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Scour at Bridge Foundations on Rock

Electronic Only Appendices

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Contents (continued) Page

APPENDIX A

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NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock

Exit this survey >>

1. Page 1

This is a questionnaire for NCHRP Project 24-29 "Scour at Bridge Foundations on Rock". The objectives of NCHRP Project 24-29 are to develop (a) a methodology for estimating the time rate of scour and the design scour depth of a bridge foundation on rock and (b) design and construction guidelines for application of the methodology. We expect that this 14-question survey will require only a few minutes of your time. The results of this survey will become part of NCHRP 24-29 and be summarized in subsequent reports. Please contact one of us directly if you are concerned about confidentiality.

Thank you for helping us with this research project. Please feel free to contact us directly.

Jeffrey R Keaton, MACTEC, jrkeaton@mactec.com, 323-889-5316
Su Mishra, Ayres Associates, mishras@ayresassociates.com, 916-563-7700

1. What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State

City/Region

Brief comment (optional)

2. Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

- Yes
- No
- Not Sure
- Other (or qualified answer up to 5,000-characters)

3. If your organization manages bridges on rock foundations, how many do you have?

- Less than 5
- 6 to 10
- More than 10
- Qualified response (optional, up to 5,000-characters)

4. If your organization manages bridges founded on rock, what type of foundations are used?

- Spread footings
- Drilled shafts
- Other (or qualified response up to 5,000-characters)

5. Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

- Not at all
- A little
- Moderate
- Quite a bit
- Extensive
- Other (or qualified response up to 5,000-characters)

6. Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

- Not at all

- A little
- Moderate
- Quite a bit
- Extensive
- Other (or qualified response up to 5,000-characters)

7. Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

- Not at all
- A little
- Moderate
- Quite a bit
- Extensive
- Other (or qualified response up to 5,000-characters)

8. Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

- Never
- Once
- A few times
- A number of times
- Not sure
- Other (or qualified response up to 5,000-characters)

9. If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

- HEC-18
- Annandale's Method
- Other (please specify; up to 5,000-characters)

10. If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

- Yes
- No
- Not Sure
- Other (or qualified response up to 5,000-characters)

Next >>

NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock

Exit this survey >>

2. Page 2 of 2

Part of this NCHRP project involves visiting bridge sites with rock foundations. Please provide information about bridges in your area, particularly if you know of bridge foundations on rock that might be good candidates for field visits.

Thank you for helping us with this research project. Please feel free to contact us directly.

Jeffrey R Keaton, MACTEC, jrkeaton@mactec.com, 323-889-5316
Su Mishra, Ayres Associates, mishras@ayresassociates.com, 916-563-7700

11. Do knick points or waterfalls exist near bridges in your area? (If you select 'Yes', please describe the locations in the box.)

- Yes
- No
- Not sure
- Other (or qualified response up to 5,000-characters)

12. If your organization has one or more bridges founded on rock, then ...

	Not at all	A little	Moderate	Quite a bit	Extensive	Don't know
Do design and/or construction practices exist for geotechnical characterization of rock?						
Do design and/or construction practices exist for evaluating scour in rock?						
Is sediment transport considered in evaluating abrasion of rock?						
Do design and/or construction practices exist for remedial treatment of eroding rock at bridge foundations?						
Has geologic and/or geotechnical field data been collected at a bridge with an eroding rock foundation?						

Has field and/or laboratory test data been developed for the foundation materials?

Would pertinent geotechnical information be available to the researchers of this NCHRP project?

13. Please describe locations where bridge foundations on rock seem to be having scour-related problems. Please describe bridge foundations on rock that clearly are NOT having problems. Please feel free to make any other comments or offer any suggestions. Please use the text box below (up to 5,000-characters) for suggestions or comments; feel free to contact the researchers directly, also.
Jeffrey R Keaton, MACTEC, jrkeaton@mactec.com, 323-889-5316
Su Mishra, Ayres Associates, mishras@ayresassociates.com, 916-563-7700

14. Thank you for taking time to fill out this questionnaire. IF YOU THINK OF SOMETHING AFTER YOU EXIT THIS SURVEY, PLEASE CLICK ON THE ORIGINAL LINK AND ENTER THE APPROPRIATE INFORMATION ON A NEW FORM; YOU WILL NOT BE ABLE TO EDIT YOUR PREVIOUSLY SUBMITTED FORM. It would be very helpful if one of us could contact you for follow up clarification and information. If you are willing to do so, please provide your contact information below (250-character limit per line) or send it directly to:
Jeffrey R Keaton, MACTEC, jrkeaton@mactec.com, 323-889-5316
Su Mishra, Ayres Associates, mishras@ayresassociates.com, 916-563-7700

Name

Affiliation

City,State

Phone

e-mail

Other 1

Other 2

Other 3

<< Prev Done >>

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

	Response Percent	Response Count
State	**100.0%**	42
City/Region	83.3%	35
Brief comment (optional)	42.9%	18
	answered question	**42**
	skipped question	**3**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

	Response Percent	Response Count
Yes	22.7%	10
No	18.2%	8
Not Sure	6.8%	3
Other (or qualified answer up to 5,000-characters)	**52.3%**	23
	answered question	**44**
	skipped question	**1**

If your organization manages bridges on rock foundations, how many do you have?

	Response Percent	Response Count
Less than 5	2.4%	1
6 to 10	4.9%	2
More than 10	**63.4%**	26
Qualified response (optional, up to 5,000-characters)	29.3%	12
	answered question	**41**
	skipped question	**4**

If your organization manages bridges founded on rock, what type of foundations are used?

	Response Percent	Response Count
Spread footings	17.1%	7
Drilled shafts	7.3%	3
Other (or qualified response up to 5,000-characters)	**75.6%**	31
	answered question	**41**
	skipped question	**4**

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

	Response Percent	Response Count
Not at all	18.6%	8
A little	14.0%	6
Moderate	9.3%	4
Quite a bit	9.3%	4
Extensive	4.7%	2
Other (or qualified response up to 5,000-characters)	**44.2%**	19
	answered question	**43**
	skipped question	**2**

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

	Response Percent	Response Count
Not at all	16.3%	7
A little	30.2%	13
Moderate	9.3%	4
Quite a bit	2.3%	1
Extensive	0.0%	0
Other (or qualified response up to 5,000-characters)	**41.9%**	18
	answered question	**43**
	skipped question	**2**

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

	Response Percent	Response Count
Not at all	**56.1%**	23
A little	9.8%	4
Moderate	7.3%	3
Quite a bit	2.4%	1
Extensive	0.0%	0
Other (or qualified response up to 5,000-characters)	24.4%	10
	answered question	**41**
	skipped question	**4**

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

	Response Percent	Response Count
Never	**40.5%**	17
Once	2.4%	1
A few times	16.7%	7
A number of times	4.8%	2
Not sure	14.3%	6
Other (or qualified response up to 5,000-characters)	21.4%	9
	answered question	**42**
	skipped question	**3**

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

	Response Percent	Response Count
HEC-18	19.4%	6
Annandale's Method	16.1%	5
Other (please specify; up to 5,000-characters)	**64.5%**	20
	answered question	**31**
	skipped question	**14**

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

	Response Percent	Response Count
Yes	11.1%	4
No	**58.3%**	21
Not Sure	5.6%	2
Other (or qualified response up to 5,000-characters)	25.0%	9
	answered question	**36**
	skipped question	**9**

Do knick points or waterfalls exist near bridges in your area? (If you select 'Yes', please describe the locations in the box.)

	Response Percent	Response Count
Yes	48.7%	19
No	25.6%	10
Not sure	10.3%	4
Other (or qualified response up to 5,000-characters)	**51.3%**	20
	answered question	**39**
	skipped question	**6**

If your organization has one or more bridges founded on rock, then ...								
	Not at all	A little	Moderate	Quite a bit	Extensive	Don't know	**Rating Average**	**Response Count**
Do design and/or construction practices exist for geotechnical characterization of rock?	5.1% (2)	7.7% (3)	17.9% (7)	20.5% (8)	**30.8% (12)**	17.9% (7)	3.78	39
Do design and/or construction practices exist for evaluating scour in rock?	**28.9% (11)**	26.3% (10)	10.5% (4)	13.2% (5)	7.9% (3)	13.2% (5)	2.36	38
Is sediment transport considered in evaluating abrasion of rock?	**65.8% (25)**	18.4% (7)	0.0% (0)	2.6% (1)	0.0% (0)	13.2% (5)	1.30	38
Do design and/or construction practices exist for remedial treatment of eroding rock at bridge foundations?	16.2% (6)	18.9% (7)	**32.4% (12)**	5.4% (2)	8.1% (3)	18.9% (7)	2.63	37
Has geologic and/or geotechnical field data been collected at a bridge with an eroding rock foundation?	**37.8% (14)**	18.9% (7)	16.2% (6)	5.4% (2)	0.0% (0)	21.6% (8)	1.86	37
Has field and/or laboratory test data been developed for the foundation materials?	**28.9% (11)**	21.1% (8)	15.8% (6)	2.6% (1)	7.9% (3)	23.7% (9)	2.21	38
Would pertinent geotechnical information be available to the researchers of this NCHRP project?	21.1% (8)	28.9% (11)	5.3% (2)	5.3% (2)	0.0% (0)	**39.5% (15)**	1.91	38
							answered question	**39**
							skipped question	**6**

Please describe locations where bridge foundations on rock seem to be having scour-related problems. Please describe bridge foundations on rock that clearly are NOT having problems. Please feel free to make any other comments or offer any suggestions. Please use the text box below (up to 5,000-characters) for suggestions or comments; feel free to contact the researchers directly, also. Jeffrey R Keaton, MACTEC, jrkeaton@mactec.com, 323-889-5316 Su Mishra, Ayres Associates, mishras@ayresassociates.com, 916-563-7700	
	Response Count
	33
answered question	**33**
skipped question	**12**

Thank you for taking time to fill out this questionnaire. IF YOU THINK OF SOMETHING AFTER YOU EXIT THIS SURVEY, PLEASE CLICK ON THE ORIGINAL LINK AND ENTER THE APPROPRIATE INFORMATION ON A NEW FORM; YOU WILL NOT BE ABLE TO EDIT YOUR PREVIOUSLY SUBMITTED FORM. It would be very helpful if one of us could contact you for follow up clarification and information. If you are willing to do so, please provide your contact information below (250-character limit per line) or send it directly to: Jeffrey R Keaton, MACTEC, jrkeaton@mactec.com, 323-889-5316 Su Mishra, Ayres Associates, mishras@ayresassociates.com, 916-563-7700

	Response Percent	Response Count
Name	**100.0%**	36
Affiliation	**100.0%**	36
City,State	**100.0%**	36
Phone	**100.0%**	36
e-mail	97.2%	35
Other 1	2.8%	1
Other 2	0.0%	0
Other 3	0.0%	0
	answered question	**36**
	skipped question	**9**

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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<< Prev | Next >> | **Jump To:** 1 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 170.93.142.2

Response Started: Fri, 1/19/07 11:13:40 AM **Response Modified:** Sat, 5/26/07 3:39:28 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Maryland

City/Region - Baltimore

Brief comment (optional) - My responsibilities are statewide

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Foundation materials are outside of the scope of Maryland's published Bridge Inventory. A file of as built plans is maintained which would include this information along with boring data

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: About 60% of our structures are founded on rock. We have limestone, shales, sandtones, rhyolites, schists, gneiss, basalt, amphibolites, and quite a bit of saprolite. In MD, the state and county systems are separate.

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Spread footings, lots of driven H piles, some drilled shafts, and a few pipe/mini piles.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Scour issues are evaluated by the Bridge Hydraulics Division with technical support from the Engineering Geology Division. Every new structure over water is evaluated. Older structures are evaluated when upgraded or when inspections indicate a need.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Scour has been an issue on older bridges, especially those inherited into the system from other owners. We have little or no scour problems with newer bridges because the scour evaluation process is so very conservative, and our bridge designers (like most)are also very conservative.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Not sure what you mean by "quantitively". Rock foundation materials are determined to be scourable or not scourable. Foundation designs in scourable rock are adjusted to deal with the condition.

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: In cooperation with the University of MD, SHA has developed its own method, ABSCOUR. I understand that it is losley based on the HEC-18. This method is available on line at: www.gishydro.umd.edu

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Our evaluation method produces a yes or no answer.

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

design survey | collect responses | analyze results

Browse Responses

Displaying 2 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 2 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 165.201.162.184

Response Started: Fri, 1/19/07 11:17:49 AM **Response Modified:** Sat, 5/26/07 3:39:28 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Kansas

City/Region - Topeka

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Yes

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: Almost all of our bridges are founded in Rock. The number is in excess of 1000.

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Spread Footings, Drilled shafts as well as pile driven into bedrock.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: We evaluate each structure for scour

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: This is moderate problem for us. Our foundation material ranges from 900tsf limestone to less than 1 tsf shales.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Moderate

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

A few times

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: HEC-18 was used most often and We also had a local university work a slake duribility study for Scour

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 3 of 45 respondents **Select a page to view below or** view a

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 67.154.216.196

Response Started: Sun, 1/21/07 1:10:01 PM **Response Modified:** Sat, 5/26/07 3:39:29 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Missouri

City/Region - Kansas City

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Not Sure

If your organization manages bridges on rock foundations, how many do you have?

No Response

If your organization manages bridges founded on rock, what type of foundations are used?

No Response

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Extensive

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Moderate

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

A few times

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

HEC-18

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 4 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 4 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 156.75.192.110

Response Started: Fri, 1/26/07 12:23:40 PM **Response Modified:** Sat, 5/26/07 3:39:35 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - **No Response**

City/Region - **No Response**

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

No

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Drilled shafts

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Quite a bit

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Moderate

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

A number of times

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Annandale's Method

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Yes

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

design survey | collect responses | analyze results

Browse Responses

Displaying 5 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 5 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 64.174.7.191

Response Started: Fri, 1/26/07 12:54:05 PM **Response Modified:** Sat, 5/26/07 3:39:35 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - **No Response**

City/Region - **No Response**

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Yes

If your organization manages bridges on rock foundations, how many do you have?

No Response

If your organization manages bridges founded on rock, what type of foundations are used?

Spread footings

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

No Response

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

No Response

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

No Response

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No Response

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 6 of 45 respondents

Response Type: Normal Response
Collector: Web Link (Web Link)
Custom Value: *empty*
IP Address: 170.3.8.253
Response Started: Mon, 1/29/07 5:15:16 AM
Response Modified: Sat, 5/26/07 3:39:36 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - New York

City/Region - Albany

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Yes

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Spread footings on rock and rock socketed drilled shafts.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Based upon an evaluation of rock cores, including RQD, and exposed bedrock at the bridge site, we estimate the scourability of the rock on a scale of one to ten. This scourability score determines whether the footing should be keyed into rock for scour protection and by how much.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

A few times

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: Several times we have tried to compare the existing rock surface to that shown on the bridge record plans to determine how much the rock has eroded. We had limited success doing this.

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

 36

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 7 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 7 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 192.149.244.9

Response Started: Mon, 1/29/07 2:32:06 PM **Response Modified:** Sat, 5/26/07 3:39:37 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Oklahoma

City/Region - Oklahoma City

Brief comment (optional) - centrally located in the state

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Not Sure

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: usually spread footingsbut we are replacing with drilled shafts

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: We had many approaches through the years. The priority one scour inspections included bridges on spread footing embedded in potentially erodible rock with ADT > 150. Those were completed before I started wotking here. (15 years ago) I don't know how they determined how it was potentially errodible. I' ll ask around.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Yes we have red bed that when embedded is very strong , but when exposed to water or air is not and we have cobbles that wash away

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Some cases the 2 that come to mind have been replaced but I know of others we are watching

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Not sure

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Not Sure

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 8 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 8 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 132.160.192.10

Response Started: Tue, 1/30/07 4:29:37 PM **Response Modified:** Sat, 5/26/07 3:39:38 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Hawaii

City/Region - Kapolei, Oahu

Brief comment (optional) - Contact Person: Curtis Matsuda, Hydraulic Design Engineer (808) 692-7561

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Rely on soil borings on As-built construction plans to determine if foundation is on solid rock or on soil. Often times, visual inspection is sufficient especially if the foundation is on solid rock.

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Spread footings

Does your organization evaluate erodibility of rock on which bridges are founded as

part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Not at all

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: n/a

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: n/a

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 9 of 45 respondents

Response Type: Normal Response
Collector: Web Link (Web Link)
Custom Value: *empty*
IP Address: 70.155.178.116
Response Started: Wed, 1/31/07 5:01:29 AM
Response Modified: Sat, 5/26/07 3:39:39 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Florida

City/Region - Gainesville

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Yes

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: OEA is a consulting firm that does not manage bridges

If your organization manages bridges founded on rock, what type of foundations are used?

No Response

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Moderate

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Moderate

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

A few times

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: OEA has developed a methodology for evaluating scour in non-cohesionless sediments (rock/clay).

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Yes

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 10 of 45 respondents

Select a page to view below or view a

<< Prev | Next >> | **Jump To:** 10 | Go >> | << | #1. Page 1

Response Type: Normal Response

Collector: Web Link (Web Link)

Custom Value: *empty*

IP Address: 165.234.90.1

Response Started: Wed, 1/31/07 5:04:43 AM

Response Modified: Sat, 5/26/07 3:39:39 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - North Dakota

City/Region - Bismarck

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

No

If your organization manages bridges on rock foundations, how many do you have?

6 to 10

If your organization manages bridges founded on rock, what type of foundations are used?

Spread footings

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

A little

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Am not aweare of any problems.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: Have not evaluated scour of rock.

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: No experience.

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survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 11 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 11 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 164.154.98.124
Response Started: Wed, 1/31/07 6:52:57 AM **Response Modified:** Sat, 5/26/07 3:39:39 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - South Dakota

City/Region - Pierre

Brief comment (optional) - Office of Bridge Design

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

No

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Both spread footings and drilled shafts have been used.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

design survey | collect responses | analyze results

Browse Responses

Displaying 12 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 12 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 207.86.126.200
Response Started: Wed, 1/31/07 10:35:13 AM **Response Modified:** Sat, 5/26/07 3:39:39 AI

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - All states east of the MS River including states immediately west of MS River VI and PR...See http://www.efl.fhwa.dot.gov/

City/Region - **No Response**

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)
Comment: Most often yes.

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)
Comment: Both drilled shafts and spread footings socketed into rock.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified

answer.)

Other (or qualified response up to 5,000-characters)

Comment: We would only evaluate scour if Geotech office determines rock to be "erodible".

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: We cover a wide area. To us rock scour is more an academic pursuit than something we seriously consider.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: We keep detailed records not of scour depths, but of channel x-secs, taken every 3 years.

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: N/A

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: N/A

 36

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 13 of 45 respondents **Select a page to view below or** view a

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 167.154.20.116

Response Started: Wed, 1/31/07 1:03:16 PM **Response Modified:** Sat, 5/26/07 3:39:39 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Nevada

City/Region - Carson City/Statewide

Brief comment (optional) - Survey completed by Chris Miller (NDOT Hydraulic Engineer) with input from Bridge and Geotechnical personnel.

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

No

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Both spread footings on rock and drilled shafts socketed into rock have been used.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified

answer.)

