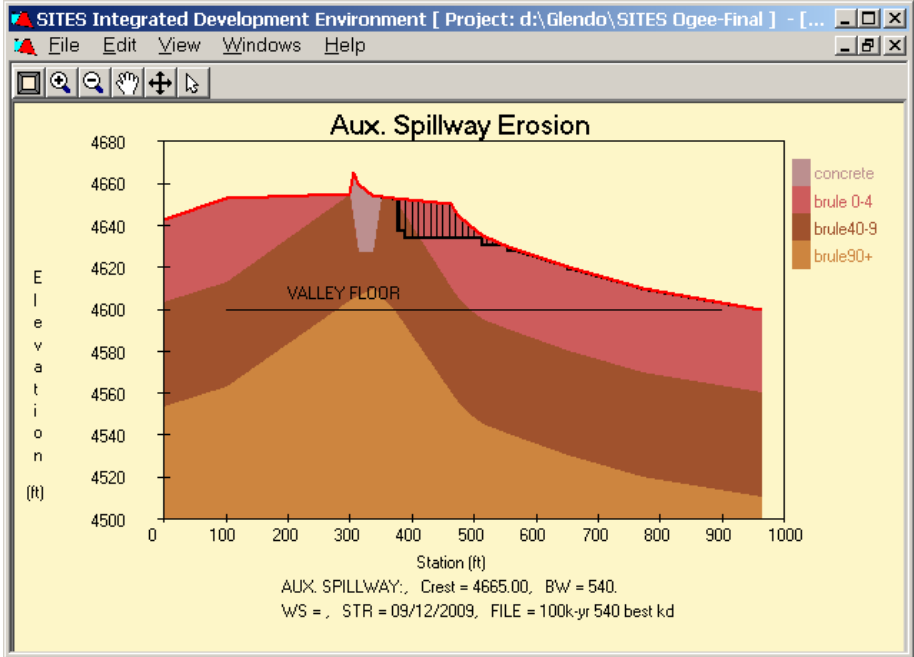


Figure 4. — Auxiliary spillway erosion predicted by SITES for the best-case k_d condition.

In the worst-case k_d condition (Figure 5), the headcutting deepens so that at the downstream side of the control structure, the headcut is deeper than the base of the RCC plug. However, the model does not predict a breach of the spillway, and also does not predict a breach for the combined, all-parameters, worst-case condition (Fig. 6).

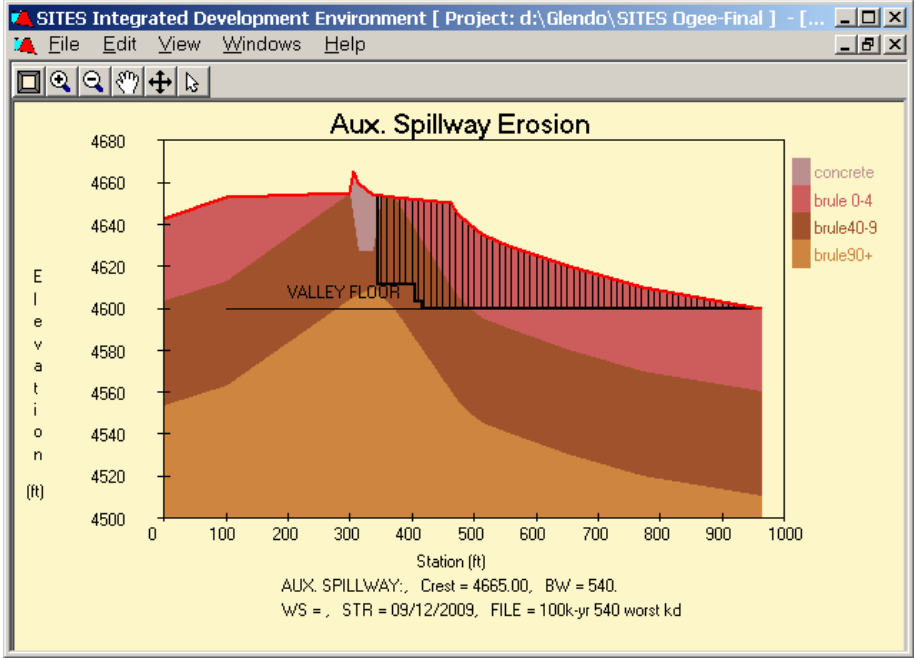


Figure 5. — Auxiliary spillway erosion predicted by SITES for the worst-case k_d condition.

