MPC-354 (Year 2)

January 1, 2012 – December 31, 2013

Project Title:
Geotechnical Limit to Scour at Spill-through Abutments (Year 2)

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The University of Wyoming

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Research Needs:
Most cases of abutment failure attributable to scour show a geotechnical failure of the spill slope of earthfill embankment associated with the abutment. The abutment column typically remains standing. Figure 1 illustrates two typical examples. Because spill-slope failure increases the flow area through a bridge waterway, and deposits material in the scour area, the maximum scour depth attainable at an abutment, and damage sustained by an abutment, appears to be limited by the geotechnical stability of an abutment's earthfill embankment. ***However, the relationship between scour and geotechnical stability of a spill-slope or embankment has never been investigated***.

The proposed study will be the first to investigate this relationship. ***It will continue as the second year of the prior, but interrupted MPC project*** (MPC 354). The MPC program was terminated in 2011 during the first year of the present project; the prior study, a two-year effort, was just getting started with producing early research findings when the MPC program ended abruptly.

Appendix A of this proposal gives a brief summary of activities accomplished during the first year of work.

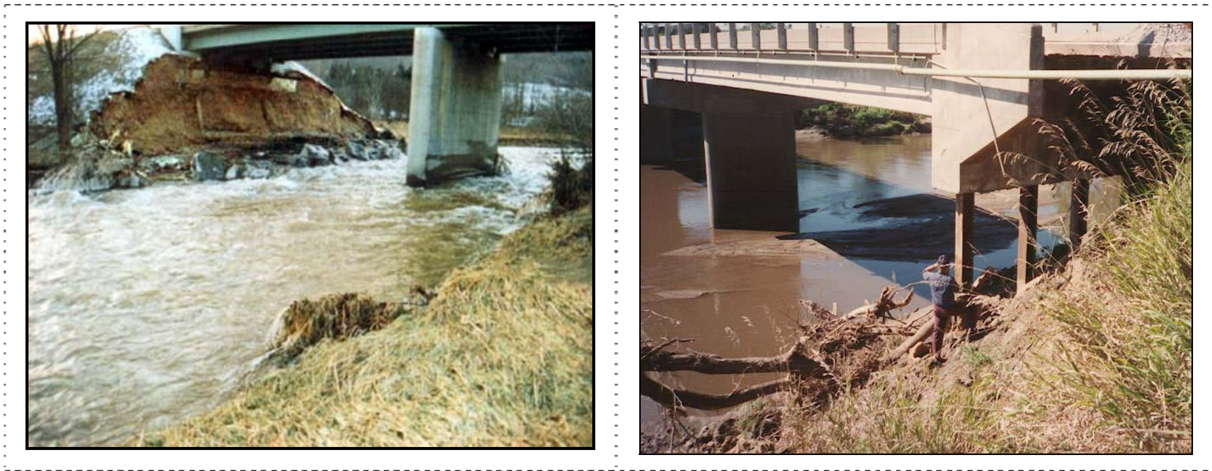
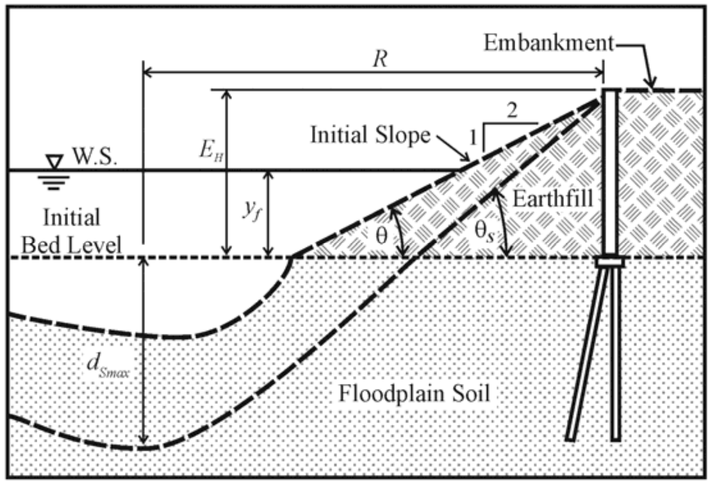


Figure 1. Abutment failure due to scour typically is attributable to the geotechnical failure of the abutments spill-slope, as illustrated by these two examples.