Other (or qualified response up to 5,000-characters)

Comment: This has not formally been done to date. However, we intend to evaluate the rock on which some "scour critical" bridges are founded in order to verify or modify the current scour critical rating.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: A little. Only one or two bridges where undermining of spread footings on rock has been discovered.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: Not applicable.

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Not applicable.

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 14 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 14 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 152.119.13.5

Response Started: Wed, 1/31/07 2:03:13 PM **Response Modified:** Sat, 5/26/07 3:39:39 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - DC

City/Region - Washington

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: FHWA employee

If your organization manages bridges on rock foundations, how many do you have?

No Response

If your organization manages bridges founded on rock, what type of foundations are used?

No Response

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: HIBT-20 wrote memo on scourability of rock in general use.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

No Response

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

No Response

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No Response

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 15 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 15 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 204.131.83.168

Response Started: Thu, 2/1/07 6:00:25 AM **Response Modified:** Sat, 5/26/07 3:39:40 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Colorado

City/Region - Lakewood

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: We do not have an inventory of bridges. But one may be kept by our individual 'clients', including the National Park Service, National Forest, and Refuge Road Program

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: We have designed bridges on rock foundations, but we don't manage the operaions and maintenance of the bridges.

If your organization manages bridges founded on rock, what type of foundations are used?

Drilled shafts

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 16 of 45 respondents

Select a page to view below or view a

<< Prev | Next >> | Jump To: 16 | Go >> | << | #1. Page 1

Response Type: Normal Response
Collector: Web Link (Web Link)
Custom Value: *empty*
IP Address: 164.64.74.44
Response Started: Thu, 2/1/07 1:28:30 PM
Response Modified: Sat, 5/26/07 3:39:41 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - New Mexico

City/Region - Santa Fe

Brief comment (optional) - Drainage Design and Bridge Design completed this questionnaire

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Yes

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: both spread footings and drilled shafts

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Moderate

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

A little

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

A few times

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

HEC-18

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 17 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 17 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 64.174.7.191

Response Started: Thu, 2/1/07 2:24:07 PM **Response Modified:** Sat, 5/26/07 3:39:41 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - California

City/Region - Sacramento

Brief comment (optional) - I work Statewide

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Our database does not, but sometimes the information is available in Geology records, Foundation Plans, etc. if you look for it.

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Both

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified

answer.)

Moderate

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Normally not, but a few cases have been problematic where we had high blow counts and yet the material was very scourable when wet.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Sometimes cross-sections or bridge inspections will note the amount of exposure of a foundation which is a way of monitoring foundations on rock.

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Not sure

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

 36

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

design survey | collect responses | analyze results

Browse Responses

Displaying 18 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 18 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 66.234.209.209

Response Started: Fri, 2/2/07 10:01:37 AM **Response Modified:** Sat, 5/26/07 3:39:41 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - California

City/Region - Walnut Creek

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Not Sure

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: Not sure how many CT has now

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Old bridges tend to be spread footings on rock and new bridges drilled shafts (sometimes spread footings -- but less often)

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified

answer.)

A little

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: A few good examples: Mad River Route 299 (04-0036L/R) maybe Van Duzen River 04 0017L/R.

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Not sure

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: Opinions of geologists

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

 36

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NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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View Summary
Browse Responses
Filter Responses
Download Responses
Share Responses

Browse Responses

Displaying 19 of 45 respondents

Select a page to view below or view a

<< Prev | Next >> | Jump To: 19 | Go >> | << | #1. Page 1

Response Type: Normal Response
Collector: Web Link (Web Link)
Custom Value: *empty*
IP Address: 144.45.95.210
Response Started: Fri, 2/2/07 12:41:54 PM
Response Modified: Sat, 5/26/07 3:39:42 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Texas

City/Region - **No Response**

Brief comment (optional) - Texas DOT

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Our Bridge Database does not identify founding strata. However we have complete plans on most on-system (state owned) strucutres. Plans are available for only a portion of our Off-system (locally owned) structures.

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Most structures are on drilled shafts. Some older structures are on footings.

Does your organization evaluate erodibility of rock on which bridges are founded as

part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Moderate

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: We have taken channel profiles for the past 10 years or so. We can compare those profiles to the channel profile shown on the original contract plans.

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

A few times

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Annandale's Method

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 20 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 20 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 64.12.116.69
Response Started: Fri, 2/2/07 7:13:35 PM **Response Modified:** Sat, 5/26/07 3:39:42 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Maryland

City/Region - Baltimore

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: We have all bridge plans in an electronic data base and most of the newere bridges have soils/rock information. We have a long-term program to obtain soils/rock information on all spread footings where the current foundation material is unknown

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Both spread footings and drilled shafts are used.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: The Office of Bridge Development works with the geologists in evaluating the quality of rock cores. We have had limited experience in using George Annandale's Erodibility Index Method for rock foundations. In particular we used the method to advantage in the design of the Woodrow Wilson Bridge to evaluate soils

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: I am not aware of any general problem with rock. We have had concerns at individual bridges with coal seams, etc.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: We have measurements of bridge inspectors for perhaps 10 to 20 years at most bridges. There are several old arch bridges on rock in Western Maryland that have been been around for a long time. There have been an instance or two where some repairs were made where the rock had been eroded

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: As nted above, we have used the Erodibility Index a few times

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Annandale's Method

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Not to my knowledge

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NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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View Summary
Browse Responses
Filter Responses
Download Responses
Share Responses

Browse Responses

Displaying 21 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 21 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 156.98.4.11
Response Started: Mon, 2/5/07 9:14:36 AM **Response Modified:** Sat, 5/26/07 3:39:43 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Minnesota

City/Region - **No Response**

Brief comment (optional) - Mn/DOT State Hydraulic Engineer

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Yes

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Spread footings

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

A little

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

A little

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: Qualitative, consider liklihood of scour based on rock type.

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

design survey | collect responses | analyze results

Browse Responses

Displaying 22 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 22 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 204.131.83.110

Response Started: Mon, 2/5/07 12:43:29 PM **Response Modified:** Sat, 5/26/07 3:39:44 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - 15 state region, western U.S.

City/Region - **No Response**

Brief comment (optional) - FHWA Federal Lands Highway Division

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Bridge inventories generally describe foundations, though mosy of our work is new bridge construction, requiring investigation.

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: We build bridges for forest highway partners, but do not manage bridges directly.

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: In order of use: driven/drilled piles, drilled shafts, micropiles, spread footings.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Geotech provides information on rock types/quality, but provides no information on erodability. Hydraulics does not consider erosion for rock in scour calculations.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Unknown. We work over a 15-state region and build several bridges a year. I do not know of any follow-on work that has asessed the potential for this problem to occur. No rock-erosion-specific problems have come up in the last 10 years to my knowledge.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Not sure

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No Response

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View Summary
Browse Responses
Filter Responses
Download Responses
Share Responses

Browse Responses

Displaying 23 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 23 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 170.141.109.39

Response Started: Tue, 2/6/07 12:12:26 PM **Response Modified:** Sat, 5/26/07 3:39:45 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Tennessee

City/Region - Nashville

Brief comment (optional) - TDOT

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: We have an R code in item 113B that indicates foundations on rock. Other coding for abutment and piers on rock as well.

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: The TN bridge database has 16,894 bridges over water. 6554 bridges have at least one substructure founded on rock. 2384 bridges have rock under all substructures. The rest are not on rock or undetermined for coding.

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: TN has bridges on spread footings, drilled shafts, and point bearing piles.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Only a problem if substructure is built on boulders, cobble, or weak or shaly bedrock.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: N/A

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: N/A

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 24 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 24 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 64.174.7.191

Response Started: Wed, 2/7/07 7:13:46 AM **Response Modified:** Sat, 5/26/07 3:39:45 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - California

City/Region - District 7(LA), District 10(central CA)

Brief comment (optional) - No Response

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Yes

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Spread footings

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Our Geotechnical Support Office provides reports analyzing the rock types and recommendations if the bridge would be scour critical or not.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Not at all

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Not sure

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

HEC-18

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Yes

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 25 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 25 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 64.174.7.191

Response Started: Fri, 2/9/07 9:36:03 AM **Response Modified:** Sat, 5/26/07 3:39:48 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - California

City/Region - **No Response**

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: New Bridges - yes. Older bridges - not necessarily.

If your organization manages bridges on rock foundations, how many do you have?

No Response

If your organization manages bridges founded on rock, what type of foundations are used?

No Response

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

No Response

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Moderate

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

No Response

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

HEC-18

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 26 of 45 respondents

Response Type: Normal Response
Collector: Web Link (Web Link)
Custom Value: *empty*
IP Address: 167.131.0.152
Response Started: Sat, 2/10/07 3:57:38 PM
Response Modified: Sat, 5/26/07 3:39:49 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Oregon

City/Region - Salem

Brief comment (optional) - Statewide knowledge

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: NBIS does not. Oregon specific scour database identifies 285 with spread footings on non-erodible rock

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Drilled shafts

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: New bridges have extensive geotechnical reports. Old bridges may or may not have information on foundations

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: 45 of the 285 are considered to have a history of scour. Records are not specific on whether foundation undermining or some other mechanism attacking channel or embankments.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Some data either not accessible or difficult to recover. May not be realible.

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: FHWA Publication SPR 382 "Predicting Scour in Weak Rock of the Oregon Coast Range" is our only serious effort.

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: I think study used Annadale's Method modified to local conditions.

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Bridges over water have channel cross-section taken at the bridge opening on a 10 year rotation. Not always done. The older the bridge the less likely the information exists.

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 27 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 27 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 164.156.153.202
Response Started: Tue, 2/13/07 6:50:26 AM **Response Modified:** Sat, 5/26/07 3:39:51 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - PA

City/Region - **No Response**

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Yes, but data is not available for many older bridges. Those with unknown foundations are treated as on soil.

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: About 6000 as a unofficial number

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Both with a few pedestals also

Does your organization evaluate erodibility of rock on which bridges are founded as

part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Rock in PA is rarely found to be errodible in the life of the bridge. In the few instance where it is an issue it is treated as soil.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: We looked into this about 15 years ago and did not find any reasonable tests. We finally concluded it was not much of an issue and did not pursue.

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 28 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 28 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 167.7.17.3
Response Started: Wed, 2/14/07 9:04:36 AM **Response Modified:** Sat, 5/26/07 3:39:53 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - South Carolina

City/Region - Columbia

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Yes

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Both spread footings and drilled shafts

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Geotech Engineer makes the decision if rock is erodable or not

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Quite a bit

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Once

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: Laboratory flume test on Limestone

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Yes

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 29 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 29 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 158.145.111.186

Response Started: Wed, 2/14/07 9:52:00 AM **Response Modified:** Sat, 5/26/07 3:39:53 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - **No Response**

City/Region - **No Response**

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: We do not maintain foundation information in our National Bridge Inventory database. We have a separate seismic database in which AASHTO soil types (I, II, III, IV) are recorded from boring logs. If the presence of bedrock is a relevant to the scour-critical determination, our hydraulic files would include an explanation of its relevance.

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: Not sure. This information is not maintained through my office, if at all.

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Not sure. This information is not maintained through my office, if at all.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: The question of rock erodibility would be approached on a case-by-case basis. I am not aware of any formalized State (of Alaska) policy that addresses rock erodibility.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: I am not aware of any rock scour problems. There are bridge sites in Alaska where bedrock is exposed and may be susceptible to chemical weathering, freeze-thaw cycles, etc., and may as a result be susceptible channel incision due to bedload transport. Again, this would be addressed on a case-by-case basis, and not through a systematic rock scour assessment.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: We maintain a record of bridge soundings at our bridges. Soundings are taken every two years during bridge inspections, and every year for scour-critical bridges.

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Not that I am aware of, though my predecessors may have.

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: Not sure.

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Not Sure

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 30 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 30 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 159.247.2.8
Response Started: Wed, 2/14/07 10:55:41 AM **Response Modified:** Sat, 5/26/07 3:39:53 AI

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Connecticut

City/Region - Newington

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Yes, however not done on a consistent basis in a database field that can be easily searced.

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Spread footings, drilled shafts, end bearing piles

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified

answer.)

Other (or qualified response up to 5,000-characters)

Comment: If the rock/foundation "interface" is exposed to stream flow it would be considered, however, most rock foundations are several feet below the stream bed surface. Several feet of scour would need to occur before rock is exposed.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Not at all

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No Response

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 31 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 31 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 64.174.7.191

Response Started: Tue, 2/20/07 8:04:18 AM **Response Modified:** Sat, 5/26/07 3:39:57 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - California

City/Region - Sacramento

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Usually not, but occasionally mentions placing the footings on rock.

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Normally spread footings, but occasionally piles driven into bedrock.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Quite a bit

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Moderate

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Not sure

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No Response

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 32 of 45 respondents **Select a page to view below or** view a

Response Type: Normal Response
Collector: Web Link (Web Link)
Custom Value: *empty*
IP Address: 64.174.7.191
Response Started: Tue, 2/20/07 9:41:35 AM
Response Modified: Sat, 5/26/07 3:39:57 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - California

City/Region - Sacramento

Brief comment (optional) - Statewide Bridge Scour Program.

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: No. However bridge archives includes Logs of Test Borings which Identif the type of foundation material.

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: all types of foundations; Spread footings, drilled shafts and including different types of driven piles that are dirven into decomposed and very soft rocks (end bearing.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Quite a bit

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: California has a wide range of geological environment, and the rocks erode differently depending on the enviornment affecting them. Example Bridges founded on massive crystalline rock will experience will be more stable than those founded on sandstone or shale.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

HEC-18

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

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Browse Responses
Filter Responses
Download Responses
Share Responses

Browse Responses

Displaying 33 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 33 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 67.107.2.243
Response Started: Tue, 2/20/07 11:02:38 AM **Response Modified:** Sat, 5/26/07 3:39:58 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - California

City/Region - San Diego

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Sometimes

If your organization manages bridges on rock foundations, how many do you have?

Less than 5

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: depends on age

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Quite a bit

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

A few times

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: Both

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

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Browse Responses
Filter Responses
Download Responses
Share Responses

Browse Responses

Displaying 34 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 34 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 159.105.164.74
Response Started: Wed, 2/21/07 6:41:10 AM **Response Modified:** Sat, 5/26/07 3:39:58 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Vermont

City/Region - Montpelier

Brief comment (optional) - Statewide coverage

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Older bridges may not have that information. Bridges constructed in the past 50 years should have detailed information on foundation type.

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Depends on depth to rock. Spread footings, drilled shafts or piles may be used.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified

answer.)

Not at all

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Not at all

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No Response

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 35 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 35 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 198.176.41.2

Response Started: Wed, 2/21/07 8:28:49 AM **Response Modified:** Sat, 5/26/07 3:39:59 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Virginia

City/Region - Richmond

Brief comment (optional) - I am a geotechnical engineer with VDOT.

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

No Response

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: Thousands.

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Spread footings, piles, and shafts.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

A little

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Don't know, but assumed to be so for mudstone, claystone, siltstone, sandstone, shale, etc.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

No Response

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: No, but have begun to look at existing methodologies to do so.

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: Annandale's is what we have only recently begun to look into.

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

 36

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NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses
Filter Responses
Download Responses
Share Responses

Browse Responses

Displaying 36 of 45 respondents

Select a page to view below or view a

<< Prev | Next >> | Jump To: 36 | Go >>

<< #1. Page 1

Response Type: Normal Response

Collector: Web Link (Web Link)

Custom Value: *empty*

IP Address: 204.113.19.8

Response Started: Thu, 2/22/07 12:47:48 PM

Response Modified: Sat, 5/26/07 3:40:00 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Utah

City/Region - All

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Most of the time soil data sheets are part of the as built drawing, therefore information is available

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Both spread and drilled shafts are used

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified

answer.)

A little

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Moderate

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

A little

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No Response

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 37 of 45 respondents

Select a page to view below or view a

<< Prev | Next >> | **Jump To:** 37 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 159.247.2.8

Response Started: Fri, 2/23/07 5:33:11 AM **Response Modified:** Sat, 5/26/07 3:40:01 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Connecticut

City/Region - Newington

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: Yes, however, not done on a consistent basis in a database field that can be easily searched.

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: spread footings, drilled shafts & micropiles drilled into rock, driven end bearing piles

Does your organization evaluate erodibility of rock on which bridges are founded as

part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: If rock/foundation “interface” is continuously exposed to stream flow it may be more of a consideration. Most rock foundations in CT are several feet below stream bed surface. Several feet of scour would need to occur to expose the rock to flow and potential for erosion to the rock. Given the nature of the rock in CT and time dependency of the process, erosion of the rock is unlikely to occur. In addition, we typically would not seat foundations on or in rock that would be susceptible to high rates of erosion (e.g. weathered rock).

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Not significant, if any.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Qualitative assessments only based on limited rock data. Have never tried to quantify depths or rates of scour in bedrock

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: FHWA memorandum “Scourability of Rock Formations”, dated July 19, 1991 (HNG-31) and HEC-18

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 38 of 45 respondents **Select a page to view below or** view a

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 136.200.212.30

Response Started: Mon, 2/26/07 7:20:46 AM **Response Modified:** Sat, 5/26/07 3:40:03 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - California

City/Region - **No Response**

Brief comment (optional) - I'm substituting "dams" for "bridges"

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Yes

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Generally I'm referring abutments and toes of a concrete dam or concrete spillways that have been placed on a bedrock surface. The latter are often anchored by dowels into bedrock. The former are embedded and sometimes evaluated for overpour scour.

Does your organization evaluate erodibility of rock on which bridges are founded as

part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Yes, as needed

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Quite a bit

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: We have file documentation (photos and notes) on jurisdictional dams going as far back as the late 1800's.

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

A number of times

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Annandale's Method

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 39 of 45 respondents **Select a page to view below or** view a

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 160.93.194.141

Response Started: Mon, 2/26/07 7:23:29 AM **Response Modified:** Sat, 5/26/07 3:40:03 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - New Jersey

City/Region - Trenton

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

No

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Shallow foundation (spread footings) and deep foundations (piles, drilled shafts)

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Not at all

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No Response

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 40 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 40 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 156.63.133.8

Response Started: Tue, 2/27/07 10:56:15 AM **Response Modified:** Sat, 5/26/07 3:40:04 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Ohio

City/Region - Columbus

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

No

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: Not exactly sure what is meant by "manages", we build bridges on shallow rock foundations, then we maintain them.

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: Spread footings on shallow competent rock and drilled shafts when rock is deeper.

Does your organization evaluate erodibility of rock on which bridges are founded as

part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: I am not sure what is being done, regarding scrour criticality evaluations.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Generally our stream velocities are low so rock scour is not as much of a concern, but we do have numerous rock types including highly erodible weathered shales.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: I only know of one bridge where we have monitored rock scour.

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

No Response

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No Response

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NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses
Filter Responses
Download Responses
Share Responses

Browse Responses

Displaying 41 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 41 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 65.40.62.11
Response Started: Tue, 2/27/07 11:39:12 AM **Response Modified:** Sat, 5/26/07 3:40:05 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Florida

City/Region - Tallahassee

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: My understanding is that you would deduce this information from the foundation type shown on the plans or in the inventory data sheet.

If your organization manages bridges on rock foundations, how many do you have?

Qualified response (optional, up to 5,000-characters)

Comment: We do not have this responsibility.

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: We do not manage bridges, but the majority of those founded on rock in this area are supported by drilled shafts.