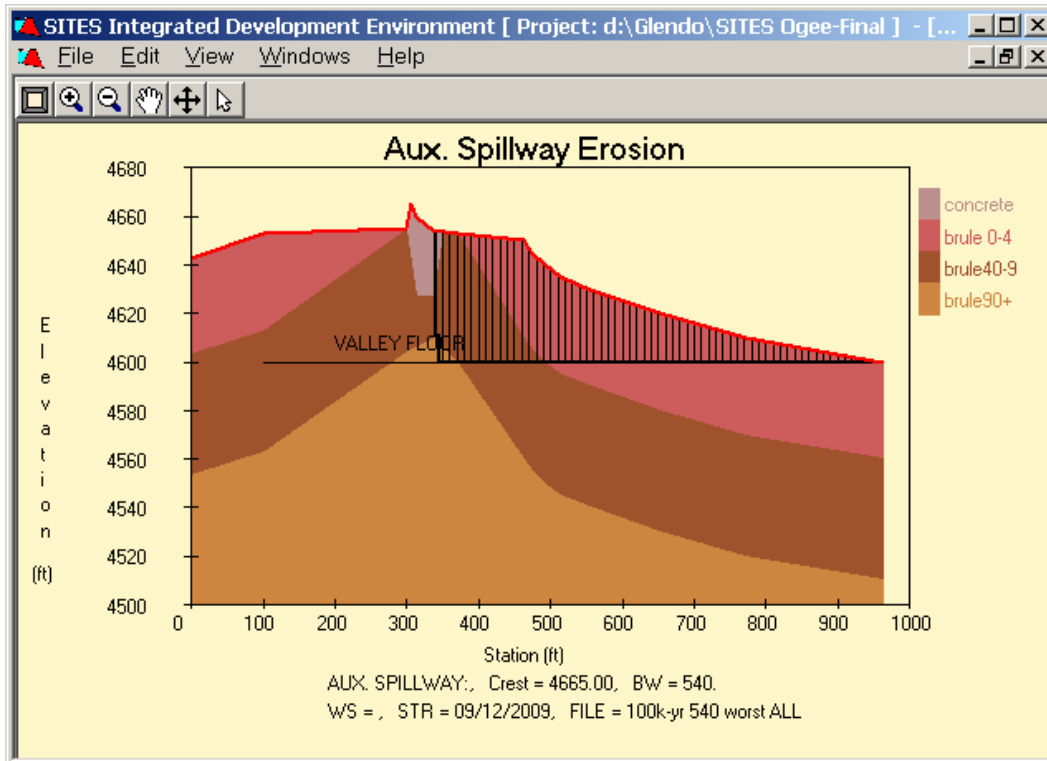


Figure 6. — Auxiliary spillway erosion predicted by SITES for the worst-case values of all erodibility parameters.

Figure 7 shows the results of one final run made with the erodibility parameters set to the base-case values, but with the spillway outflow discharges reduced to 25% of the values for the routed 100,000-yr flood. The deepest headcut is predicted to be just 5 ft deep and does not advance upstream. This run should indicate the type of erosion that could be expected to occur during spillway operations that are most likely to occur during the service life of the dam and spillway.

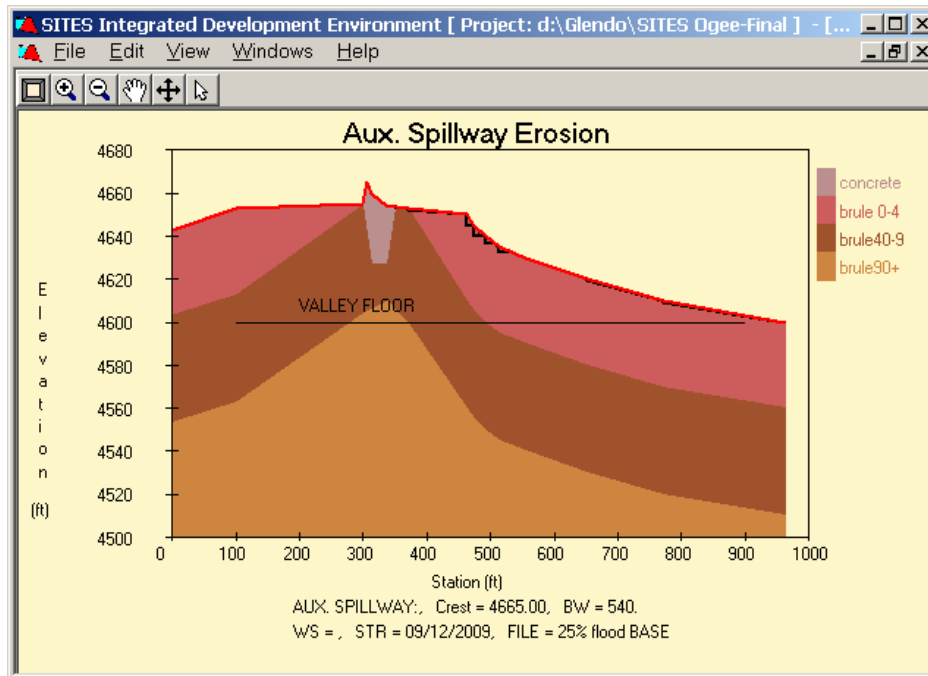


Figure 7. — Predicted headcut erosion for a spillway outflow hydrograph with flow magnitudes reduced to 25% of the 100,000-yr flood values. Erodibility parameters are set to the “most likely” values, or base-case condition.