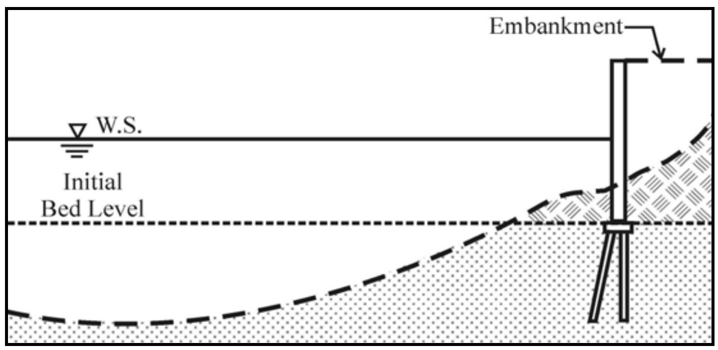
The project addresses the research question that scour at spill-through abutments is best characterized as largely a geotechnical design concern and less of a hydraulics concern, because the geotechnical strength of the spill-slope limits the extent of scour. The actual depth of flow-induced scour leading to embankment failure can be unremarkable. Typically, scour depths at spill-through abutments are modest, at least when viewed after the flood event that caused the scour, and when other factors such as channel morphology effects are excluded. Though numerous illustrations of scour at spill-through abutments show failed embankment and channel bank, methods currently available for estimating scour do not address the geotechnical aspects of scour at spill-through abutments

When scour causes the spill-slope to become unstable, spill-slope soil slides into the scour region and the flow transports it away. Further deepening leads to more slope instability and erosion, until eventually, the erosion extends to the abutment column (Figure 2a, b). Still further erosion breaches the embankment, increasing the flow area, and relaxing flow velocities through the bridge waterway.

The leading design guides, and bridge-monitoring guides, inadequately characterize scour at bridge abutments. For example, the recent FHWA publication NIH (2009) “Stream Instability, Bridge Scour and Countermeasures,” for instance inaccurately portrays an abutment structure and its flow field, and says nothing about how abutments actually are built, and possibly fail subject to scour. Figure 3 is taken from the publication. A similar comment can be made for the FHWA design guide HEC-18 (Richardson et al. 2001).



(a)



(b)

Figure 2. Deepening scour destabilizes the embankment face, causing the slope to fail and to erode back to a limiting condition. When the slope erodes back past the abutment column, the embankment breaches, and scour attains an equilibrium state: the scour limit for an embankment face eroded back to an extent defined in terms of angle for embankment-slope stability, θ_S, and column position (a); and, embankment failure beyond this limit leads to embankment breaching and flow relaxation (b)

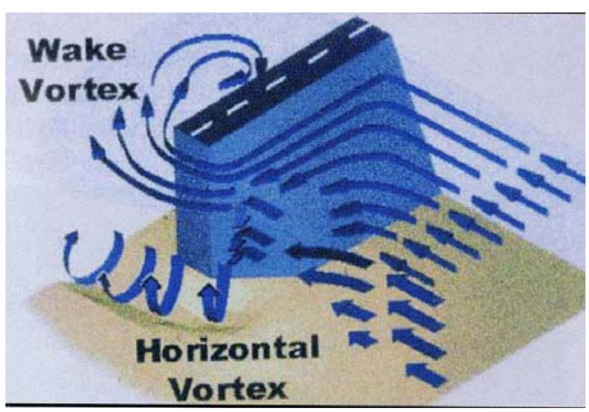


Figure 3. This sketch portrays an <u>unrealistic</u>, or at least very uncommon, view of abutment scour; taken from NHI (2009) "Stream Instability, Bridge Scour and Countermeasures"

Research Objectives:
The overall project has the following principal objectives:

1. Comprehensively define the essential geotechnical aspects associated with scour of spill-through abutments;
2. Show that the stability of an abutment's spill-slope limits scour depth; and,
3. Formulate a practical method relating abutment scour depth to the shear strength of the abutment's earthfill embankment. The relationship would provide a useful check on scour depth estimated using existing (and largely inadequate) methods for scour-depth prediction (e.g., as in HEC-18 recommended by the Federal Highway Administration).