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Again, we do not manage the bridges, but we have never seen our clients account for the erodibility of rock.

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: I am only aware of one instance in South Florida where Biscayne Bay is directly connected to the Atlantic Ocean through Haulover's Cut. We prepared retrofit plans to maintian foundation stability. I would expect there are others around the state with similar problems.

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: n/a

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: n/a

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 42 of 45 respondents

Response Type: Normal Response

Collector: Web Link (Web Link)

Custom Value: *empty*

IP Address: 165.206.209.230

Response Started: Tue, 2/27/07 1:52:19 PM

Response Modified: Sat, 5/26/07 3:40:05 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Iowa

City/Region - Ames

Brief comment (optional) - Iowa DOT

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Yes

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Spread footings

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

A little

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: Scour Safe if Spread Footings are founded in: >4' - of Weathered or Broken Limestone Any Depth - Any Limestone other than Weathered or Broken >7'- Any shale other than Hard (or very firm) Shale Any Depth - Hard (or very firm) Shale > 10' - Very firm Glacial Clay

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

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Browse Responses

Displaying 43 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 43 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 170.93.142.2

Response Started: Thu, 3/8/07 8:00:03 AM **Response Modified:** Sat, 5/26/07 3:40:14 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Maryland

City/Region - SHA

Brief comment (optional) - Office of Bridge Development

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

Other (or qualified answer up to 5,000-characters)

Comment: SHA bridge plans are available in an electronic file data base. For newer bridges borings are included on the plans

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: spread footings, drilled shafts, driven piles and micro piles

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified

answer.)

Extensive

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: Never lost a bridge to scour. Some minor scour experienced at a few sites

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: SHA has a process for evaluating scour in rock

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Annandale's Method

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 44 of 45 respondents **Select a page to view below or** view a

<< Prev | Next >> | **Jump To:** 44 | Go >> | << | #1. Page 1

Response Type: Normal Response **Collector:** Web Link (Web Link)
Custom Value: *empty* **IP Address:** 69.60.34.98
Response Started: Fri, 4/6/07 6:55:49 AM **Response Modified:** Sat, 5/26/07 3:41:02 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - Mississippi

City/Region - Jackson

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

No

If your organization manages bridges on rock foundations, how many do you have?

6 to 10

If your organization manages bridges founded on rock, what type of foundations are used?

Spread footings

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Not at all

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

Not at all

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Other (or qualified response up to 5,000-characters)

Comment: There is rock in the Tallahatta Formation. We have had bridge replacement projects in Montgomery County where this formation is prevalent, but no attempt at evaluating scour has been utilized other than engineering judgement with HEC-18.

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

HEC-18

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

survey title:
NCHRP 24-29 Questionnaire - Scour at Bridge Foundations on Rock Edit Title

Browse Responses

Displaying 45 of 45 respondents **Select a page to view below or** view a

Response Type: Normal Response **Collector:** Web Link (Web Link)

Custom Value: *empty* **IP Address:** 199.90.35.12

Response Started: Tue, 5/8/07 9:13:18 AM **Response Modified:** Sat, 5/26/07 3:41:37 AM

What is your general location? (We would like specific details in your responses, including your contact information so we could make follow up calls; however, we welcome any and all information even if you wish to remain anonymous.) Each field will accept up to 250 characters.

State - North Carolina

City/Region - Raleigh

Brief comment (optional) - **No Response**

Does the inventory of bridges in your area identify if the foundation is soil or rock? (Please use the 'Other' box if you would like to give a qualified answer, even if it is 'yes' or 'no'.)

No

If your organization manages bridges on rock foundations, how many do you have?

More than 10

If your organization manages bridges founded on rock, what type of foundations are used?

Other (or qualified response up to 5,000-characters)

Comment: We use both Drilled Shafts and Spread footings

Does your organization evaluate erodibility of rock on which bridges are founded as part of evaluating scour criticality? (Select 'Other' if you would like to give a qualified answer.)

A little

Is rock erosion or rock scour a problem in your area, particularly at bridge foundations? ['Rock' can range from massive and weakly cemented to jointed and hard; feel free to comment on the rock in your area.] (Select 'Other' if you would like to give a qualified answer.)

Not at all

Does your organization have records of long-term scour of specific bridge foundations on rock? (Select 'Other' if you would like to give a qualified answer.)

A little

Has your organization tried to evaluate scour of rock quantitatively? (Select 'Other' if you would like to give a qualified answer.)

Never

If your organization has evaluated scour of rock, what method was used? (Select 'Other' if you would like to give a qualified answer.)

Other (please specify; up to 5,000-characters)

Comment: We usually do not evaluate scour of rock but We have the EFA device from Texas A&M to evaluate scour of soil.

If your organization has evaluated scour of rock, has time-rate-of-scour been considered? (Select 'Other' if you would like to give a qualified answer.)

No

NUMERICAL MODELLING OF SCOUR AT BRIDGE FOUNDATIONS ON ROCK

E.F.R. Bollaert[1]

ABSTRACT

The National Cooperative Highway Research Program – Project 24-29 is geotechnical site characterization in scour-relevant terms for use by hydraulic engineers. Project goals are time-rate of scour and design scour depth at bridge foundations on rock for integration with Federal Highway Administration Hydraulic Engineering Circular HEC-18, Evaluating Scour at Bridges.

The present paper presents an application of the Comprehensive Scour Model (CSM, Bollaert 2002) to quarrying and plucking of fractured rock near bridge pier foundations. Numerical modeling of rock block plucking and corresponding ultimate scour depth has been performed for a large number of hydrodynamic and geomechanic situations with practical relevance.

The two-phase transient numerical model simulates the time evolution of quasi-steady and turbulent forces around a single rock block and allows expressing the potential movements of the block as a function of the flow turbulence and the stream power in the scour hole that forms around the bridge pier. The hydraulic action on the rock blocks is automatically adapted during formation and growth of the scour hole.

Both the ultimate scour depth and the scour threshold flow velocity are determined as a function of the shape, dimensions and protrusion of the rock block, of the average upstream river bed slope and of the angle of the rock joints. The ultimate scour depth estimate is non-dimensionalized by the bridge pier diameter.

The numerical model is particularly useful to point out the influence of flow turbulence eddies and block protrusion on the physical process of sudden rock block ejection.

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Hydrodynamic uplift of rock blocks around bridge piers

1. Introduction

This appendix describes a combined analytical-numerical method developed to assess the hydrodynamic uplift of rock blocks generated by turbulent flows around bridge piers. The method describes and computes the physics that are directly responsible for block ejection and provides an estimate of the ultimate depth of scour during floods at a bridge pier founded in fractured rock.

2. Hydrodynamic parameters

2.1 Upstream of the bridge pier

The method uses the upstream available stream power $SP_{w,a}$ (see Figure 1) as the main hydraulic parameter of interest. This parameter is defined as:

$SP_{w,a} = V_a \cdot \tau_{w,a}$ [W/m^2]

in which V_a [m/s] stands for the average flow velocity upstream and $\tau_{w,a}$ [N/m^2] stands for the average wall shear stress upstream.

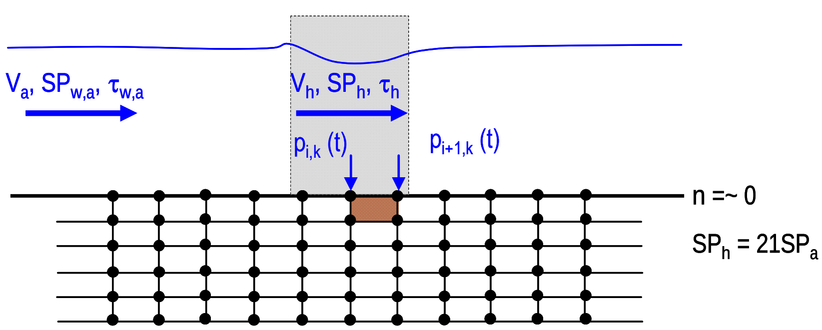


Figure 1: Hydrodynamic parameters at bridge pier founded on rock

Beside the available stream power upstream, the following parameters are also used:

- $SP_{t,a}$ = turbulent approach stream power = $7.853 * \rho * (\tau_{w,a}/\rho)^{(3/2)}$
- $SP_{t,a,\,adj}$ = adjusted turbulent approach stream power = $k_1 k_2 SP_{t,a}$
- k_1/k_2 = accounting for pier shape and flow attack angle

The turbulent stream power $SP_{t,a}$ in the upstream flow is defined as the proportion of the total available stream power that is applied to the bottom and that is directly related to turbulence production in the near-bed region. Based on Schlichting & Gersten (2000), this stream power is directly related to pressure fluctuations at the bottom. The turbulent stream power applied to the bed is finally adjusted by means of the non-dimensional parameters k_1 and k_2, which account for the pier shape respectively the flow attack angle following HEC-18 (Richardson et al., 1993).

Average flow velocity and bottom shear stress are computed based on the unitary discharge Q [m^3/s/m], the bottom slope S [-] and the Manning roughness coefficient n [s/$m^{1/3}$]. The range of flow conditions tested is summarized at Table 1 for three types of flows:

1. Steep Slope Flood Flow (SSFF)
2. Flood Flow (FF)
3. Normal High Flow (NHF)

Steep bottom slopes are between 1 and 10%, while normal bottom slopes are between 0.05 and 1 %. Unitary discharges range from 2 to 50 [m^3/s/m]. Manning roughness is situated between 0.03 and 0.065 [s/$m^{1/3}$], depending on the bottom slopes tested.

2.2 At the bridge pier

As shown in Figure 1, the available and turbulent (applied) stream powers $SP_{w,a}$ and $SP_{t,a}$ are transformed into available and turbulent stream powers $SP_{w,h}$ and $SP_{t,h}$ acting locally in the scour hole at the bottom near the bridge pier. These local stream powers have been determined by physical modeling in the 1990's (FHWA research; Smith, 1994) and have been adapted here to match with rocky foundations:

$$SP_h/SP_a = 2.6217(n^*h_b/D)^{(-0.6945)}$$

in which h_b [m] is the rock block height, D [m] is the bridge pier diameter and n [-] stands for the number of layers that have been scoured. For example, at start of scour formation, the available and turbulent stream powers at the bottom next to the bridge pier are considered to be about 21 times the corresponding stream powers in the river upstream.

During scour formation, this stream power ratio reduces following the above presented equation. For example, for n = 4, Figure 2 shows that $SP_{t,h}$ is reduced to only 2.62 times $SP_{t,a}$. Hence, this progressive reduction in stream power in the scour hole allows defining the corresponding local flow velocity $V_{w,h}$ [m/s], the local kinetic energy $E_{w,h}$ [m], and the average and turbulent wall shear stresses $\tau_{w,h}$ and $\tau_{t,h}$ [N/m^2].

The local kinetic energy in the scour hole $E_{w,h}$ is used to define the quasi-steady pressure field around a rock block near the bridge pier. These pressures are expressed in [m] by multiplying $E_{w,h}$ with non-dimensional pressure coefficients. The pressure coefficients depend on the protrusion of the rock block compared to its surroundings as well as on the orientation of the joints between the blocks compared to the flow direction. Following Figure 3 and based on Reinius (1986) and USBR (2007), the following simplified range of values has been used during the computations:

Steep Slope Flood Flow (SSFF)	Q [m3/s/m2]	S [-]	n
SSFF - cas1	2	1E-02	0.065
SSFF - cas2	10	1E-02	0.065
SSFF - cas3	15	1E-02	0.065
SSFF - cas4	2	5E-02	0.065
SSFF - cas5	10	5E-02	0.065
SSFF - cas6	15	5E-02	0.065
SSFF - cas7	2	1E-01	0.065
SSFF - cas8	10	1E-01	0.065
SSFF - cas9	15	1E-01	0.065

Flood Flow (FF)	Q [m3/s/m2]	S [-]	n
FF - cas1	10	5E-05	0.03
FF - cas2	20	5E-05	0.03
FF - cas3	50	5E-05	0.03
FF - cas4	10	5E-04	0.03
FF - cas5	20	5E-04	0.03
FF - cas6	50	5E-04	0.03
FF - cas7	10	1E-03	0.03
FF - cas8	20	1E-03	0.03
FF - cas9	50	1E-03	0.03

Normal High Flow (NHF)	Q [m3/s/m2]	S [-]	n
NHF- cas1	5	5E-05	0.03
NHF- cas4	5	1E-04	0.03
NHF- cas6	10	1E-04	0.03
NHF- cas7	5	5E-04	0.03

Table 1: Parameter values used for the approach flow conditions

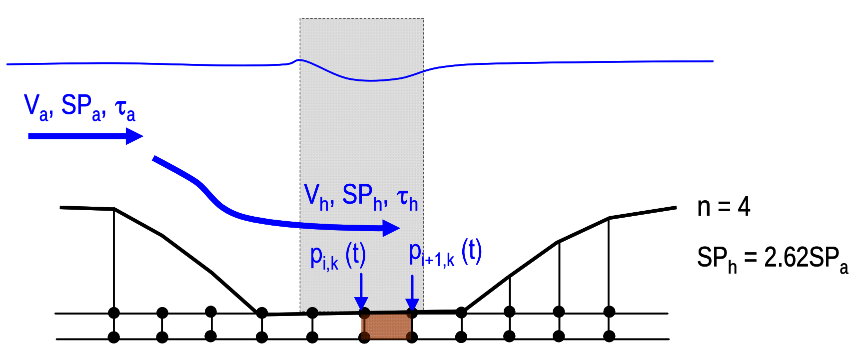


Figure 2: Hydrodynamic parameters at start of scour

$C_6 = C_7 = \sim 0$
$C_5 = C_8 = 0, 0.5$ or 1.0, directly depending on offset of block
$C_{up,net}$ = Average (C6;C7) – Average (C5;C8)

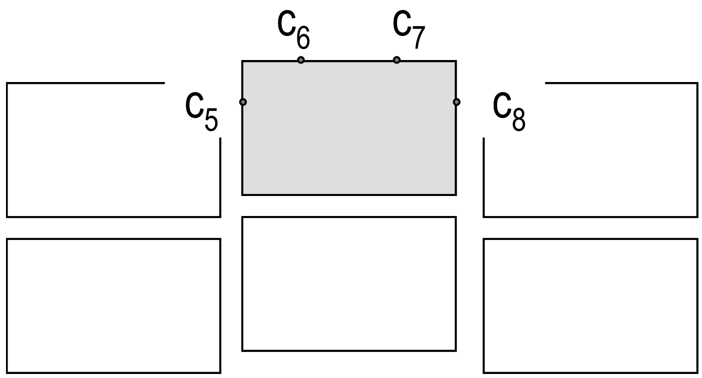


Figure 3: Location of dynamic pressure coefficients used to quantify quasi-steady pressures around a rock block (based on Reinius, 1986)

Next, the turbulent bottom shear stress $\tau_{t,h}$ is used to determine the RMS (root-mean-square) and extreme pressure fluctuations on a rock block in the scour hole near the bridge pier. Based on Emmerling (1973), the following expressions are used:

$$p' = 3 \cdot \tau_{t,h}$$
$$p+ = 18 \cdot \tau_{t,h}$$

By combining both quasi-steady pressures and turbulent pressure fluctuations, the total dynamic pressure signal on the rock blocks can be defined. For simplicity, a sinusoidal pressure shape has been used, defined as follows (see Figure 4):

$$p(t) = \frac{1}{2} \cdot B \cdot \sin(\omega \cdot t) + C$$

$B = p^+$ = maximum positive pressure deviation from quasi-steady pressure value
$C = 0.5 \cdot p^+ + C_5 \cdot E_{w,h}$
$\omega = 2\pi f$, with $f = 10$ Hz

For convenience and stability during the numerical computations, no negative total pressures have been used. Also, the sinusoidal dynamic pressure signal has been systematically applied to both joint entrances separating the rock block from both adjacent blocks (following a 2D approach, see Figure 3), without any time lag between both pulses (simultaneous action). Finally, the surface pressure field acting at the surface of the block (in between both joints) has been neglected. As such, the modeled pressure situation may be considered as the most critical situation that might be encountered in practice.

The frequency of the pressure signal has been defined at 10 Hz, corresponding to a frequency that may easily be reached in practice by turbulent flow around a bridge pier.

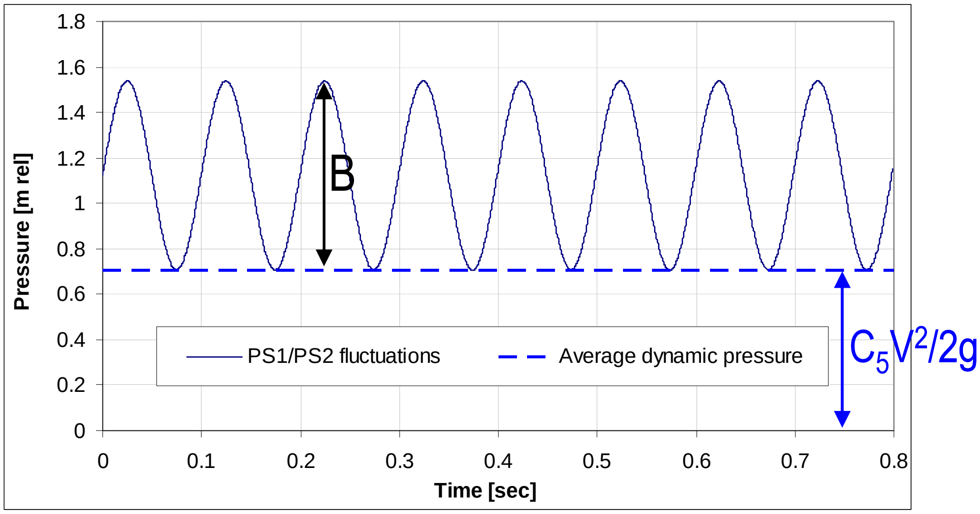
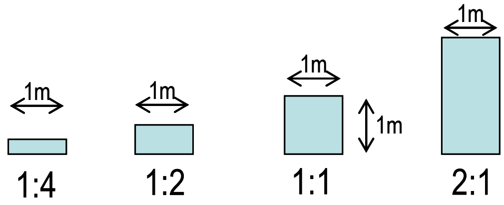


Figure 4: Determination of total dynamic pressure signal applied to the joints between the rock blocks

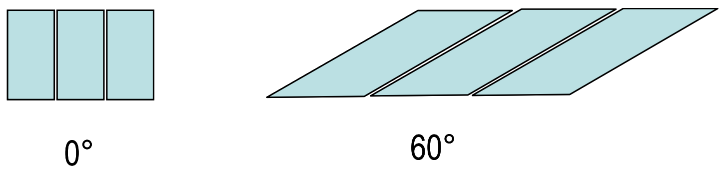
3. Geomechanical parameters

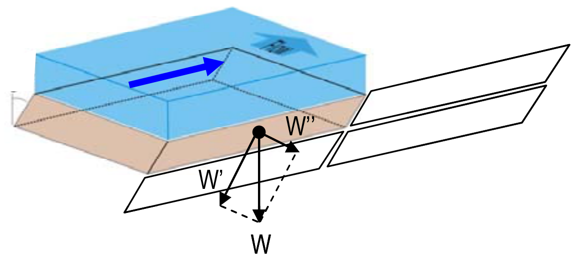
The main geomechanical parameters considered during the modeling are:

1. *Block shape and dimensions*: side length of block L_b [m], height of block h_b [m], ratio L_b/h_b. The side length has been fixed at 1m, while the height has been varied.