Conclusions

The SITES model was used to simulate potential headcut erosion in the Glendo Dam auxiliary spillway channel for the 100,000-yr flood event and for a lesser flood that may be representative of floods likely to occur during the service life of the project. A variety of scenarios were considered ranging from best-case to worst-case combinations of the parameters that describe the erodibility of the materials in the spillway channel. The results proved to be most sensitive to the detachment rate coefficient, k_d . Values of this parameter were estimated using field and laboratory erosion tests and by comparison to erodibility parameters measured by other investigators on cohesive soils that are likely to be more erodible than the Brule siltstone material. Although very significant headcut erosion was predicted by the SITES model for several scenarios, a complete breach of the spillway was not predicted for any case. Erosion in the condition representing combined worst-case values of all parameters was severe enough that it would completely expose the downstream side of the RCC plug. However, because the SITES model was designed to provide conservative estimates of erosion and because conservative decisions were made in the selection of input parameters for this analysis, the combined worst-case scenario is believed to be extremely unlikely to occur. The results obtained from the modeling provide a justifiable basis for accepting the current design of the spillway.

Table 5. — Results of SITES erosion analysis modeling.

Layer		Input Parameters			Results - Headcut Depth and Station (Spillway Crest = Station 306. Stationing is arbitrary and relates only to this analysis.)								
		Representative diameter of material in headcut <i>inches</i>	Headcut Index, K_h	detachment rate coefficient, k_d <i>ft/hr/psf</i>									
0-40 ft	Parameter range	27 - 40.4	7.2 - 11.2	0.00057 - 0.0037									
	Most likely value	34	7.2	0.0011									
40-90 ft	Parameter range	33.8 - 75	62 - 148	0.00057 - 0.0037									
	Most likely value	58	117	0.00057									
>90 ft	Parameter range	33.8 - 93	65 - 164	0.00057 - 0.0037									
	Most likely value	58	130	0.00057									
Case Name		Parameter values by layer (0-40 / 40-90 / >90)			Most upstream				Deepest				
		Depth	Initial station	Advanced to station...	Total advance	Depth	Initial station	Advanced to station...	Total advance	Depth	Initial station	Advanced to station...	Total advance
		<i>ft</i>	<i>ft</i>	<i>ft</i>	<i>ft</i>	<i>ft</i>	<i>ft</i>	<i>ft</i>	<i>ft</i>	<i>ft</i>	<i>ft</i>	<i>ft</i>	<i>ft</i>
Base case		34 / 58 / 58	7.2 / 117 / 130	0.0011 / 0.00057 / 0.00057	22.7	492	349	143	26.2	514	354	160	
Best case (diam.)		40.4 / 75 / 93	7.2 / 117 / 130	0.0011 / 0.00057 / 0.00057	18.3	475	349	126	25.6	514	365	149	
Best case (K_h)		34 / 58 / 58	11.2 / 148 / 164	0.0011 / 0.00057 / 0.00057	18.4	475	350	125	25.7	514	373	141	
Best case (k_d)		34 / 58 / 58	7.2 / 117 / 130	0.00057 / 0.00057 / 0.00057	15.1	475	377	98	18.6	492	388	104	
Best case (ALL)		40.4 / 75 / 93	11.2 / 148 / 164	0.00057 / 0.00057 / 0.00057	6.1	475	385	90	17.1	492	427	65	
Worst case (diam.)		27 / 33.8 / 33.8	7.2 / 117 / 130	0.0011 / 0.00057 / 0.00057	23.1	492	349	143	26.7	514	349	165	
Worst case (K_h)		34 / 58 / 58	7.2 / 62 / 65	0.0011 / 0.00057 / 0.00057	22.8	492	348	144	26.4	514	348	166	
Worst case (k_d)		34 / 58 / 58	7.2 / 117 / 130	0.0037 / 0.0037 / 0.0037	28.8	514	345	169	51.4	829	416	413	
Worst case (diam. & K_h)		27 / 33.8 / 33.8	7.2 / 62 / 65	0.0011 / 0.00057 / 0.00057	23.2	492	347	145	26.7	514	347	167	
Worst case (ALL)		27 / 33.8 / 33.8	7.2 / 62 / 65	0.0037 / 0.0037 / 0.0037	43.4	652	341	311	53.6	818	346	472	
25% of 100,000-yr hydrograph - base case		34 / 58 / 58	7.2 / 117 / 130	0.0011 / 0.00057 / 0.00057	5.1	462	462	0	Most upstream headcut is also deepest				

Bold entries are different from the most likely value (different from base case)
Note that station 351 ft is the downstream end of the concrete apron below the spillway crest

References

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Appendix: Graphical Output of All SITES Model Runs