The information and insights obtained from the project will significantly enhance understanding of abutment scour, and improve abutment design. Appendix A briefly indicates the work that had been accomplished during the first year of work.

Research Methods:
The research entails diagnosis of a set of field cases of scour at abutments, focused laboratory tests conducted with a large flume, and formulation of a practical design method. Implementation of this methodology was just getting successfully underway during prior MPC project (MPC 354), when that MPC program was interrupted in 2011. It is fully anticipated that the present project will handily pick up from that initial start.

Specifically, the project comprises the following tasks:

1. Review pertinent literature on abutment scour;
2. Investigate selected field cases of abutment scour to determine the geotechnical failure modes of spill-slope failure;
3. Formulate an approach for evaluating the geotechnical limit to maximum scour depth at a spill-through abutment. The approach will involve one or more formulations of abutment scour from a geotechnical perspective;
4. Carry out a select number of flume experiments to verify, in a controlled manner, the formulated relationship (or set of relationships) between scour depth and the shear strength of compacted earthfill spill-slope;
5. Determine if riprap on a spill-slope aids or hinders the geotechnical stability of a spill-slope. Riprap protects the spill-slope against erosion by water, but, by adding weight and not strength, may hasten spill-slope instability;
6. Recommend a practical design relationship for use in assessing abutment scour depths; and,
7. Provide a comprehensive final report to be written and submitted to the MPC Program.

A brief elaboration of the main tasks ensues.

<u>1. Model Formulation</u>
The project entails completion of an incisive review of the literature on abutment scour so as to develop a concise summary on the state-of-practice regarding current design methods. The PI's background expertise in the topic area will facilitate the review. Particular focus of the review will be design recommendations presently in FHWA's HEC-18 publication, and reports prepared by the National Cooperative Highway Research program (NCHRP).

The formulation will provide an estimate to the limit of the abutment scour possible at an abutment. It will do so for several modes of spill-slope failure. A preliminary formulation has been developed, as outlined below. Figure 2a, b illustrates the geotechnical limit for a spill-slope. As scour deepens, it reduces the stability of the earthfill embankment at the abutment, adjusting the embankment slope to its equilibrium slope. When the slope is exceeded, embankment material slides into the scour region (Figure 2a) and the flow transports it away. Further deepening leads to more slope instability and erosion, until eventually, the erosion extends to the abutment column. Because the cross section of flow increases (Figure 2b), further erosion results in breaching of the embankment and relaxation of the flow around the abutment.

It is possible to formulate the geotechnical limit to maximum scour depth. Figure 2 illustrates this limit. As indicated in Figure 2a, and found in the flume experiments, the location of deepest scour, d_{Smax}, was a radial distance, R, out from the abutment column. For the present study (and many abutment embankments), the constructed embankment slope was 2 horizontal to 1 vertical, such that the requirement for embankment slope stability, when the slope extends back to the abutment column, is

$$\theta_S = \tan^{-1}\left(\frac{E_H + d_{S\max}}{R}\right) \tag{1}$$

where E_H is embankment height. Adjusting Eq. (1), gives an estimate for the limiting values of d_{Smax};

$$d_{S\max} = R\tan\theta_S - E_H \tag{2}$$

The flume experiments, augmenting case-study field observations, are needed to show how R varies with the abutment length.

The maximum scour depth at the abutment should not exceed the limit given by Eq. (2). Note that this limit can actually be attained, especially when θ_S is large, such as for an earthfill embankment formed of compacted stiff clay. A larger scour depth leads to breaching of the embankment and flow relaxation through the bridge waterway (Figure 2b). The limiting scour-depth analysis should be further investigated for a range of earthfill materials, along with varying combinations of compacted embankment earthfill and floodplain soils. The preliminary formulation of Eqs (1) and (2) is somewhat simplified, but is nonetheless indicative of how to estimate a limiting scour depth.