2. *Joint angle with the vertical*: fixed at 0° (vertical joints) or 60°.





Frictional forces inside the joints have been neglected for the case of vertical joints, but have been considered for the 60° joints because of the component of gravity that is oriented perpendicularly to the joints. The following approach has been adopted:

- the weight of the block is subdivided into a component along the joint axis (W') and a component perpendicular to the joint axis (W''),
- W' stabilizes the block along its orientation of movement out of the surrounding mass,
- W'' stabilizes the block by (perpendicular) compression of the joints between the blocks and by applying a joint friction angle μ,
- an additional frictional force F = W''μ is added to the computation of the net uplift force along the orientation of potential block movement
- the dip direction is not considered to influence the net uplift force

3. *Block density*: fixed at 2650 kg/m^3.

4. *Block protrusion*: from perfectly smooth (offset = 0 cm) to very rough (offset = min. 10 cm)

4. Bridge pier parameters

The bridge pier has been modeled in a very simple manner by accounting for the following parameters:

1. *Bridge pier diameter D (or width B):* fixed at 2 m

2. *Angle of bridge pier with flow angle*: 0° or 45°

The angle between the bridge pier alignment and the approach flow is accounted for by means of a k parameter that is applied to the stream power, following HEC-18 (Richardson et al., 1993). For 0° and 45° angles, and a pier length to width ratio of 4, this k parameter equals 1.0 respectively 2.3.

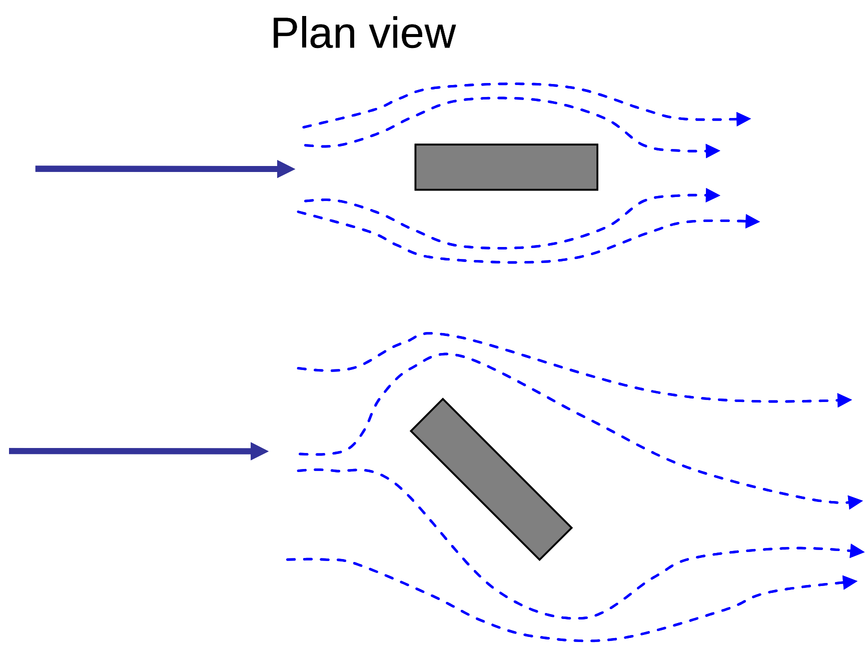


Figure 5: Angle of bridge pier with flow angle as considered in the numerical modeling

5. Numerical modeling of rock block uplift

A transient two-phase numerical modeling of the quasi-steady and fluctuating turbulent pressures acting inside the joints surrounding a single rock block has been performed (Bollaert, 2002, 2004). Figure 6 illustrates the basic configuration used for the numerical computations.

The model applies the sinusoidal boundary pressure signal at the joint entrances of the rock block and computes the pressures inside the joints all around the block. Only one single rock block is considered. This block is considered to be located at the bottom in the immediate vicinity of the bridge pier. Based on the rock block dimensions, the computations are performed layer per layer, with the layer height set equal to the block height. The pressures are computed as presented in Figure 7.

Uplift or ejection of a rock block is computed by defining at each time step the total uplift force on the block. As illustrated in Figure 8, this total uplift force is composed of three distinct components (Bollaert and Hofland, 2004):

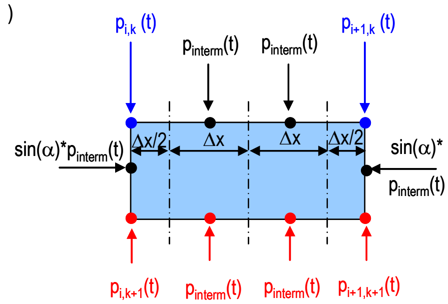
1. static uplift force = buoyancy forces
2. quasi-steady uplift forces = f (block protrusion, local flow velocity in scour hole)
3. turbulent uplift forces = f(local stream power, shear stresses, pressure fluctuations)

At each time step Δt:

Surface pressure/force over block = $\Sigma\,(\,p_{i,k}(t)*\Delta x/2\; + \;p_{i+1,k}(t)*\Delta x/2\; + \;\Sigma(p_{interm}(t))*\Delta x/n\,)$

Underpressure/force over block = $\Sigma\,(\,p_{i,k+1}(t)*\Delta x/2\; + \;p_{i+1,k+1}(t)*\Delta x/2\; + \;\Sigma(p_{interm}(t))*\Delta x/n\,)$

NET pressure/force over block = Underpressure – Surface pressure



During time period t:

NET IMPULSION I_{NET} = $\int$ (Underpressure – Surface pressure) dt

during each period of positive NET pressure/force on block

NET IMPULSION I_{NET} = mass block * velocity block $= m_b * V_b = \rho_b * g * V_b$

BLOCK UPLIFT HEIGHT h_{up} = $(V_b * V_b) / 2g$

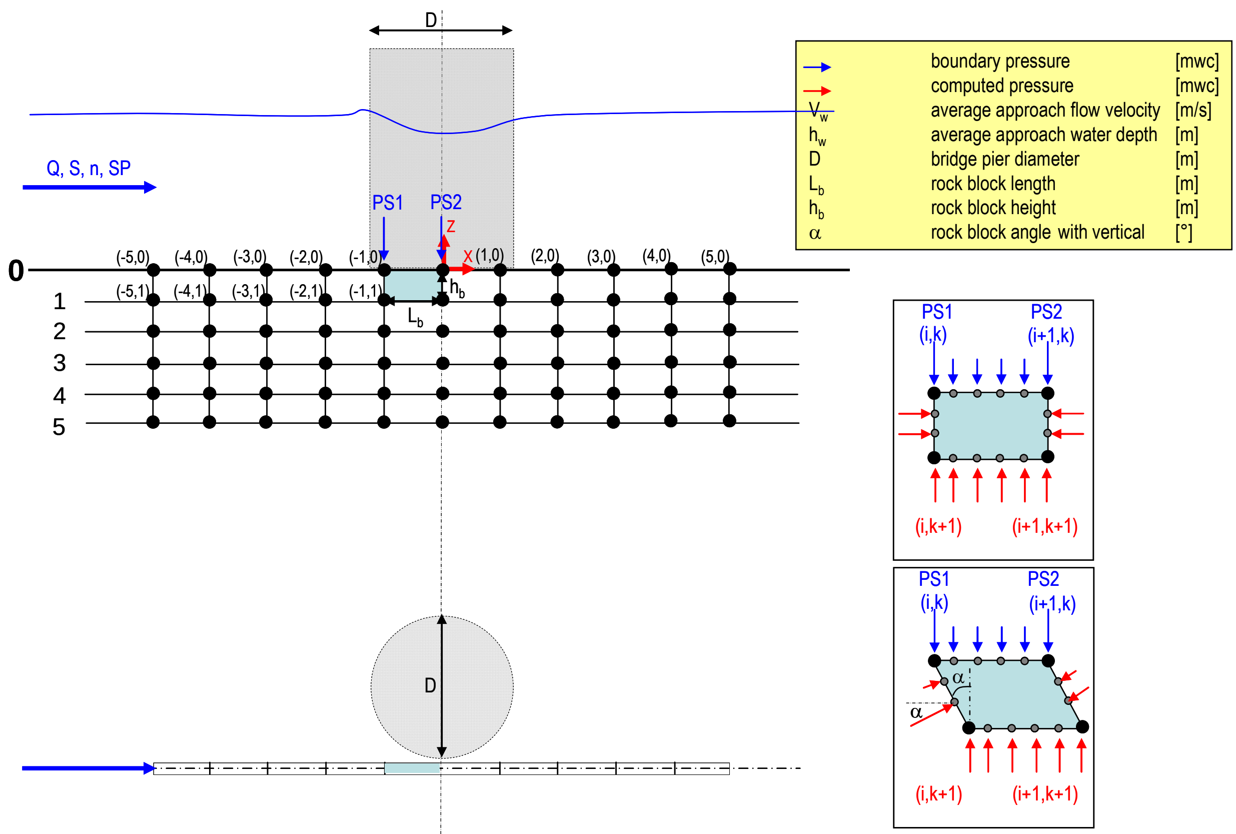


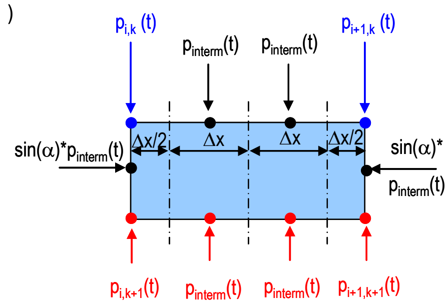
Figure 6: Determination of transient numerical modeling of dynamic pressures around a rock block at a bridge pier

<u>At each time step Δt:</u>

Surface pressure/force over block = $\Sigma\,(\,p_{i,k}(t)*\Delta x/2\; + \;p_{i+1,k}(t)*\Delta x/2\; + \;\Sigma(p_{interm}(t))*\Delta x/n\,)$

Underpressure/force over block = $\Sigma\,(\,p_{i,k+1}(t)*\Delta x/2\; + \;p_{i+1,k+1}(t)*\Delta x/2\; + \;\Sigma(p_{interm}(t))*\Delta x/n\,)$

NET pressure/force over block = Underpressure – Surface pressure



<u>During time period t:</u>

NET IMPULSION I_{NET} = $\int$ (Underpressure – Surface pressure) dt
during each period of positive NET pressure/force on block

NET IMPULSION I_{NET} = mass block * velocity block $= m_b * V_b = \rho_b * g * V_b$

BLOCK UPLIFT HEIGHT h_{up} = $(V_b * V_b) / 2g$

Figure 7: Numerical computation of dynamic pressures on a rock block at a bridge pier

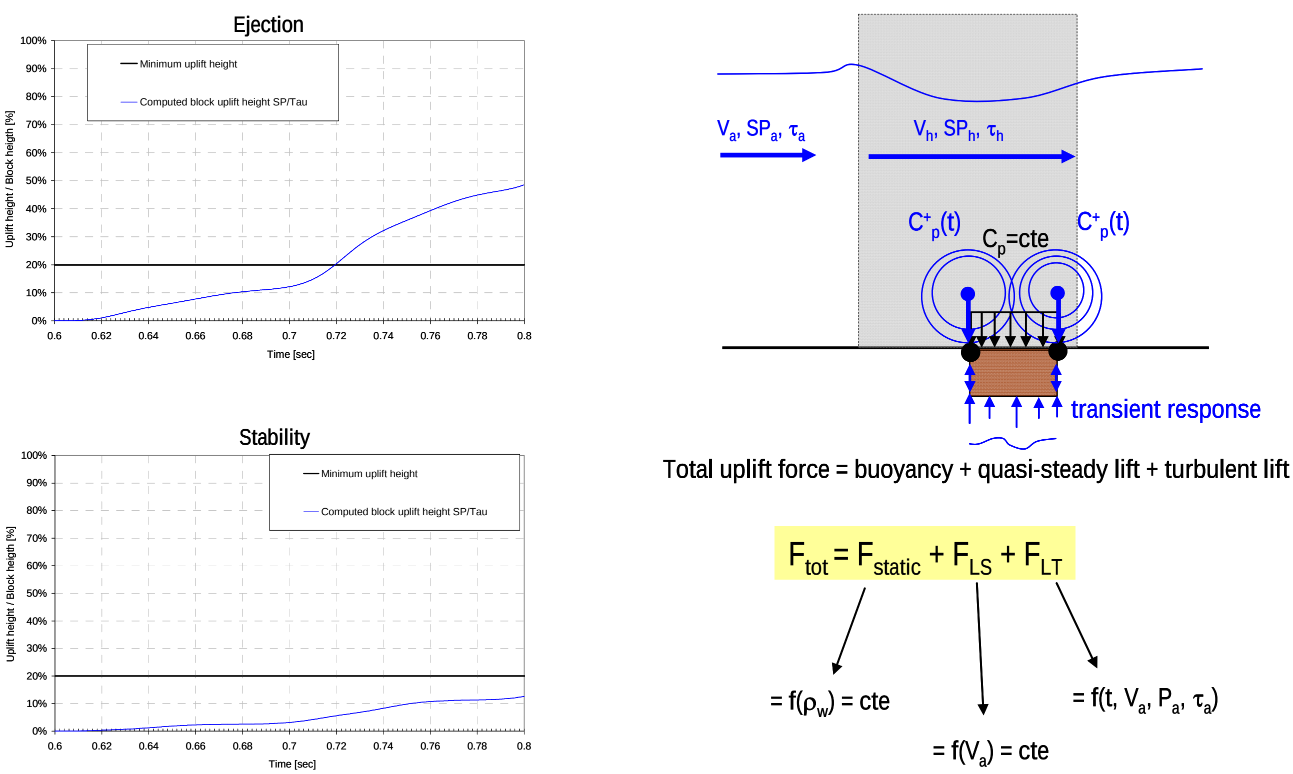


Figure 8: Determination of net uplift forces generated by dynamic pressures around a rock block at a bridge pier

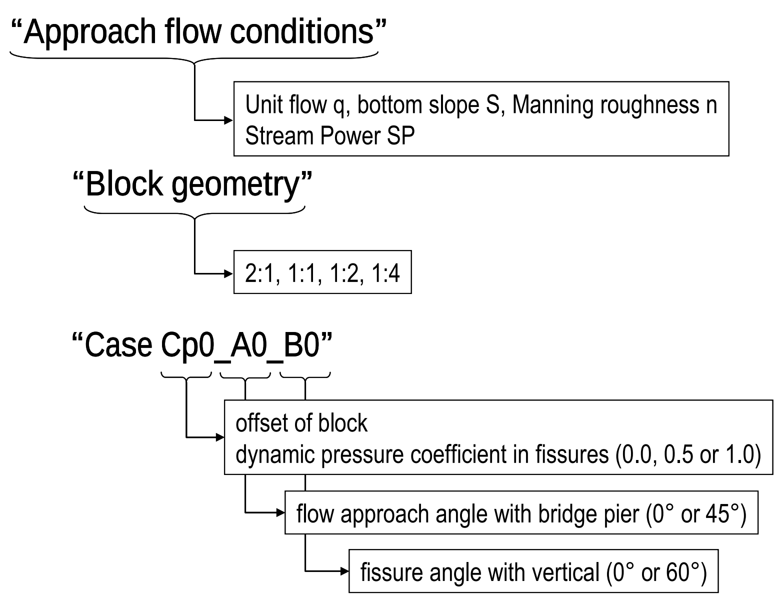
During time periods for which the net uplift force on the block is positive, the block will be submitted to a net uplift impulsion. This net uplift impulsion is then transformed into a net uplift velocity that is given to the mass of the block. Finally, the net uplift velocity is transformed into a net uplift height.

The block is considered to be ejected when its net uplift height is larger than or equal to 20% of the total block height (Bollaert, 2004).

Once the single rock block is found to be ejected by the pressures, the whole layer is considered to be eroded and the next layer is computed until no block movement is detected anymore.

6. Model results

The results of the numerical computations of rock block uplift are presented in the appendices and are based on the following terminology:



For each of the parametric combinations defined above, the following results are presented:

1. *Non-dimensional ultimate scour depth* Z_{sc}/D (scour depth / pier diameter or width) as a function of specific discharge upstream, for different bottom slopes S and different block shapes (2:1, 1:1, 1:2 and 1:4)
2. *Non-dimensional ultimate scour depth* Z_{sc}/D (scour depth / pier diameter or width) as a function of average flow velocity upstream, for different bottom slopes S and different block shapes (2:1, 1:1, 1:2 and 1:4)

3. *Critical block uplift velocity V_{crit}* [m/s] as a function of the bottom slope, for different block geometries (2:1, 1:1, 1:2 and 1:4)
4. *Critical block uplift velocity V_{crit}* [m/s] as a function of the shape of the block, for different bottom slopes (0.1 to 10 %).

Figures 9 to 12 illustrate examples of computational results for the Case Cp0_A0_B0, i.e. for rock blocks without any protrusion, a bridge pier that is perfectly aligned with the approach flow angle and vertically oriented rock joints.

Spreadsheets containing calculations for Figures 9 to 12 are included in Appendix C.

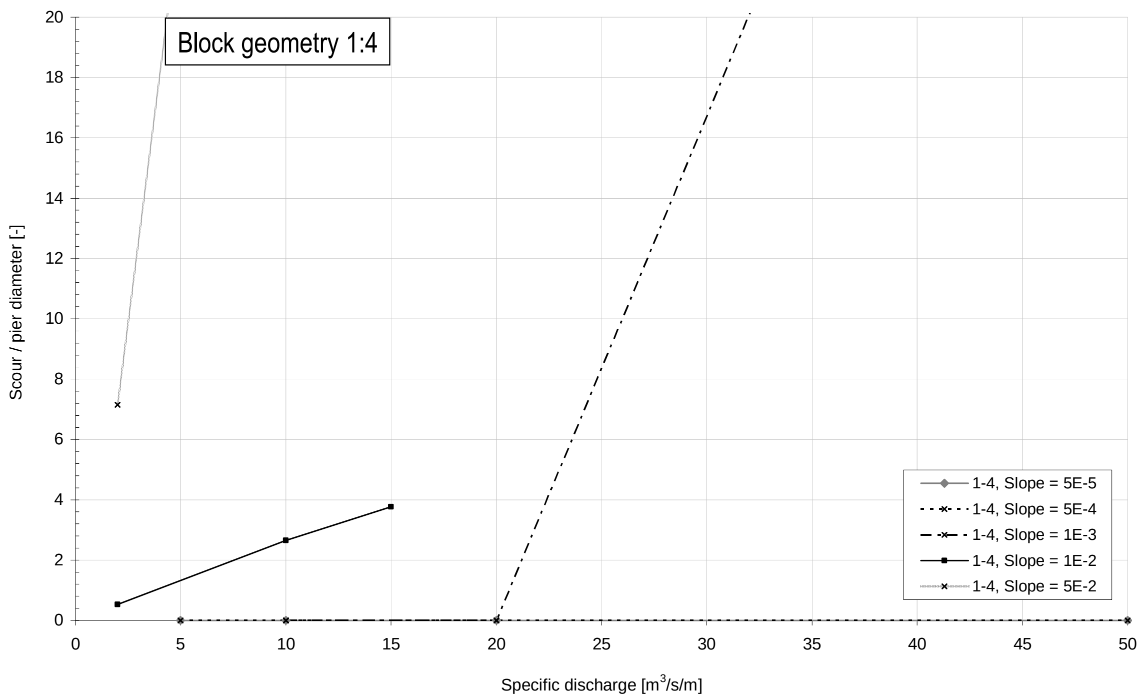


Figure 9: Non-dimensional ultimate scour Z_{sc}/D as a function of specific discharge upstream, for different bottom slopes S and a block shape of 1:4 (Cp0_A0_B0)

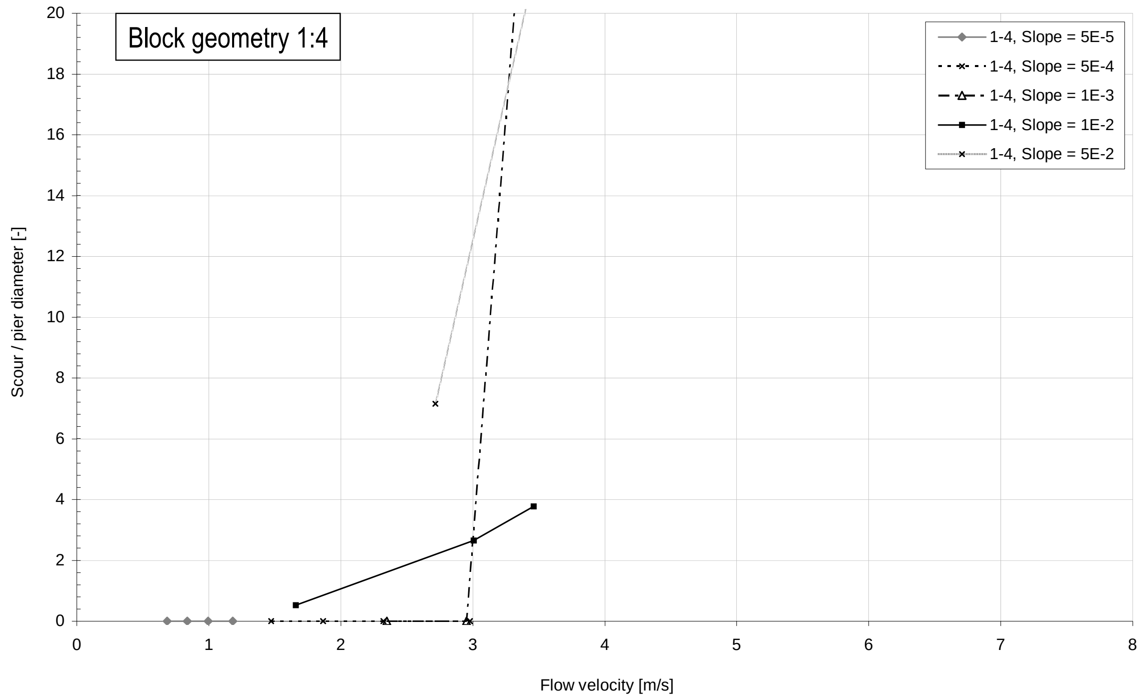


Figure 10: Non-dimensional ultimate scour Z_{sc}/D as a function of specific discharge upstream, for different bottom slopes S and a block shape of 1:4 (Cp0_A0_B0)

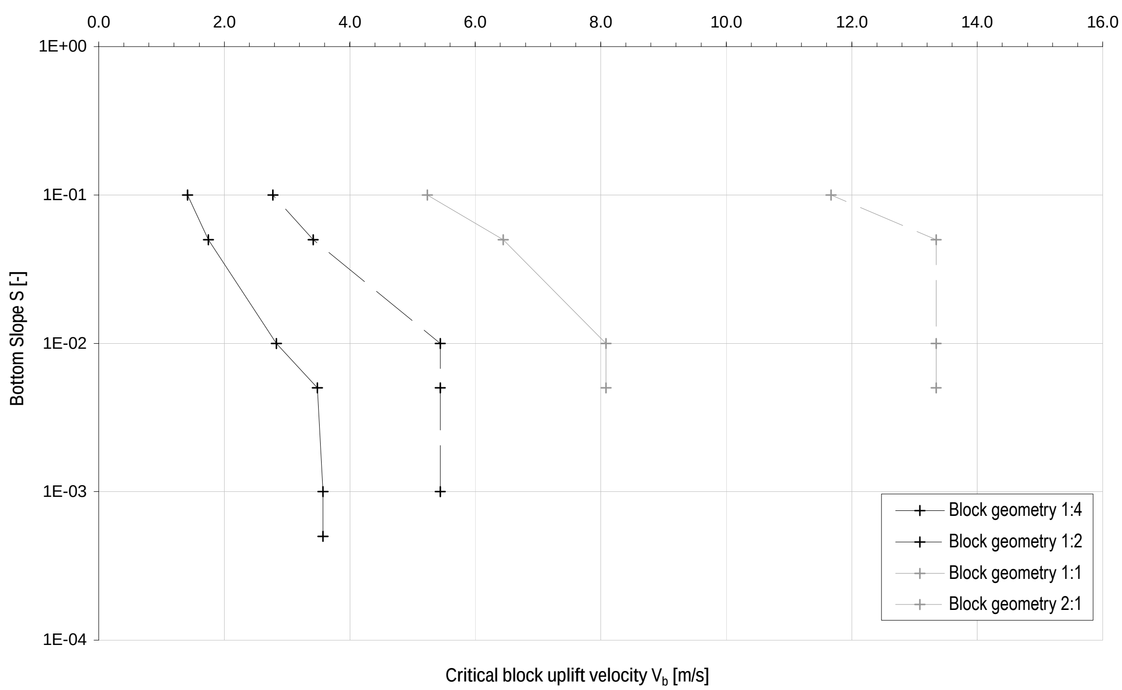


Figure 11: Critical block uplift velocity V_{crit} as a function of bottom slope, for different block shapes (Cp0_A0_B0)

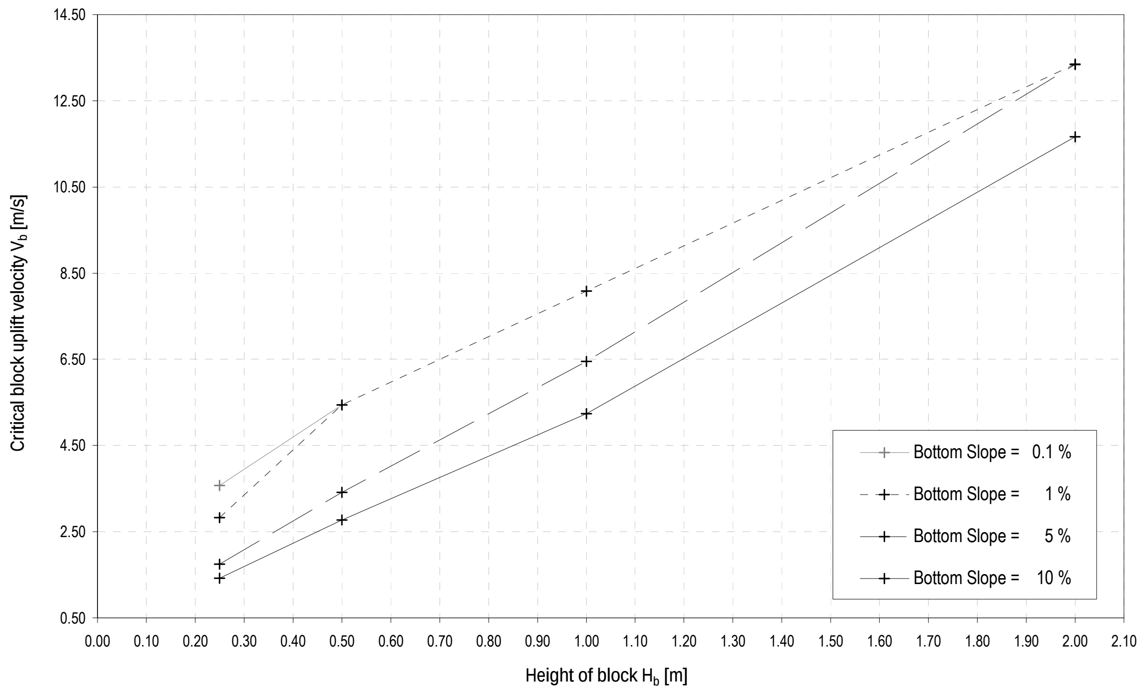


Figure 12: Critical block uplift velocity V_{crit} as a function of block geometry (height for side length of 1m), for different bottom slopes (Cp0_A0_B0)

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NCHRP 24-29 Scour at Bridge Foundations on Rock
Numerical Models from Appendix C

Height_CP0_S0_A0_B0_v3.xls
Height_CP0_S0_A0_B60_v3.xls
Height_CP0_S0_A45_B0_v3.xls
Height_CP0_S0_A45_B60_v3.xls
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Height_CP10_S0_A45_B60_v3.xls

Vcritique_CP0_S0_A0_B0_v3.xls
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United States
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**Natural
Resources
Conservation
Service**

Part 628 Dams
National Engineering Handbook

Chapter 52 Field Procedures Guide for the Headcut Erodibility Index

Issued August 1997
Revised March 2001

Chapter 52 Field Procedures Guide for the Headcut Erodibility Index

Contents:

Figure

Chapter 52 — Field Procedures Guide for the Headcut Erodibility Index

628.5200 Introduction

This chapter presents field procedures and terminology used in the determination of the parameters that form the headcut erodibility index, K_h, given in equation 51–13 of Part 628, Chapter 51, Earth Spillway Erosion Model. The criteria were developed primarily from the analysis of data collected by the U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) and Agricultural Research Service (ARS). The data resulted from studies of spillway performance at 125 earth auxiliary spillways in 10 states between 1983 and 1993.

The concept of a headcut erodibility index was first developed by Moore et al. (1994) based on the analogy between bulldozer drawbar power required for ripping earth materials and the hydraulic power associated with turbulent energy dissipation at a headcut. The classification system presented in Temple and Moore (1997) enables any type of earth material, whether engineered or natural, to be characterized quantitatively with regard to its hydraulic erodibility under various hydraulic conditions. The system, based closely on Kirsten's (1982, 1988) ripability index, allows earth material to be classified on a continuous basis from loose granular or soft cohesive soils through extremely hard, massive rock. The geological parameters that constitute the index include earth material strength, block or particle size, discontinuity or interparticle bond shear strength, and shape of material units and their orientation relative to streamflow.

Trained professionals can conduct the identification procedures relatively easily and at low cost in the field. Each parameter is expressed in quantitative terms to avoid uncertain interpretation and are logarithmically scaled to improve accuracy of assessments. Terminology used in developing the field identification tests is, to the extent possible, consistent with industry usage.

The headcut erodibility index, K_h, represents a measure of the resistance of the earth material to erosion. The index is the scalar product of the indices for its constituent parameters. The index takes the general form:

$$K_h = M_s \times K_b \times K_d \times J_s \qquad [52\text{–}1]$$

where:

- M_s = material strength number of the earth material
- K_b = block or particle size number
- K_d = discontinuity or interparticle bond shear strength number
- J_s = relative ground structure number

The number, M_s, expresses the unconfined compressive strength of an intact representative sample of the material itself without consideration of innate geologic variability within the mass. The number, K_b, refers to the mean block size of intact rock material (the cube root of the volume) as determined by the spacing of discontinuities within the rock mass or mean grain size for granular material (Barton et al. 1974). The number, K_d, represents the shear strength of a discontinuity in a rock mass, or the strength of interparticle bonds of the gouge (soil material) within the aperture of a discontinuity; it also represents shear strength of interparticle bonds in granular soils (Barton et al. 1974). The number, J_s, accounts for the structure of the ground with respect to streamflow. It is a complex function that considers orientation and shape of individual blocks, as determined by the measurement of the spacing, dip angles, and dip directions of joint sets, with respect to direction of streamflow.

628.5201 Geological mapping

Engineering geological mapping includes identification, characterization, and spatial representation of zones of geologic material that meet similar engineering performance criteria. Geologic material (soil, rock) is mapped according to zones consistent in hydraulic erodibility characteristics expressed in terms of the headcut erodibility index, K_h.

Before initiating a fixed line survey of discontinuities (appendix 52A), conventional geological mapping must be conducted to determine soil and rock types; to delineate major geological structures, such as faults, dikes, and lithologic contacts; and to identify any significant stratigraphic discontinuities within the mass. Plane table, air photo, and conventional surveying techniques may be applied to develop a geologic evaluation map.

Each zone of geologic material at a site is identified according to formal nomenclature (e.g., St. Peter Sandstone) or assigned an informal name. If a geologic formation has multiple beds or units of widely differing erodibility, each unit may be identified alphanumerically, such as Rock Unit L-6. Mapping solely on the basis of lithology can, in some instances, be misleading (Dearman 1974). Mapping units should be delineated according to their similarities in hydraulic erodibility.

628.5202 Earth material classification

The term earth material (or geologic material) is considered to embrace the entire spectrum of soil and rock materials, whether natural or engineered. Earth materials range on a broad continuum from very loose, cohesionless, granular soil or very soft, cohesive soil through extremely hard, massive rock.

(a) Soil material

Soil material is classified in the field according to ASTM D 2488, Standard Practice for Description and Identification of Soils (Visual-Manual Procedure). If greater precision is needed, representative samples may be collected for laboratory analysis and classified according to ASTM D 2487, Standard Test Method for Classification of Soils for Engineering Purposes.

(b) Transitional material

Earth material transitional between soil and rock is differentiated by strength rather than geologic origin. Material with a uniaxial (unconfined) compressive strength less than 1.25 MPa is normally taken to be soil (Geological Society of London (GSL) 1977). If, however, an earth material, regardless of origin, is in such a condition that it can be classified by criteria in ASTM D 2488, it shall be considered a soil when determining the headcut erodibility index. Appendixes in ASTM D 2488 provide additional guidance in dealing with unusual material.

(c) Rock material

Rock material is classified by a simplified geologic scheme based on genetic category, structure, composition, and grain size. Table 52–1 is a rock type classification modified from GSL (1979). Common rock type names are assigned in the field generally without need for costly lab tests or thin sections. Common terminology, such as schist, is preferred over technically correct, but jargon-rich terms, such as albite-epidote-amphibolite-schist. Detailed mineralogical and fabric descriptors are used only for correlation purposes or whenever they have engineering significance.

Table 52–1 Rock type classification (code number in parentheses)

Genetic Group	Predominant grain size, mm (sieve no.)	Detrital Sedimentary			Chemical Organic	Metamorphic		Pyroclastic	Igneous			
Usual Structure		Bedded			Bedded	Foliated	Massive	Bedded	Massive			
Composition			Grains of rock, quartz, feldspar, and clay minerals	At least 50% of grains are of carbonate	Salts, carbonates, silica, carbonaceous	Quartz, feldspars, micas, dark minerals	Quartz, feldspars, micas, dark minerals, carbonates	At least 50% of grains are of igneous rock	Quartz, feldspars, micas, dark minerals: Acid	Quartz, feldspars, micas, dark minerals: Intermediate	Feldspar; dark minerals: Basic	Dark minerals: Ultrabasic
Very coarse-grained	75 (3")	Rudaceous	Grains are of rock fragments; Rounded grains: CONGLOMERATE (11)	CALCIRUDITE (23); LIMESTONE (undifferentiated) (21)	CLINKER (31); SALINE ROCKS Halite (32) Anhydrite (33) Gypsum (34)	TECTONIC BRECCIA (41); MIGMATITE (42)	METACONGLOMERATE (51)	Rounded grains: AGGLOMERATE (61)	PEGMATITE (71)			
Coarse-grained		Rudaceous	Angular grains: BRECCIA (12)			GNEISS (43)	MARBLE (52); GRANULITE (53)	Angular grains: VOLCANIC BRECCIA (62)	GRANITE (72)	DIORITE (81); GRANODIORITE (82)	GABBRO (91)	PYROXENITE (01)
Medium-grained	4.75 (4)	Arenaceous	Grains are mainly mineral fragments; SANDSTONE (13); ARKOSE (14); GRAYWACKE (Argillaceous ss) (15)	CALCARENITE (24)	CALCAREOUS ROCKS	SCHIST (44); Amphibolite (45)	QUARTZITE (54)	TUFF (63)	SYENITE (73)	ANORTHOSITE (83)	DIABASE (92)	
Fine-grained	0.074 (200)								APLITE (74)	MONZONITE (84)		PERIDOTITE (02)
Very Fine-grained	0.005	Argillaceous or Lutaceous	MUDSTONE (16); SHALE: fissile mudstone (17); SILTSTONE>50% fine-grained particles (18); CLAYSTONE>50% very fine grained particles (19)	MARLSTONE (22); CALCISILTITE (25); CHALK (26); CALCILUTITE (27)	LIMESTONE (35); DOLOMITE (36)	PHYLLITE (46); Mylonite (47); SLATE (48)	HORNFELS (55)	Fine-grained TUFF (64); Very fine-grained TUFF (65)	RHYOLITE or FELSITE (75)	Dacite (85); ANDESITE (86)	BASALT (93)	DUNITE (03); NEPHELINE-BASALT (04)
Glassy Amorphous					SILICEOUS ROCKS Chert (37) Flint (38); CARBONACEOUS ROCKS; LIGNITE/COAL (39)	Ultramylonite (49)		Welded TUFF (66); PUMICE (67)	VOLCANIC GLASSES: OBSIDIAN (76)	PITCHSTONE (87)	TACHYLYTE (94)	

628.5203 Field procedure for evaluating constituent parameters

(a) Material strength number (M_s)

(1) Field identification

The material strength number is determined separately for cohesionless soil (table 52–2), cohesive soil (table 52–3), and rock (table 52–4). Standard definitions are relied on for distinction between these various materials. The values of the parameters are based on field identification tests, or, alternatively, rigorous standard testing. Scales of relative density, consistency, and hardness are correlated with ranges in strength. The relative density scales for cohesionless soil, cohesive soil, and rock are as used by Korhonen et al. (1971), Jennings et al. (1973), and GSL (1977), respectively.

The material strength number for cohesionless soils in table 52–2 are correlated with values for in situ deformation modulus (ASTM D 1194, Standard Test Method for Bearing Capacity of Soil for Static Load and Spread Footings), using Kirsten's (1988) unpublished data.