It could be noted for an analysis of abutment geotechnical stability that riprap presence does not enhance geotechnical stability. Riprap adds weight to the slope, but does not increase the shear strength of the earthfill forming the embankment.

For abutments on footing foundations, a limiting maximum scour-depth coincides with the undermining of the footing and the possible geotechnical collapse of the earthfill embankment behind the abutment column. This limit also could be formulated, at least in approximate terms. A formulation is not given here, but the photographs of failed abutments show such a geotechnical collapse, and directly indicate how the formulation might be formulated.

3. Flume Experiments

The flume experiments will be proof-of-concept tests involving a hydraulic model of a spill-through abutment and embankment formed of compacted soil whose laboratory-scale shear strength will be varied. The flume constructed with the aid of MPC funds (Grant: NDSU48510ETMA) will be used for the experiments. The abutment and embankment will be replicated at a length scale of 1:30 to 1:40, placed on a simulated, erodible floodplain subject to scour. Flow will be recirculated through the flume, enabling the scour to develop until the replicated spill-slope fails. Scour depth will be related to the shear strength of the replicated embankment, and the relationship used to verify the preliminary formulation presented above, or an advanced version of the formulation.

4. Case-Study Evaluation

A set of case-studies of abutment scour will be assembled and investigated in terms of the geotechnical aspects of scour and spill-slope erosion or failure. This task entails working with the Wyoming Dept of Transportation (WYDOT), other state DOTs, and the Lakewood office of the Federal Highway Administration (FHWA). Principal Investigator Robert Ettema has good working relationship with design engineers at FHWA and WYDOT.

5. Reporting

The project's findings will be reported in a progress report and a final report. The final report will be a well-illustrated documentation of the projects results. It will include example design calculations using the formulation described above. Additionally, the main findings from the project will be reported via one or more conference paper

Expected Outcomes

The research findings facilitated by the flume, aiding the numerical model results, will lead to improved estimation of scour depth at bridge abutments, and thereby to improved design of bridge waterways. Also it will help in the design and placement of effective scour countermeasure methods. ***This project is the first time that geotechnical and hydraulic aspects of abutment failure due to scour have been investigated systematically***.

The insights and design information obtained from the project will be of immediate interest to bridge designers, as well as to bridge inspection personnel, working for State Departments of Transportation or other entities.

The Wyoming Technology Transfer Center (T^2/LTAP) will ensure the dissemination of the findings of this study. The project includes dissemination of research findings by means of one or more conference papers.

Relevance to Strategic Goals:

The project's outcomes will address important aspects of the following strategic goals associated with the MPC program and the U.S. Transportation Research Board generally:

1. Infrastructure Longevity (better abutments);
2. Improved Infrastructure Design (better and safer abutments);
3. Environmental Impacts of Infrastructure (abutment effects on flow and erosion);
4. Low-Cost Safety Improvements (effective placement of scour countermeasures).

Education Benefits:
The project will involve a Masters-degree student assisted by an undergraduate student, notably in the conduct of the flume experiments. A lecture giving an overview of the project, its motivation and outcomes, plus lab visit to the flume experiment, will be included in the schedule for the required civil program course CE3300 Hydraulic Engineering. Further, the 1st-Year course ES 1000 Introduction to Engineering will include a brief overview of the project and a visit to the flume experiment.

Work Plan:
The Project is structured as a two-year effort, with components completed in each year; much of the first year has been completed. Table 1 gives the project's work plan for Year 2 (a full two-year schedule is available if needed). The tasks briefly described in section "Research Method," are enumerated Tasks 1- 5, in Table 1. The final report will be submitted by the end of month 12. As noted above, Appendix A indicates the work completed during Year 1.

Table 1. Schedule for work plan during the Year 2 of work (in 3-month blocks); note that some tasks may be more-or-less continuous during the project, in accordance with research findings that may indicate the need for additional, interactive formulation/experiments/simulation

Task	Months			
	1-3	4-6	7-9	10-12
1. Model formulation	■			
2. Numerical model	■	■	■	
3. Flume (lab) experiment	■	■	■	
4. Case study evaluation		■	■	
5. Final report				■

Project Cost:
Table 2 gives an overall budget summary for Years 1 and 2; Year 1 having already been completed. The Project's budget for Year 2 (present request) is detailed in Table 2. The amount requested from the MPC program is $43,015.