Table 52–2 Material strength number, M_s, for cohesionless soil 1/

Relative density	Field identification tests	SPT 2/ 5/ (blows/0.3 m) 4/ 5/	In situ deformation modulus (IDM) (MPa) 5/	M_s 3/
Very loose	Particles loosely packed. High percentage of voids. Very easily dislodged by hand. Matrix crumbles easily when scraped with point of geologic pick. Raveling often occurs on excavated faces.	< 5	< 0.005	< 0.02
Loose	Particles loosely packed. Some resistance to being dislodged by hand. Large number of voids. Matrix shows low resistance to penetration by point of geologic pick.	5 - 10	0.005 - 0.01	0.02 - 0.05
Medium dense	Particles closely packed. Difficult to dislodge individual particles by hand. Voids less apparent. Matrix has considerable resistance to penetration by point of geologic pick.	10 - 30	0.01 - 0.03	0.05 - 0.10
Dense	Particles very closely packed and occasionally very weakly cemented. Cannot dislodge individual particles by hand. The mass has very high resistance to penetration by point of geologic pick. Requires many blows of geologic pick to dislodge particles.	30 - 50	0.03 - 0.08	0.10 - 0.20
Very dense	Particles very densely packed and usually cemented together. Mass has high resistance to repeated blows of geologic pick. Requires power tools for excavation.	> 50	0.08 - 0.2	0.20 - 0.45

1/ Cohesionless soil is a material with a plasticity index (PI) less than or equal to 10. Use table 52–3 for cohesive soils.
2/ Standard Penetration Test, SPT (ASTM D 1586) used for most sandy-type cohesionless soils. In situ deformation modulus (IDM) (ASTM D 1194) used for most gravel-type soils and coarse detritus.
3/ M_s of a cohesionless soil is approximately determined from results of IDM testing by the following relationship:

$$M_s = 1.7\ (IDM)^{0.832} \text{ for IDM in MPa}$$

4/ Cohesionless soils in which blow counts are greater than 50 or IDM is greater than 200 kPa to be taken as rock, for which the hardness may be obtained from table 52–4.
5/ Correlation between SPT and IDM should be used as a guide only as results may vary in different geologic areas. Lab strength tests are recommended on soil materials to support SPT or field assessment tests.

Scales for consistency of cohesive soil (table 52–3) and hardness of rock material (table 52–4) are based on GSL (1977). These ranges are correlated with values for unconfined compressive strength as determined by ASTM D 2166 Standard Test Method for Unconfined Compressive Strength for Cohesive Soil and ASTM D 2938 Standard Test Method for Unconfined Compressive Strength of Rock Core Specimens, respectively. Field identification tests given in tables 52–3 and 52–4 are from GSL (1977), International Society for Rock Mechanics (ISRM 1981), and USDA (1978). Material strength numbers given in tables 52–3 and 52–4 represent rounded off products of uniaxial compressive strengths and coefficients of relative density. Penetrometer blow count data (ASTM D 1586, Standard Test Method for Penetration Test and Split-Barrel Sampling of Soils) given in tables 52–2 and 52–3 are derived from Lambe and Whitman (1969).

Table 52–3 Material strength number, M_s, for cohesive soil

Consistency	Field identification tests	SPT (blows/0.3 m)	Unconfined compressive strength (UCS) (kPa)	M_s
Very soft	Exudes between fingers when squeezed in hand.	< 2	< 40	< 0.02
Soft	Easily molded with fingers. Point of geologic pick easily pushed into shaft of handle.	2 - 4	40 - 80	0.02 - 0.05
Firm	Penetrated several centimeters by thumb with moderate pressure. Molded by fingers with some pressure.	4 - 8	80 - 150	0.05 - 0.10
Stiff	Indented by thumb with great effort. Point of geologic pick can be pushed in up to 1 centimeter. Very difficult to mold with fingers. Just penetrated with hand spade.	8 - 15	150 - 300	0.10 - 0.20
Very stiff	Indented only by thumbnail. Slight indentation by pushing point of geologic pick. Requires hand pick for excavation.	15 - 30	300 - 625	0.20 - 0.45

Notes:
1. Cohesive soil is material with a plasticity index (PI) greater than 10. Use table 52–2 for cohesionless soils.
2. 1 kPa equals 1 kN/m^2.
3. Vane shear strength (ASTM D 2573, field; ASTM D 4648, lab) also may be used for unconfined compressive strength (ASTM D 2166).
4. Cohesive soils in which blow counts are greater than 30 or strengths greater than 625 kPa are to be taken as rock, for which the hardness can be obtained from table 52–4.
5. Cohesive soils must be evaluated for hardness in the saturated condition.
6. M_s of a cohesive soil also can be determined as the product of unconfined compressive strength (in MPa) times its coefficient of relative density. For most cohesive soils, M_s is approximately determined by:

   $M_s = 0.78\ (UCS)^{1.09}$ for UCS ≤ 10 MPa, and M_s = UCS for UCS > 10 MPa.
7. Correlation between SPT and UCS should only be used as a guide, as results may vary in geologic areas. Lab strength tests are recommended on soil materials to support SPT or field assessment tests. Vane shear strength values also are applicable in the lower strength ranges.

The material strength number of soil material is equal to the product of its unconfined compressive strength times the coefficient of relative density. To support the field assessments, laboratory tests for strength and bulk density are recommended for representative undisturbed soil samples.

Uniaxial compressive strength of intact rock material is normally determined by a standard laboratory test method (ASTM D 2938). Because large differences in rock strength are required to appreciably affect the headcut erodibility index, the precision afforded by expensive laboratory tests is rarely justified. Experience shows that conducting field estimates of rock material hardness is a practical way of obtaining adequate assessments of strength. The field identification tests for assessing rock material hardness are given in table 52–4.

Table 52–4 Material strength number, M_s, for rock

Rock material hardness [1/]	Uniaxial compressive strength (MPa) [2/]	Field identification tests	M_s [3/]
Very soft rock or Hard, soil-like material	0.6 - 1.25	Scratched with fingernail. Slight indentation produced by light blow of point of geologic pick. Requires power tools for excavation. Peels with pocket knife.	0.45 - 1.0
Soft rock	1.25 - 5.0	Hand-held specimen crumbles under firm blows with point of geologic pick.	1.0 - 4.5
Moderately soft rock	5.0 - 12.5	Shallow indentations (1 to 3 mm) produced by light blows with point of geologic pick. Peels with pocket knife with difficulty.	4.5 - 12.5
Moderately hard rock	12.5 - 50.0	Cannot be scraped or peeled with pocket knife. Intact hand-held specimen breaks with single blow of geologic hammer. Can be distinctly scratched with 20d common steel nail.	12.5 - 50
Hard rock	50.0 - 100.0	Intact hand-held specimen requires more than one hammer blow to break it. Can be faintly scratched with 20d common steel nail.	50 - 100
Very hard rock	100.0 - 250.0	Intact specimen breaks only by repeated, heavy blows with geologic hammer. Cannot be scratched with 20d common steel nail.	100 - 250
Extremely hard rock	> 250.0	Intact specimen can only be chipped, not broken, by repeated, heavy blows of geologic hammer.	> 250

1/ Hardness categories are based solely on hardness characteristics, not geologic origin. For example, a highly weathered shale may classify as firm cohesive soil, and a partially lithified recent soil may classify as moderately soft rock. The transition, however, generally occurs within the 0.60 to 1.25 MPa range.

2/ 1.0 MPa approximately equals 145 pounds per square inch, or 10.4 tons per square foot.

3/ M_s is equal to the product of uniaxial compressive strength, UCS (ASTM D 2938), and coefficient of relative density. For most rock or rock-like materials, M_s is approximately determined by:

$$M_s = 0.78\,(UCS)^{1.09} \text{ for UCS} \leq 10 \text{ MPa, and } M_s = UCS \text{ for UCS} > 10 \text{ MPa.}$$

(2) Other identification methods

Other methods for determining hardness include:

- ASTM D 5873 Test Method for Determining Hardness of Rock by the Rebound Hammer Method—Used for rock categories that have hardnesses varying between very soft and very hard.
- The pocket penetrometer—Used for most soils with strength less than 2.00 MPa.

(b) Block/particle size number (K_b)

The term K_b represents the mean size of individual material units as determined by the spacing of discontinuities in a rock mass, or it is a function of particle diameter of cohesionless granular soils, including detritus and boulder formations. The number can be calculated by a variety of approaches.

(1) Rock and rock-like materials

For rock and rock-like materials, the primary method to calculate K_b is:

$$K_b = \frac{RQD}{J_n} \qquad [52\text{–}2]$$

where:
RQD = rock quality designation
J_n = joint set number

RQD, a standard parameter in drill core logging, can be determined from drill cores according to methods in Deere and Deere (1988) and ASTM D 6032, Standard Test Method for Determining RQD of Rock Core, or from a joint count per cubic meter of rock mass, as defined in Barton et al. (1974). RQD represents the sum of the length of core pieces greater than 0.1 meter divided by the total core run length (generally 1.5 meters), expressed in percent (Deere and Miller 1966 or Deere and Deere 1988).

The term, J_n, is the joint set number, table 52–5. The joint set number is a scale factor representing the effect of different individual discontinuity spacings relative to the average discontinuity spacing. The factor accounts for the shape of the material units or, alternatively, the relative occurrence of different joint sets.

Depending on the type of data available, RQD also can be determined in alternative ways, as summarized below, and for which 5 is less than or equal to RQD less than or equal to 100.

$$RQD = \left(115 - 3.3J_C\right) \qquad [52\text{–}3]$$

$$RQD = \left(105 - \frac{10}{D}\right) \qquad [52\text{–}4]$$

$$RQD = \left[105 - \frac{10}{\left(J_X J_Y J_Z\right)^{0.33}}\right] \qquad [52\text{–}5]$$

where:
J_c = joint count number representing the number of joints per cubic meter

$$J_c \cong \left(\frac{3}{D}\right) + 3 \quad \text{(as given in table 52–6)}$$

where:
D = mean block diameter, in meters

Mean block size is taken as the cube root of the product of the average spacings of joint sets, J_x, J_y, J_z, measured in three mutually perpendicular directions, x, y, z, as explained in Appendix 52A, The Fixed Line Survey, such that:

$$D = \left(J_x J_y J_z\right)^{0.33}, \text{ for } D \geq 0.10 \text{ m} \qquad [52\text{–}6]$$

Table 52–5 Joint set number, J_n

Intact; no or few joints	1.00
One joint set	1.22
One joint set plus random	1.50
Two joint sets	1.83
Two joint sets plus random	2.24
Three joint sets	2.73
Three joint sets plus random	3.34
Four joint sets	4.09
More than four joint sets	5.00

(2) Cohesive soils and coarse detritus, gravels, and boulders

For intact, cohesive soils and coarse detritus, gravels, and boulder formations for which D > 0.1 meter, K_b = 1. For strongly cemented materials that lack discontinuities, RQD = 100 and J_n = 1. If soil joints occur within the soil mass, use equation 52–3 to obtain RQD and apply the applicable value for J_n to obtain K_b by equation 52–2.

Whether material units erode as individual constituent particles or by blocks of material depends on the occurrence of discontinuities within the mass. In rock formations, only discontinuities that effectively break the mass into discrete blocks are to be considered.

(3) Identification of joint set spacing

Joint set spacing (J_x, J_y, J_z) is the average spacing of joints within a given set, expressed in meters. The fixed line survey method (appendix 52A) can be used to determine joint spacing.

Bedding plane partings form a systematic joint set. Although a different set of terms for bedding plane partings has been used for years in classic field geology, the recommendation is to use one set of terms common to both bedding plane partings and high angle joint sets. Descriptive terms should be consistent with the usage in table 52–7.

(4) Identification of particle size

Mean diameter (D_{50}) of granular soil materials is determined by the visual-manual procedures given in ASTM D 2488.

(c) Discontinuity/interparticle bond shear strength number

The discontinuity/interparticle bond shear strength number (K_d) is represented as:

$$k_d = \frac{J_r}{J_a} \qquad [52–7]$$

where:
J_r = joint roughness number
J_a = joint alteration number

J_r represents the degree of roughness of opposing faces of a rock discontinuity (table 52–8), and J_a the degree of alteration of the materials that form the faces (table 52–9).

(1) Discontinuity strength

The shear strength of a rock discontinuity is directly proportional to the degree of roughness of the opposing faces and inversely proportional to the degree of alteration. Joint roughness affects the shear strength

Table 52–6 Joint count number, J_c, from RQD 1/ 2/

No. joints per cubic meter (J_c)	Rock quality designation (RQD)	No. joints per cubic meter (J_c)	Rock quality designation (RQD)
33	5	18	55
32	10	17	60
30	15	15	65
29	20	14	70
27	25	12	75
26	30	11	80
24	35	9	85
23	40	8	90
21	45	6	95
20	50	5	100

1/ RQD ≅ 115 - 3.3 J_c; or
2/ For blocks with mean diameters, D ≥ 0.10 meter, J_c ≅ (3/D) + 3

Table 52–7 Spacing categories for joint sets

Joint set spacing categories: Bedding plane partings	Joint set spacing categories: High angle joints	Spacing (meters)
Massive/unstratified	Extremely wide	> 6.000
Very thick-bedded	Very wide	2.000 - 6.000
Thick-bedded	Wide	0.600 - 2.000
Medium-bedded	Mod. wide	0.200 - 0.600
Thin-bedded	Mod. close	0.060 - 0.200
Very thin-bedded	Close	0.020 - 0.060
Laminated	Very close	0.006 - 0.020
Thinly laminated	Shattered	0.002 - 0.006
Fissile	Fissured	< 0.002

of a discontinuity particularly in cases of undisplaced and interlocked features, such as unfilled (open) joints. The relative influence of wall roughness on shear strength declines as aperture width or infilling thickness increases.

Values for J_r and J_a apply primarily to the joint set or discontinuity in the rock mass most likely to fail. Experience in stratified sedimentary rocks indicates this joint set is typically bedding plane partings, if parting spacing is significantly smaller than the spacing of major high-angle joint sets. If bedding plane partings classify as very thick bedded or unstratified, the joint set closest to being perpendicular to streamflow tends to be most adverse.

(2) Interparticle bond shear strength

If the material under consideration occurs as a soil mass or as gouge in the apertures of rock discontinuities, the interparticle bond shear strength number, K_d, is represented by the quotient J_r/J_a, that, in turn, is approximately equal to tan ϕ'_r, where ϕ'_r is the residual (minimum) friction angle. The residual friction angle can be estimated according to a relationship with soil index properties (Stark and Eid, 1994).

Figure 52–1 presents a correlation of drained residual friction angle (ϕ'_r) and liquid limit (LL) for shear tests conducted on cohesive clays at an effective normal stress of 100 kPa, a value considered typical of near surface materials. The data form three distinct curves according to three ranges of clay size fraction:

For ≤ 20% clay, $\phi'_r = 169.58\,(LL)^{-0.4925}$ [52–7]

For 25 – 45% clay, $\phi'_r = 329.56\,(LL)^{-0.7100}$ [52–8]

For ≥ 50 % clay, $\phi'_r = 234.73\,(LL)^{-0.6655}$ [52–9]

The interparticle bond shear strength number (K_d) of a cohesive soil is predicted by a rational correlation between soil index properties and residual shear strength by the following method (Moore, 2001).

Table 52–8 Joint roughness number, J_r

Joint separation	Joint roughness condition (intermediate scale; small scale)	J_r 1/
Joints are tight or become closed during hydraulic flow	Discontinuous joints; stepped	4.0
	Rough/irregular; undulating (e.g., tension joints, rough sheeting joints, rough bedding)	3.0
	Smooth; undulating (e.g., smooth sheeting, nonplanar foliation and bedding)	2.0
	Slickensided; undulating	1.5
	Rough/irregular; planar	1.5
	Smooth; planar (e.g., planar sheeting joints, planar foliation and bedding)	1.0
	Slickensided; planar	0.5
Joints are open and remain open during hydraulic flow 2/	Joints are either open or contain relatively soft gouge of sufficient thickness to prevent wall contact during hydraulic flow	1.0
	Joints contain swelling clays	1.0

1/ For intact, cohesive material J_r = 3.0.
2/ Consider joints open when aperture width exceeds amplitude of asperities (intermediate scale roughness) of joint faces.

1. Determine the liquid limit by ASTM D 4318, Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, and report the result to the nearest one percent.
2. Determine clay content (the percent finer than 0.002 mm) by ASTM D 422, Standard Test Method for Particle-Size Analysis of Soils, and report the result to the nearest five percent.
3. Use the clay content value to select the appropriate equation (52–7, 52–8, or 52–9) to predict effective residual friction angle, ϕ'_r, and report the result to the nearest one-tenth degree.

Typical ranges of friction angles for various materials are provided in table 52–9. If the residual friction angle calculated by this method differs significantly from these values, consider conducting laboratory or in situ standard test methods, such as:

- ASTM D 3080, Direct Shear Test of Soils Under Consolidated Drained Conditions
- ASTM D 6467, Torsional Ring Shear Test to Determine Drained Residual Shear strength of Cohesive Soils

Once the friction angle is determined, the interparticle bond shear strength number, K_d, is determined by

$$K_d \cong \tan \phi'_r \qquad [52\text{-}10]$$

Table 52–9 Joint alteration number, J_a

Field identification of gouge (infilling)	J_a for aperture width < 1.0 mm [1/]	J_a for aperture width 1.0 - 5.0 mm [2/]	J_a for aperture width ≥ 5.0 mm [3/]	Typical ϕ'_r °
Joint tightly healed with hard, nonsoftening, impermeable mineral filling, e.g., quartz, calcite, or epidote.	0.75	1.0	1.5	- - -
Clean, open joint with fresh or discolored (unweathered) walls only; no infilling.	1.0	1.5	2.0	- - -
Discolored to disintegrated joint walls; infilling is sand or gravel with < 15% cohesionless fines in matrix; with or without disintegrated or crushed rock fragments.	2.0	4.0	6.0	(25 – 30)
Discolored to disintegrated joint walls; cohesionless, nonswelling, low to nonplastic fines in matrix; with or without disintegrated or crushed rock fragments.	3.0 [4/]	6.0 [4/]	10.0 [4/]	(15 – 24)
Disintegrated to decomposed joint walls; nonswelling, lean clay or clay matrix, or low friction clays, such as chlorite, talc, mica, serpentine, gypsum, graphite, kaolinite, or other sheet silicates; with or without disintegrated or crushed rock fragments.	4.0 [4/]	8.0 [4/] [5/]	13.0 [4/] [5/]	(10 – 14)
Disintegrated to decomposed joint walls; fat clay, swelling clay, such as montmorillonite, or clay matrix, with or without disintegrated or crushed rock fragments.	5.0 [4/]	10.0 [4/] [5/]	18.0 [4/] [5/]	(6 – 9)

1/ Joint walls effectively in contact.
2/ Joint walls come into contact after approximately 100 mm shear.
3/ Joint walls do not come into contact at all upon shear. Use this column to determine J_a for intact, cohesive granular materials, for which $J_r = 3.0$. Alternatively, $\tan \phi'_r$ can be substituted for the quotient J_r/J_a where ϕ'_r is the equivalent residual (minimum) friction angle.
4/ Values added to Barton et al. (1974) data.
5/ Also applies when disintegrated or crushed rock fragments occur in clay matrix without wall contact.

(3) Identification of joint roughness

Joint roughness (J_r) condition is described in simple terms based on two scales of visual observation: an intermediate scale (meters) and a small scale (centimeters).

The intermediate scale of roughness is divided into three categories: stepped, undulating, and planar. The small scale of roughness is superimposed on the intermediate scale and is also divided into three groups: rough, smooth, and slickensided. The term slickensided is used only if previous shear displacement is evident along the discontinuity.

The joint roughness number depends upon the roughness condition, whether the discontinuities are tight or become closed when subjected to hydraulic flow, and whether they become opened and remain open during flow (table 52–8). A joint is considered open when the aperture width exceeds the amplitude of the asperities (intermediate scale roughness) of the opposing faces.

To maintain uniformity in the assessment of joint roughness, typical examples of each category must be identified and photographed at each site where the roughness classification is used.