Table 2. Summary of Project Costs

Period	Total	MPC Funds Requested
Year 1	$71,714	$34,120
Year 2 (requested)	$86,031	$43,014
Total	$157,745	$77,134

Table 3. Project Budget (Present Request for Year 2)

Budget Item	University	USDOT	Total
Salaries & Benefits			
PI Robert Ettema (0.50mm.)	6,801	0	6,801
PI John Turner (1.0mm.)		7,271	7,271
Lab Staff (1.6mm)	4,400	3,050	7,450
Grad. Student, MS (12.0mm.)	4,125 (3 summer mm.)	12,375 (9 AY mm.)	16,500
Benefits	5,103	4,702	9,805
Total Salaries and Benefits	20,429	27,398	47,827
Domestic Travel	1,100	1,000	2,100
Lab materials, power, water, space fee	4,300	2,000	6,300
Student Tuition	4,572	0	4,572
Total Direct Costs	30,400	30,400	60,799
Indirect Costs	12,616	12,615	25,232
TOTAL COSTS (Second Year)	**43,016**	**43,015**	**86,031**
Federal Share	0	**43,015**	**43,015**
Matching Share	43,016	0	43,016

Projects require a non-federal dollar-to-dollar match for MPC funds received. The matching funds would be provided by University of Wyoming.

TRB Keywords:
Safety, Rural Transportation, Transportation Systems, Safe Travel, Public Services, Safe Driving

References:

National Highway Institute (2009), “Stream Instability, Bridge Scour and Countermeasures.” Federal Highway Administration, US Dept of Transportation, McLean, VA.

Richardson, E. and Davis, S. (2001), "Evaluating Scour at Bridges," Report FHWA-NHI-01-001, Federal Highway Administration, Hydraulic Engineering Circular No. 18, McLean, VA.

Appendix A: Brief Summary of Accomplishments in Year 1 (MPC 354, Funded Earlier)

The accomplishments from the first year of work (funded before the MPC interruption in 2011) are summarized here, with example results provided.

A.1 Literature Review

The project has completed an extensive review of literature regarding abutment scour, in particular the geotechnical aspects of abutment scour. The need to evaluate present knowledge about abutment scour processes and failure conditions, and determine the extents to which existing scour-estimation methods reflect this knowledge, has been expressed in several publications prepared by national agencies and societies in the US: e.g., NCHRP Reports 24-08 (*Scour at Bridge Foundations: Research Needs*) and 20-07(178) (Parola et al. 1996, Lagasse et al. 2004), as well as NCHRP Report 417 (Parola et al. 1998), USGS 2002, and Kattell and Eriksson 1998). All of these publications allude to the geotechnical considerations attending abutment scour, but none fully identifies the central role such considerations play. Additionally, the fairly recent compendia, books, and monographs on bridge scour (e.g., Richardson and Davis, 1995, Hoffmans and Verheij 1997, Hamill 1998, Richardson and Lagasse 1999, Melville and Coleman 2000, FHWA 2001 & 1996) give useful summaries of scour research and design relationships, but they do not address the geotechnical aspects of abutment scour.

At the outset of the present study it was found necessary to better define the terms abutment, abutment scour, and abutment failure. These terms are not clearly defined in scour literature or in the common vernacular about scour. Abutments comprise several structural parts, notably an abutment column supporting one end of a bridge deck, and the column is set amidst, or backed by, a compacted earthfill approach embankment. This review uses the term “abutment” to describe the full structure – approach embankment and abutment column. Abutment scour herein is taken to be scour at the bridge-opening end of an abutment, and directly attributable to the flow field developed by flow passing around an abutment. Other flow and channel-erosion processes cause scour at abutments. One such process often leading to abutment failure is lateral erosion and shifting of the approach channel immediately upstream of an abutment; the approach flow then impinges against the abutment flank. Many field observations of abutment scour mix abutment scour (as defined above) and scour caused by channel shifting.

Abutment scour may cause one or both of the abutment components to fail. Observations of abutment scour indicate that the scour frequently may initiate a geotechnical-type failure of the earthfill embankment. Failure of the abutment column itself is less commonly observed. Although failure of the embankment may occur with the abutment column (and bridge structure) remaining intact, it is a most undesirable condition that renders the bridge approach dangerous for road vehicles. Given the incomplete prevailing understanding of scour mechanics, scour sensitivity to a large number of variables, and the large number of variables potentially to be taken into account, it is not surprising that existing methods for estimating scour depths at bridge abutments do not include geotechnical considerations, and are markedly empirical involving hydraulic data based largely on laboratory flume data. There has been no study offering a systematic study of how geotechnical variables (notably, the various factors affecting shear strength of the compacted soil forming a spill-slope influence scour.

A.2 Stability Calculations

The project is using the Rocscience software package *Slide*[1] *(4.0)* for a parametric numerical simulation experiments to investigate how the following considerations affect scour development and spill-slope stability for spill-through abutments:

1. The role of embankment soil strength on maximum scour depth;
2. How soil-saturation extent and floodplain water level affect embankment stability, and thereby scour depth;
3. The manner whereby riprap load (stone size and thickness of riprap layer) affect embankment geotechnical stability; and,
4. Flow elevation and embankment height influences on spill-slope stability and scour depth.

Slide is a 2D slope-stability program quite widely used for evaluating the safety factor or probability of failure, of circular or non-circular failure surfaces in soil or rock slopes. It analyzes the stability of slip surfaces using vertical slice limit equilibrium methods (e.g., Bishop, Janbu, Spencer, as indicated in the footnote below). Individual slip surfaces can be analyzed, or search methods can be applied to locate the critical slip surface for a given slope. Deterministic (safety factor) or probabilistic (probability of failure) analyses can be carried out using *Slide*. Finite-element groundwater (seepage) analysis, for steady state or transient conditions, is included in *Slide*.

The screen shot shown in Figure A-1 is a typical spill-slope (2H:1V), including a riprap layer that adds loading to the spill-slope. The spill-slope soil is treated as being unsaturated (such that water in the channel acts to counter the weight forces of soil forming the spill-slope. Figure A-1 shows all of the circular failure planes analyzed for this arrangement, as well as the minimum calculated factor of safety for the slope with regard to the assumed failure planes.

For a given geometry of spill-slope and initial flow depth around the abutment, the steps involved in conducting the parametric investigation using *Slide* are listed below:

1. Assign values to the shear strength of the spill-slope soil, which will be assumed to be unsaturated;
2. Assign an equivalent uniform load acting on the spill-slope owing to a certain layer thickness of riprap;
3. Pre-select a scour depth assumed to occur near the spill-slope toe;
4. Run *Slide* for a range of failure surfaces, gradually determining the surface for which the spill-slope fails;
5. Repeat the simulation runs for the following variable adjustments –
    i. Change assumed strength of spill-slope soil
    ii. Change thickness of riprap layer
    iii. Change assumed saturation condition of spill-slope soil
    iv. Change the location of pre-selected maximum scour depth
6. Prepare a series of plots relating –
    i. Maximum scour depth versus spill-slope soil strength (no failure) for a given thickness of riprap layer
    ii. Maximum scour depth versus thickness of riprap layer (no failure) for a given spill-slope soil strength
    iii. Repeating the above curves for the soil strength assumed saturated