Values for J_r can range between 4.0 (for tight, discontinuous joints in massive rock) and 0.5 (for slickensided planar surfaces with a swelling clay infilling commonly associated with faulted rock).

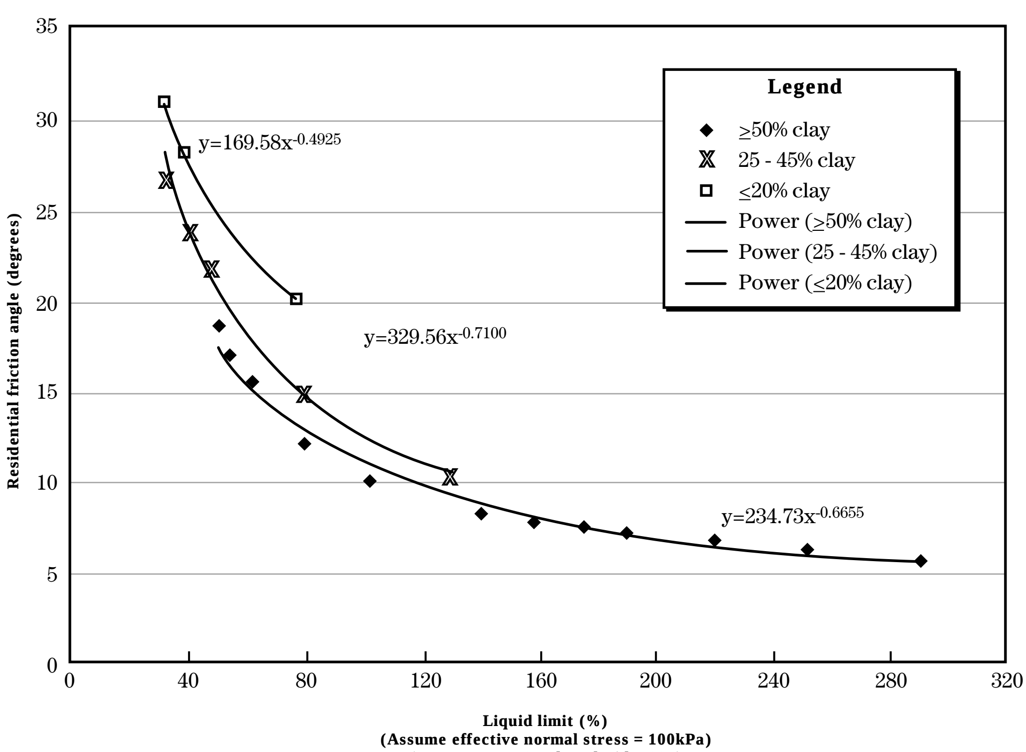
(4) Identification of joint alteration number

The joint alteration number (J_a) is a function of the nature of the infilling, the width of the aperture, and weathering condition of the joint face material. Use table 52–9 for values of J_a.

(5) Identification of infilling

Material occupying the aperture between joint faces is variously called infilling, gouge, breccia, or mylonite (for faults). Materials deposited in an opening include airborne or washed-in materials, such as silt, clay, and

Figure 52–1 Residual friction angle versus liquid limit for three ranges in clay content



other organic and mineral matter, or partly or completely remineralized vein deposits. Wide apertures may contain washed-in gravel or rock fragments disintegrated from the joint walls or crushed by faulting.

Infilling should be described and classified in the field according to ASTM D 2488 or in the laboratory by D 2487. Chemically precipitated or remineralized material should be identified by composition (quartz, calcite, gypsum, epidote).

The strength of the infilling is estimated by using the field tests given in tables 52–2 and 52–3 or by measuring with a pocket penetrometer or pocket vane shear tester.

(6) Measurement of aperture width

Aperture, or planar separation, refers to the opening between opposing faces of a joint, fracture, fissure, or fault. The aperture width is measured at a sufficient number of places along the trace of the joint to obtain an average for the joint. Table 52–10 provides categories of aperture width ranges to facilitate documentation of data. If the width varies across more than one range, record the length of the trace over which the width category applies. For example, a 20-meter-long joint has a narrow aperture width (6 to 20 mm) for 13 meters and widens to moderately narrow (20 to 60 mm) for 7 meters. The variability may be clarified by describing the joint in separately labeled segments and plotting the location of the joint on a geologic evaluation map.

Table 52–10 Aperture width

Aperture width category	Width range (mm)
Wide	> 200
Moderately wide	60 – 200
Moderately narrow	20 – 60
Narrow	6 – 20
Very narrow	2 – 6
Extremely narrow (hairline)	< 2

(7) Identification of weathering condition of joint face material

Weathering is the physical disintegration or chemical decomposition of earth materials that results in changes in the color, texture, composition, density, or form, with little or no transport of the loosened or altered material. The scope of weathering is limited to the condition of the joint face material. Use table 52–11 to classify the weathering condition of the joint face rock material of identified joints.

(d) Relative ground structure number

The relative ground structure number (J_s) represents the orientation of the effective dip of the least favorable discontinuity with respect to spillway flow. The number takes into account the effect of the relative shape of the material units (as determined by joint set spacings) or the ease with which the spillway flow penetrates the ground and dislodges individual material particles.

For practical expediency the rock mass is assumed to be intersected by two primary joint sets in the plane at right angles to spillway flow. The value of J_s is expressed in terms of the relative spacing of the two

Table 52–11 Weathering condition of joint face material

Descriptor	Weathering condition of joint face material
Fresh	No sign of weathering.
Discolored	Iron-stained or discolored, but otherwise unweathered.
Disintegrated	Physically disintegrated to a soil condition with original fabric still intact; material is friable; mineral grains are not decomposed.
Decomposed	Chemically altered to a soil condition with original fabric still intact; some or all of mineral grains are decomposed.

joint sets, the dip angle and the dip direction of the closer spaced set relative to the direction of spillway flow. In this methodology, soil material is considered intact (without structure), in which case $J_s = 1$.

To calculate the effective dip (q), the apparent dip of the bedrock is first determined by using the following relationship, expressing horizontal angles in degrees azimuth and vertical angles in degrees:

$$\tan a = (\tan b)(\sin c) \qquad [52–11]$$

where:
- a = apparent dip of discontinuity
- b = true dip of discontinuity
- c = (strike of discontinuity) – (spillway flow direction)

Effective dip is defined as the apparent dip of the discontinuity adjusted for the slope of the spillway channel, α. Dip direction is measured perpendicular to the strike. If the absolute value of the dip direction (expressed in degrees azimuth) minus the spillway flow direction (expressed in degrees azimuth) is less than 90 degrees (including 0°; i.e., north) or greater than 270 degrees, the dip direction is considered to be with the direction of spillway flow; otherwise, it is considered against the flow.

If the spillway flow direction is with the apparent dip

$$q = a - \alpha \qquad [52–12]$$

If spillway flow direction is against the apparent dip

$$q = a + \alpha \qquad [52–13]$$

Use the calculated value of effective dip to determine J_s from table 52–12.

The ratio of joint spacing, r, reflects the relative shape of the material unit. It is the quotient of the average spacing of the two most dominant high angle joint sets. Select a value for r nearest to 1:1, 1:2, 1:4, or 1:8. For values of r less than 1:8, J_s is taken as r = 1:8.

Table 52–12 Relative ground structure number, J_s

Dip direction 1/ of least favorable joint set (degrees)	Effective dip angle of least favorable joint set 2/ (degrees)	- - - - Ratio of joint spacing, r - - - - 1:1	1:2	1:4	1:8
With flow:					
180/0	90	1.00	1.00	1.00	1.00
0	85	0.72	0.67	0.62	0.56
0	80	0.63	0.57	0.50	0.45
0	70	0.52	0.45	0.41	0.38
0	60	0.49	0.44	0.41	0.37
0	50	0.49	0.46	0.43	0.40
0	40	0.53	0.49	0.46	0.44
0	30	0.63	0.59	0.55	0.53
0	20	0.84	0.77	0.71	0.68
0	10	1.22	1.10	0.99	0.93
0	5	1.33	1.20	1.09	1.03
0/180	0	1.00	1.00	1.00	1.00
Against flow:					
180	5	0.72	0.81	0.86	0.90
180	10	0.63	0.70	0.76	0.81
180	20	0.52	0.57	0.63	0.67
180	30	0.49	0.53	0.57	0.59
180	40	0.49	0.52	0.54	0.56
180	50	0.53	0.56	0.58	0.60
180	60	0.63	0.67	0.71	0.73
180	70	0.84	0.91	0.97	1.01
180	80	1.22	1.32	1.40	1.46
180	85	1.33	1.39	1.45	1.50
180/0	90	1.00	1.00	1.00	1.00

1/ Use dip direction of least favorable joint set with respect to direction of spillway flow.
2/ Using the true dip angle (of least favorable joint set in vertical plane containing direction of streamflow), make corrections for apparent dip and the slope of stream channel to obtain effective dip using formulas 52–8, 52–9, and 52–10.
Note: For granular materials, $J_s = 1.00$.
For values of r less than 1:8, take J_s as for r = 1:8.

(1) Determination of orientation

Use a geological compass to measure the orientation of joints and spillway channel flow direction at the point where erosion initiates, such as, at an overfall (headcut). If the joint surface is exposed three-dimensionally, express its orientation in terms of strike-and-dip. If the outcrop is so smooth and flat that only the trace of the joint is discernible, express the orientation of the trace in terms of trend and plunge.

Plot the locations of all measurements on a geologic evaluation map using standard symbols for strike-and-dip or trend and plunge; record ground coordinates and elevation on field data sheets.

628.5204 Summary

Field procedures are presented for evaluating the constituent geological parameters that form the headcut erodibility index, K_h. The parameters include earth material strength, block or particle size, discontinuity shear strength or interparticle bond shear strength, and relative ground structure. The fixed line survey is recommended for conducting a systematic inventory of structural discontinuities in a rock mass. Soil properties are identified using ASTM standards. Earth material transitional between soil and rock is differentiated by strength rather than geologic origin. All parameters can be assessed rapidly in the field using simple identification tests and measurements. Because input values are based on logarithmic scales, adverse results from inaccurate assessments cannot occur easily for materials with strengths exceeding 1.0 MPa. Laboratory analyses for unconfined strength, bulk density, and shear strength are recommended for weaker materials to corroborate results of field assessments. However, in the absence of laboratory data, the method that results in the more conservative values is recommended.

628.5205 References

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Appendix 52A Fixed Line Survey

Definition

A fixed line survey is an inventory of all structural discontinuities that intersect a linear traverse of specified length and orientation.

Application

The fixed line survey is used to systematically inventory a variety of attributes of joints and fractures including joint set spacing and orientation, joint roughness, joint face alteration, aperture width, and type of infilling.

In complex structural domains where joint and fracture patterns are difficult to discern, a fixed line survey can be applied to inventory a representative sample of the joints for assessment of joint attributes. Subtle joint patterns can often be differentiated using statistical analysis afforded by joint orientation diagrams.

The line survey method is unlikely to bias results as compared to fracture set sampling, area sampling, or other sampling methods that rely heavily on observer judgment (Piteau 1970). Caution is advised, however, in structural domains where joint set patterns are systematic because a survey line parallel with the trend of a dominant joint set may result in undersampling and data bias.

Procedure

The rock outcrop in the area of interest must be well exposed, clean, and accessible for measurement and study. Cleaning can be accomplished by whatever means is necessary and available, including power equipment, hand tools, or pressurized air or water.

To determine the average spacing of a systematic, persistent, high-angle joint set, orient a measuring tape perpendicular to the trend of the joint set. The length of the survey line depends on the spacing of the joints and the amount of exposed outcrop. The recommended length is 10 meters or 10 joints, whichever is greater. Widely spaced joints may require a longer survey line to obtain a meaningful average. In some instances, outcrop limitations require shorter lines. For each persistent joint set, determine average spacing by dividing the length of the survey line by the number of joints in the set that intersects the survey line.

To determine the average spacing of bedding plane partings or sheeting joints on steep outcrops, use a telescoping range pole or a weighted tape against the face to facilitate measurement. In situations where the vertical component is unexposed or inaccessible, use drilling logs or drill core samples of nearby test holes, if available, to estimate the spacing.

For complex structural domains with abundant unique (random) fractures, establish three mutually perpendicular axes for survey lines. Establish one axis parallel with and another perpendicular to the streamflow direction. The third axis, the vertical component, is handled as described above. Calculate mean block size by taking the cube root of the product of the average joint set spacings for the three surveyed directions.

To improve the determination of the average joint set spacing in a given dimension, survey more than one line. For example, consider using three parallel survey lines 5 meters apart and average the results. The number of lines needed is a function of the size and geologic complexity of the site.

For more details on the line survey method, refer to publications by International Society for Rock Mechanics (1981), Geological Society of London (1977), or F.G. Bell (1992).

Documentation

Plot the location of each survey line on a geologic evaluation map and record its orientation, elevation, and ground coordinates or stationing on data sheets. Measure the attributes of all structural discontinuities that intersect the fixed lines according to procedures described in this appendix and record the information on data sheets.

Headcut Erodibility Index Flow Chart

The Headcut Erodibility Index of a material is represented as the scaler product of the indices for its constituent parameters in the form:

$$K_h = M_s \times K_b \times K_d \times J_s$$

Computation of the headcut erodibility index for any earth (geologic) material:

1. Use criteria in ASTM D 2488 to determine if the geologic material of interest is soil or rock.

2. If soil, use plasticity index (PI) to determine if it is cohesive (PI >10) or cohesionless (PI ≤10) soil.

The Headcut Erodibility Index is then determined separately for cohesive soil, cohesionless soil, and rock, as follows.

3. Material strength number (M_s)

cohesive soil	$M_s = 0.78\ (UCS)^{1.09}$	(use table 52–3)
cohesionless soil	$M_s = 1.7\ (IDM)^{0.832}$	(use table 52–2)
rock for which UCS ≤10	$M_s = 0.78\ (UCS)^{1.09}$	(use table 52–4)
rock for which UCS >10	$M_s = (UCS)$	(use table 52–4)

Note: If data are available, use coefficent of relative density times UCS to obtain M_s directly for any material for which UCS ≤10.

USC = Unconfined Compressive Strength.
IDM = In situ Deformation Modulus.

4. Particle size number of soils (K_b)

jointed cohesive soil $K_b = \frac{RQD}{J_n}$ (use tables 52–5 and 52–6)

where: $RQD = 115 - 3.3\ J_c$ and $5 \le RQD \le 100$

massive (unjointed) cohesive soil $K_b = 1$

cohesionless soil where D < 0.1 m $K_b = \frac{RQD}{J_n} = \frac{5}{5} = 1$

cohesionless soil where D ≥ 0.1 m $K_b = \frac{\left\{105 - \left(\frac{10}{D}\right)\right\}}{J_n}$

5. Block size number of rock (K_b)

RQD is known and D ≥0.1 m $K_b = \frac{RQD}{J_n}$ (use tables 52–5 and 52–6)

RQD is unknown $K_b = \frac{\left\{105 - \left(\frac{10}{D}\right)\right\}}{J_n}$

where: D is the cube root of the volume of the average block size determined by joint set spacings

6. For interparticle bond shear strength of soils, $K_d \cong \tan \phi'_r$, such that

for clay fraction (≤ 20%), $\phi'_r = 169.58 (LL)^{-0.4925}$
for clay fraction (25 – 45%), $\phi'_r = 329.56 (LL)^{-0.7100}$
for clay fraction (≥ 50%), $\phi'_r = 234.73 (LL)^{-0.6655}$

where:
ϕ'_r = residual (minimum) friction angle (°)
effective normal stress = 100 kPa
clay fraction = percent finer than 0.002 mm
LL = liquid limit (%)

7. For discontinuity shear strength of rock $K_d = \frac{J_r}{J_a}$ (use tables 52–8 and 52–9)

8. Relative ground structure number (J_s)

The number is based on table 52–12, which is represented graphically as a curve in Kirsten (1988, ASTM, STP-984, p. 57). The curve used in the spreadsheet is taken as for r = 1, and is represented by the following mathematical expressions:

First, the effective dip, q, is calculated by converting the apparent dip of the least favorable joint set in the rock mass by using the following relationship expressing horizontal angles in degrees azimuth and vertical angles in degrees:

$$\tan a = (\tan b)(\sin c)$$

where:
a = apparent dip of discontinuity
b = true dip of discontinuity
c = (strike of discontinuity) – (spillway flow direction)

The effective dip is the apparent dip of the discontinuity adjusted for the slope of the spillway channel, α. Dip direction is measured perpendicular to the strike. If the absolute value of the dip direction (expressed in degrees azimuth) minus the spillway flow direction (expressed in degrees azimuth) is less than or equal to 90° (including 0°; i.e., north) or greater than or equal to 270°, the dip direction is considered to be with the direction of spillway flow; otherwise, it is considered against the flow.

If the spillway flow direction is with the apparent dip:

$$q = a - \alpha$$

If the spillway flow direction is against the apparent dip:

$$q = a + \alpha$$

Values for J_s can be interpolated from table 52–12 or can be calculated directly from the following curve-matching formulas that are used in the spreadsheet.

For dip direction with the flow:

$$J_s = 1.004 + 7.42132(q) - 56.25696(q)^2 + 156.64285(q)^3 - 226.16576(q)^4 + 179.69753(q)^5 - 74.43984(q)^6 + 12.57373(q)^7$$

For dip direction against the flow:

$$J_s = 0.99926 - 4.85356(q) + 25.54649(q)^2 - 78.44504(q)^3 + 135.73875(q)^4 - 129.63181(q)^5 + 63.81557(q)^6 - 12.57373(q)^7$$

Computation of hydraulic energy, E, as peak stream power (kW/m):

The energy head is calculated using the Bernoulli equation combined with the continuity equation:

1. $$H_L = \frac{V_1^2}{2g} + d_1 - 1.5\left(\frac{V_1^2 d_1^2}{g}\right)^{0.33} + H_O$$

where:
- V_1 = velocity of flow in the exit channel associated with peak discharge
- g = acceleration of gravity
- d_1 = depth of flow corresponding to V_1 in exit channel
- H_o = $(z_1 - z_2)$

where:
- z_1 = elevation of end of constructed exit channel
- z_2 = elevation of flood plain.

2. $$E = \left\{62.4\frac{(0.746043)}{550}\right\} V_1 d_1 H_L$$

Appendix 52C Field Data Sheets

Data Sheets for Headcut Erodibility Index, K_h

(Use one set of sheets for each material) Set ____ of ____

General Information

Watershed name: ______________________ Site number: ________ State: ______

Investigator: ______________ Title: ______________ Date: ______________

Type of investigation:
- Reconnaissance .... ______
- Preliminary .... ______
- Detailed/design .... ______
- As-built/construction .... ______
- Spillway performance .... ______

Intensity of investigation:
- Subjective survey .... ______
- Objective survey .... ______

Photograph numbers: ______________________

Earth Material (Soil/Rock) Unit Identification

Formal rock type name or alphanumeric designation: ______________________ Rock code from table 4: ______

Soil group name (ASTM D 2488): ______________________ Unified classification symbol: ______

Location (show on geol. map/sketch): Station __________ Offset (lt) ______ Offset (rt) ______ Elevation ______

Locality type (check one): Natural exposure______ Channel side slope ______ Channel floor ______

Earth Material Information

Table 1 Color (choose from up to three columns for selected material condition)

Condition: Fresh - dry .... ________
Condition: Fresh - wet .... ________
Condition: Altered - dry .... ________
Condition: Altered - wet .... ________

light _____		white	_____
dark _____	yellowish _____	yellow	_____
	buff _____	buff	_____
	orangish _____	orange	_____
	brownish _____	brown	_____
	pinkish _____	pink	_____
	reddish _____	red	_____
	bluish _____	blue	_____
	purplish _____	purple	_____
	olive _____	olive	_____
	greyish _____	gray	_____
		black	_____

Table 2 Summary of parameters determined for the headcut erodibility index, K_h

Parameter	Determination
MPa (table 5 or 6)	____________
RQD (table 7)	____________
J_n (table 8)	____________
J_s (use spreadsheet)	____________
J_r (table 9)	____________
J_a (table 10)	____________

Note: Use spreadsheet to calculate K_h.