[1] See http://www.eng-forum.com/articles/articles/slides.pdf

iv. Repeating a sub-set of curves for selected location of maximum scour depth

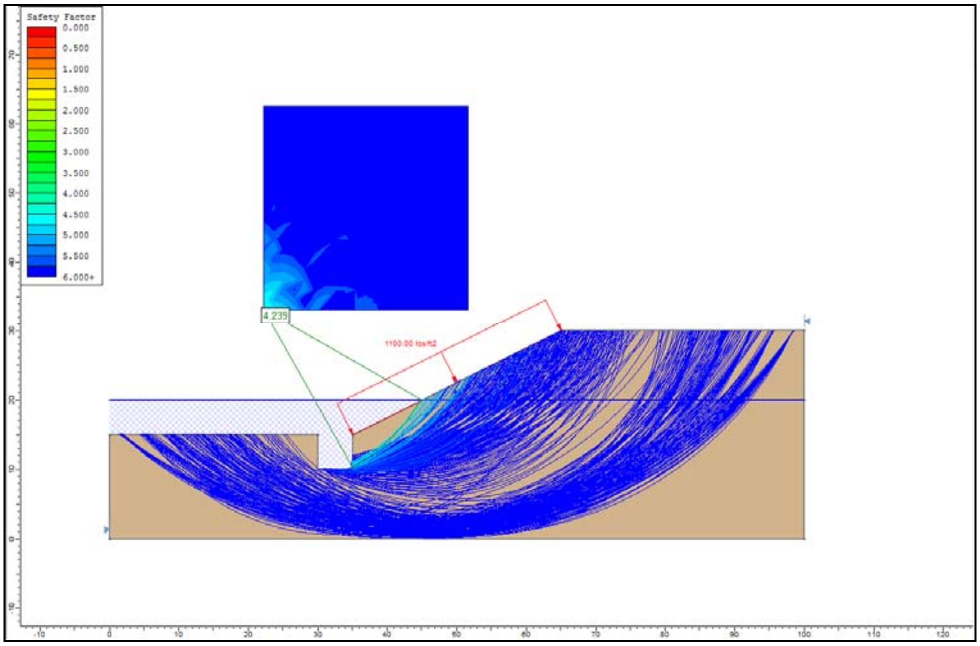


Figure A-1. Slip failure surfaces calculated using the Rocscience software ***Slide (4.0).*** *For the spill-slope configuration, riprap layer(represented as a uniform load on the spill-slope), and example scour depth depicted, the spill-slope remains stable at the pre-selected scour depth. However, a deeper pre-selected scour depth may result in spill-slope failure (i.e., a safety factor less than 1)*

A.3. Lab Flume Experiments

The simulation investigation using *Slide* does not replicate the actual, full failure of the spill-slope failure, insofar that it cannot replicate the subsequent lateral erosion of exposed spill-slope soil by flowing water. To investigate the full failure of a spill-slope requires that a series of laboratory experiments be conducted.

Our present understanding, based on observations of abutment scour provided by WYDOT Hydraulic Engineer W. Bailey, and photographs of abutment failures elsewhere, is that

- Spill-slope shear strength indeed limits scour depth
- Once the spill-slope fails, the lateral erosion of exposed (and erodible) spill-slope soil occurs faster than further scour deepening of the waterway
- Spill-slope erosion increases flow area, reduces flow velocities, and dumps material into scour region at the base of the spill-slope.

The flume experiments will be conducted in the university's Water Resource Laboratory. The design of the experiments is presently underway. The experiments themselves will be completed by late 2011. Figure A-2 illustrates the flume to be used. The flume was constructed with funding support from Mountain Plains Consortium funding (MPC Project: NDSU48510ETMA). It is an open channel fitted with false floor so as to accommodate a sand recess surrounding the test abutment. The channel dimensions are 3.66m (12ft) in width, fitted with a 2.44m (8ft) wide floodplain, 18.29m (60ft) in length and 1.22m (4ft) in maximum depth.

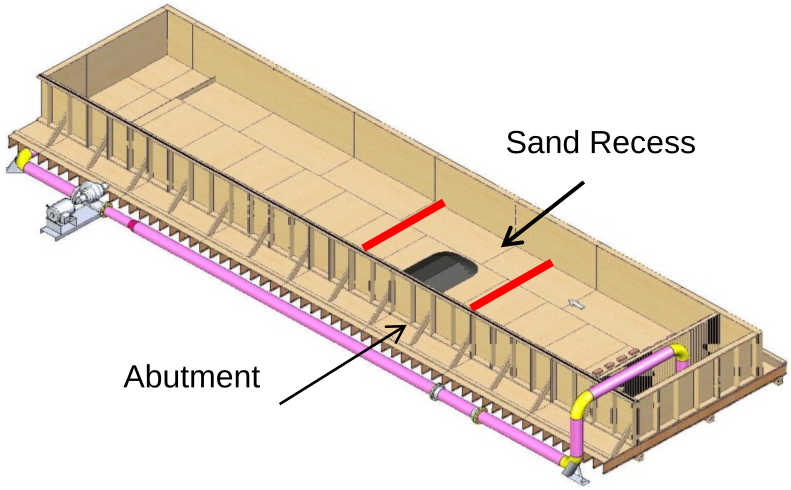


Figure A-2. The water re-circulating flume at the University of Wyoming, showing the test abutment (black) and the outline of the sand recess that will be subject to clear-water scour (for an abutment sited on a floodplain). Flow is from the reader's right

The test abutment will be approximately a 1:30 geometric scale of common spill-through abutment forms (in plan). It will be formed from weakly compacted soil, likely sand with a clay fraction. Initial experiments will ascertain the appropriate mix of sand and clay to ensure realistic geotechnical performance of the spill-slope.

A.4 Field Cases

We have been in close contact with WYDOT Hydraulic Engineer Bill Bailey. He has provided field data and photographs for six field sites (e.g., the site depicted in Figure A-3). The main features of each site have been documented. Appendix B, below, summarizes the main features of each site. We anticipate inspecting several sites during the current (2012) peak runoff flow period, likely to occur during late May through June.

Figure A-3. View of an eroded spill-slope bridge abutment at bridge at Cottonwood Creek, WY. Abutment scour eroded the channel bed, which then resulted in spill-slope failure (including collapse of riprap rock). Lateral erosion of exposed spill-slope soil ensued (Photo courtesy of William Bailey, WYDOT)

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Appendix B: Summary of Features at Possible Wyoming Bridge Sites

Cottonwood Creek near Ft. Laramie

- Short contraction
- No bedrock limit
- High terrace on east side sand consolidated sand. Conglomerate of a sand gravel, cobble
- Confluence with North Platte River 2000 feet downstream
- Downstream railroad structure
- Good Survey of the channel up and downstream
- BRI-STARS model
- The highway terrace on outside bendway will not recede at a rapid rate since the flood plain on east side is small to non-existent. The mass of the large terrace would not quickly recede, however some useful application of the proposed method might yield some valid findings. Abutment scour equations would predict very deep abutment scour that did not occur due to mass wasting of the terrace. The flood duration was not likely very long for this small watershed
- Blocked flow due to wide flood plain is not the classic case. Abutment protruded into main channel. The west flood plain contracted but the riprap protected the roadway embankment minor damage to the west abutment year is has the large L* effective length
- Choked flow conditions

Richeau Creek, I-25 near Chugwater, WY

- Bedrock limited scour depth
- Long contraction
- Choked flow conditions
- Known highwater marks as indirect estimate of flood discharge
- BRI-STARs model
- Moderate fill height flooplain on both sides
- Bridge may be somewhat under sized, backwater height > 2 feet at 100-year flood

Murphy Creek I-25, WY

- Extreme Backwater height known flood high-water elevation
- Long contraction, flow expansion downstream erosion
- HEC-RAS model
- BRI -STARS model
- High roadway embankment fill formed from compacted silty sand
- Bridge is undersized backwater height excessive
- High terrace on the south side wide floodplain on north side. Eccentric crossing
- Blue shale bedrock located 10- 15 below streambed. Stream bed sand with some gravel and 4” diameter rock

Rock Creek Near Rock River WY

- Coarse bed material gravel cobble boulder
- Bedrock limits scour depth
- Roadway overtopping
- Erosion\ scour got behind the bridge abutment and failed the roadway embankment
- Roadway overtopped

Horseshoe Creek I-25 near Glendo, WY

- Coarse bed material gravel cobble boulder
- Shallow overbank approach flow
- The highway terrace will not recede at a rapid rate since the channel is somewhat incised. The mass of the large terrace would not quickly recede. Application of the proposed method might yield some valid findings. Abutment scour equations would predict very deep abutment scour
- Highwater marks measured. Discharge unknown

<u>Middle Popo Agie River in Lander, WY</u>

- Coarse bed material cobble boulder
- Erosion and scour behind the bridge abutment
- Road overtopping
- Low embankment fill height