Table 3 Dry density (unit weight)

lb/ft^3	Mg/m^3	Check one	lb/ft^3	Mg/m^3	Check one	lb/ft^3	Mg/m^3	Check one
< 60	< 0.96	___	90 - 100	1.44 - 1.60	___	130 - 140	2.08 - 2.24	___
60 - 70	0.96 - 1.12	___	100 - 110	1.60 - 1.76	___	140 - 150	2.24 - 2.40	___
70 - 80	1.12 - 1.28	___	110 - 120	1.76 - 1.92	___	150 - 160	2.40 - 2.56	___
80 - 90	1.28 - 1.44	___	120 - 130	1.92 - 2.08	___	> 160	> 2.56	___

Test method used (check one): Field estimate: ____ Laboratory test: ____ Lab value: ____

Note: 1.0 pound per cubic foot (lb/ft^3) approximately equals 0.0160 megagram per cubic meter (Mg/m^3).

Table 4 Rock type classification (code number in parentheses)

Genetic Group	Predominant grain size, mm (sieve no.)	Detrital Sedimentary			Chemical Organic	Metamorphic		Pyroclastic	Igneous			
Usual Structure		Bedded			Bedded	Foliated	Massive	Bedded	Massive			
Composition		Grains of rock, quartz, feldspar, and clay minerals	At least 50% of grains are of carbonate		Salts, carbonates, silica, carbonaceous	Quartz, feldspars, micas, dark minerals	Quartz, feldspars, micas, dark minerals, carbonates	At least 50% of grains are of igneous rock	Quartz, feldspars, micas, dark minerals		Feldspar; dark minerals	Dark minerals
									Acid	Intermediate	Basic	Ultrabasic
Very coarse-grained	75 (3")	Rudaceous: Grains are of rock fragments. Rounded grains: CONGLOMERATE (11); Angular grains: BRECCIA (12)	LIMESTONE (undifferentiated) (21)	CALCIRUDITE (23)	CLINKER (31); SALINE ROCKS: Halite (32), Anhydrite (33), Gypsum (34)	TECTONIC BRECCIA (41); MIGMATITE (42)	TECTONIC BRECCIA (41); METACONGLOMERATE (51)	Rounded grains: AGGLOMERATE (61); Angular grains: VOLCANIC BRECCIA (62)	PEGMATITE (71)			
Coarse-grained	4.75 (4)					GNEISS (43)	MARBLE (52); GRANULITE (53)		GRANITE (72)	DIORITE (81); GRANODIORITE (82)	GABBRO (91)	PYROXENITE (01)
Medium-grained	0.074 (200)	Arenaceous: Grains are mainly mineral fragments. SANDSTONE (13); ARKOSE (14); GRAYWACKE (Argillaceous ss) (15)		CALCARENITE (24)	CALCAREOUS ROCKS	SCHIST (44)	QUARTZITE (54)	TUFF (63)	SYENITE (73)	ANORTHOSITE (83)	DIABASE (92)	PERIDOTITE (02)
Fine-grained	0.005					Amphibolite (45)	Amphibolite (45)		APLITE (74)	MONZONITE (84)		
Very Fine-grained		Argillaceous or Lutaceous: MUDSTONE (16); SHALE: fissile mudstone (17); SILTSTONE>50% fine-grained particles (18); CLAYSTONE>50% very fine grained particles (19)	MARLSTONE (22)	CALCISILTITE (25); CHALK (26); CALCILUTITE (27)	LIMESTONE (35); DOLOMITE (36)	PHYLLITE (46); Mylonite (47); SLATE (48)	HORNFELS (55); Mylonite (47)	Fine-grained TUFF (64); Very fine-grained TUFF (65)	RHYOLITE or FELSITE (75)	Dacite (85); ANDESITE (86)	BASALT (93)	DUNITE (03); NEPHELINE-BASALT (04)
Glassy Amorphous					SILICEOUS ROCKS: Chert (37), Flint (38); CARBONACEOUS ROCKS; LIGNITE/COAL (39)	Ultramylonite (49)	Ultramylonite (49)	Welded TUFF (66); PUMICE (67)	VOLCANIC GLASSES: OBSIDIAN (76)	VOLCANIC GLASSES: PITCHSTONE (87)	VOLCANIC GLASSES: TACHYLYTE (94)	

Determination Of Strength, MPa

Table 5 Consistency or hardness categories for rock material and cohesive soil

Consistency or hardness category	Field assessment tests	SPT (N)	Typical range in unconfined compressive strength (MPa)	Strength value selected (MPa)
Very soft soil*	Exudes between fingers when squeezed in hand. Easily penetrated several cm with fist.	< 2	< 0.04	________
Soft soil*	Easily molded with fingers. Head of geologic hammer easily pushed in to shaft of handle.	2 - 4	0.04 - 0.08	________
Firm soil*	Penetrated several cm. by thumb with moderate pressure. Molded by fingers with some pressure.	4 - 8	0.08 - 0.15	________
Stiff soil*	Indented by thumb with great effort. Point of geologic pick pushed in up to 1 cm. Very difficult to mold with fingers. Can be just penetrated with hand spade.	8 - 15	0.15 - 0.30	________
Very stiff soil*	Indented only by thumbnail. Slight indentation by pushing point of geologic pick into material. Requires hand pick for excavation.	15 - 30	0.30 - 0.60	________
Very soft rock or hard, soil-like material	Scratched with fingernail. Slight indentation by light blow of point of geologic pick. Requires power tools for excavation. Peels with pocket knife.	> 30	0.60 - 1.25	________
Soft rock	Handheld specimen crumbles under firm blows with point of geologic pick.		1.25 - 5.0	________
Moderately soft rock	Shallow indentations (1–3 mm) by firm blows with point of geologic pick. Peels with difficulty with pocket knife.		5.0 - 12.5	________
Moderately hard rock	Cannot be scraped or peeled with pocket knife. Intact hand-held specimen breaks with single blow of geologic hammer. Can be distinctly scratched with 20d common steel nail.		12.5 - 50	________
Hard rock	Intact handheld specimen requires more than one hammer blow to break it. Can be faintly scratched with 20d common steel nail.		50 - 100	________
Very hard rock	Intact specimen breaks only by repeated, heavy blows with geologic hammer. Cannot be scratched with 20d common steel nail.		100 - 250	________
Extremely hard rock	Intact specimen can only be chipped, not broken by repeated, heavy blows of geologic hammer.		> 250	________

Method used to determine consistency or hardness (check one):

Field assessment:	_____	Rebound hammer (ASTM D 5873):	_____	Pocket penetrometer:	_____
Uniaxial lab test:	_____	Pocket vane shear test:	_____	Other: ____________	_____

Notes:
(1) Cohesive soil is material with a plasticity index (PI) greater than 10. Use table 6 for cohesionless soils.
(2) Standard Penetration Test (SPT) refers to ASTM D 1586, where N equals blow count in blows per 0.3 meter.
(3) Consistency/hardness categories are based solely on physical characteristics, not geologic origin. For examples, a highly weathered shale may classify as Firm soil, and a partially lithified, Recent soil may classify as Moderately Soft Rock. The transition from soil to rock, however, usually occurs within the 0.60 to 1.25 MPa range.
(4) Materials marked with (*) must be evaluated for hardness in a saturated condition.
(5) 1.0 Megapascal (MPa) or 10 Kg/cm^2 equals 145.039 pounds per square inch (psi), or 10.443 tons per square foot (tsf).
(6) Correlation between SPT and UCS should be used as a guide only as results may vary in different geologic areas. Lab strength tests are recommended on soil materials to support SPT or field assessment tests. Vane shear strength values also are applicable in the lower strength ranges.

Determination Of Strength, MPa

Table 6 Relative density categories for cohesionless soil

Relative density category	Field assessment tests	SPT (N)	In situ deformation modulus (MPa)	Strength value selected (MPa)
Very loose	Particles loosely packed. High percentage of voids. Very easily dislodged by hand. Matrix crumbles easily when scraped with point of geological pick. Excavated faces often unravel.	< 5	< 0.005	__________
Loose	Particles loosely packed. Some resistance to being dislodged by hand. Large number of voids. Matrix shows low resistance to penetration when pushed by point of geologic pick.	5 - 10	0.005 - 0.01	__________
Medium dense	Particles closely packed. Difficult to dislodge individual particles by hand. Voids less apparent. Matrix has considerable resistance to penetration when struck by point of geologic pick.	10 - 30	0.01 - 0.03	__________
Dense	Particles very closely packed and occasionally very weakly cemented. Cannot dislodge individual particles by hand. The mass has very high resistance to penetration when struck by point of geologic pick. Requires many blows of geologic pick to dislodge particles.	30 - 50	0.03 - 0.08	__________
Very dense	Particles very densely packed and usually cemented together. Mass has high resistance to repeated blows of geologic pick. Requires power tools for excavation.	> 50	0.08 - 0.20	__________

Notes: (1) Cohesionless soil is material with a plasticity index (PI) less than or equal to 10. Use table 5 for cohesive soils.
(2) Standard Penetration Test (SPT), where N equals blow count in blows per 0.3 m, is used for most sandy-type cohesionless soils. In situ Deformation Modulus is used for most gravel-type soils and coarse detritus.
(3) Cohesionless soils in which blow counts are greater than 50, or In situ Deformation Modulus is greater than 0.200 MPa, are to be taken as rock, for which the hardness may be obtained from table 5.

Determination Of Relative Ground Structure Number, J_s

1. Draw plan view sketch of spillway. Show north arrow.
2. Spillway flow direction at end of exit channel (or at headcut): __________° (azimuth).
3. Exit channel slope: __________°.
4. Strike: _______° (azimuth), and dip: ________° of bedrock (or least favorable joint set) at end of exit channel.
5. Bedrock dip direction: __________° (azimuth).
6. Enter data from items 2 through 5 into spreadsheet to calculate J_s factor.

Determination of Block Size Number, RQD/J_n

Determine RQD by method 1, 2, or 3 below, depending on the type of data available. Determine joint set number, J_n, using table 8. Then, determine block size number, RQD/J_n.

1. Determine RQD (rounded to nearest whole number between 5 and 100) from drilling logs. If no logs are available, use method 2 or 3 below. RQD: ___________
2. Determine mean block diameter, D, based on spacing of joint sets in rock mass. Use a line survey to measure average joint spacing within a set. Plot location of survey lines on a map/sketch.
   A. For systematic joint sets:
      — Lines 1 and 2 are for the two most persistent, high-angle, intersecting joint sets.
      — Line 3 is for bedding plane partings or sheeting joints.
   B. For apparently random fractures:
      — Line 1 is set perpendicular to channel flow direction (x axis).
      — Line 2 is set parallel to channel flow direction (y axis).
      — Line 3 is for bedding plane partings or sheeting joints in the vertical direction (z axis) .

Survey line (axis)	a Line trend (azim °)	b Line plunge (°)	c Line length (meters)	d Total number of joints	e Average spacing (c/d)
Line 1 (x)					
Line 2 (y)					
Line 3 (z)					

   C. Use values in column e above to calculate mean block diameter, $D = (ex\ ey\ ez)^{0.333}$ = _________ meters.
   D. Calculate RQD from mean block diameter, D, as follows:
      $RQD \approx [105 - (10/D)]$: ____________.
3. RQD also may determined from joint count number, J_c (number of joints per m^3 of rock mass), by:
   A. A direct count of the joints in a cubic meter of rock mass and converting J_c to RQD according to table 7, or
   B. Estimating J_c from mean block diameter, D, where:
      $J_c \approx (3/D) + 3$ (for $D \geq 0.1$ m) ≈ ____________, and then calculate RQD from J_c by:
      $RQD \approx (115 - 3.3\ J_c)$: ____________, for $5 \leq RQD \leq 100$.

Table 7 Relationship between J_c and RQD

RQD	J_c	RQD	J_c
5	33	55	18
10	32	60	17
15	30	65	15
20	29	70	14
25	27	75	12
30	26	80	11
35	24	85	9
40	23	90	8
45	21	95	6
50	20	100	5

Table 8 Joint set number, J_n

Number of joint sets in rock mass	J_n	Check one
Intact; no or few joints	1.00	______
One joint set	1.22	______
One joint set plus random	1.50	______
Two joint sets	1.83	______
Two joint sets plus random	2.24	______
Three joint sets	2.73	______
Three joint sets plus random	3.34	______
Four joint sets	4.09	______
More than four joint sets	5.00	______

Determination of Shear Strength Number, J_r/J_a

Table 9 Joint roughness number, J_r

Joint separation	Joint roughness condition	J_r
Joints are tight or become closed during hydraulic flow.	Discontinuous joints; stepped	4.0
	Rough/irregular; undulating (e.g., tension joints, rough sheeting rough bedding)	3.0
	Smooth; undulating (e.g., smooth sheeting, nonplanar foliation, and bedding)	2.0
	Slickensided; undulating	1.5
	Rough/irregular; planar	1.5
	Smooth; planar (e.g., planar sheeting joints, planar foliation, and bedding)	1.0
	Slickensided; planar	0.5
Joints are open and remain open during hydraulic flow.	Joints are either open or contain soft gouge thick enough to prevent wall contact during flow.	1.0
	Joints contain swelling clays.	1.0

Note: Consider a joint open when aperture width exceeds the amplitude of the asperities of joint faces.

Table 10 Joint alteration number, J_a

Field identification of gouge (infilling)	J_a for aperture width < 1.0 mm 1/	J_a for aperture width 1.0 - 5.0 mm 2/	J_a for aperture width ≥ 5.0 mm 3/	Typical ϕ'_r °
Joint tightly healed with hard, nonsoftening, impermeable mineral filling, e.g., quartz, calcite, or epidote.	0.75	1.0	1.5	- - -
Clean, open joint with fresh or discolored (unweathered) walls only; no infilling.	1.0	1.5	2.0	- - -
Discolored to disintegrated joint walls; infilling is sand or gravel with < 15% cohesionless fines in matrix; with or without disintegrated or crushed rock fragments.	2.0	4.0	6.0	(25 – 30)
Discolored to disintegrated joint walls; cohesionless, nonswelling, low to nonplastic fines in matrix; with or without disintegrated or crushed rock fragments.	3.0 4/	6.0 4/	10.0 4/	(15 – 24)
Disintegrated to decomposed joint walls; nonswelling, lean clay or clay matrix, or low friction clays, such as chlorite, talc, mica, serpentine, gypsum, graphite, kaolinite, or other sheet silicates; with or without disintegrated or crushed rock fragments.	4.0 4/	8.0 4/ 5/	13.0 4/ 5/	(10 – 14)
Disintegrated to decomposed joint walls; fat clay, swelling clay, such as montmorillonite, or clay matrix, with or without disintegrated or crushed rock fragments.	5.0 4/	10.0 4/ 5/	18.0 4/ 5/	(6 – 9)

1/ Joint walls effectively in contact.
2/ Joint walls come into contact after approximately 100 mm shear.
3/ Joint walls do not come into contact at all upon shear. Use this column to determine J_a for intact, cohesive granular materials, for which $J_r = 3.0$. Alternatively, tan ϕ'_r can be substituted for the quotient J_r/J_a where ϕ'_r is the equivalent residual (minimum) friction angle.
4/ Values added to Barton et al. (1974) data.
5/ Also applies when disintegrated or crushed rock fragments occur in clay matrix without wall contact.

Area Survey of Discontinuity Attributes

Instructions for classifying discontinuity attributes by an area survey:

1. Assign each discontinuity an ID number and record on the summary data sheet; show its location on geologic evaluation map or sketch.
2. Select appropriate code numbers from tables 11 through 15 and record on data sheet.
3. Classify infilling using ASTM D 2488 (USCS); record soil classification symbols on data sheet.
4. Determine strength of infilling using tables 5 or 6; record on data sheet.

Table 11 Joint set spacing categories

Bedding plane partings	Joint sets	Spacing (meters)	Category
Massive/ unstratified	Extremely wide	> 6.000	1
Very thick-bedded	Very wide	2.000 - 6.000	2
Thick-bedded	Wide	0.600 - 2.000	3
Medium bedded	Mod. wide	0.200 - 0.600	4
Thin-bedded	Mod. close	0.060 - 0.200	5
Very thin-bedded	Close	0.020 - 0.060	6
Laminated	Very close	0.006 - 0.020	7
Thinly laminated	Shattered	0.002 - 0.006	8
Fissile	Fissured	< 0.002	9

Table 12 Discontinuity types

Discontinuity type	Code
Stratigraphic	
lithosome (sharp contact)	1
unconformity	2
Structural	
Plastic deformation	
Foliation	
— schistosity	3
— gneissosity	4
Banded rock	5
Folded rock	6
Fracture deformation	
Random fracture	7
Systematic joint set	8
Bedding plane parting	9
Sheeting joint	10
Slaty cleavage	11
Fault	12
Other	13

Table 13 Joint persistence categories

Joint persistence category	Trace length (meters)	Code
Very low	< 1	1
Low	1 - 3	2
Medium	3 - 10	3
High	10 - 20	4
Very high	> 20	5

Table 14 Aperture categories

Aperture category	Range (mm)	Code
Wide	> 200	1
Moderately wide	60 - 200	2
Moderately narrow	20 - 60	3
Narrow	6 - 20	4
Very Narrow	2 - 6	5
Extremely narrow (hairline)	< 2	6

Table 15 Weathering condition categories for joint face material (to support table 10)

Category	Weathering condition of joint face material	Code
Fresh	No sign of weathering.	1
Discolored	Iron-stained or discolored, but otherwise unweathered.	2
Disintegrated	Physically disintegrated to a soil condition with original fabric still intact. Material is friable and mineral grains are not decomposed.	3
Decomposed	Chemically altered to a soil condition with original fabric still intact. Some or all mineral grains are decomposed.	4

Summary Data Sheet

Table #	12	Discontinuity measurements				13	14	15	D 2488	5, 6
Discon. ID #	Discon. type code	Trend (azim)	Dip (°)	Dip direction (azim)	Joint persis. (m)	Joint persis. code	Apert. categ. code	Joint weath. code	Infill. class (USCS)	Infill. strength (MPa)

Spillway Profile

1. In the space below sketch the spillway profile.
2. Label materials by ID (as given on page 1).
3. Show elevations of tops of materials, ground surface at major slope breaks, and flood plain.

** Notes on Using This Spreadsheet

1. Refer to NEH Part 628, Chapter 52, "Field Procedures Guide for the Headcut Erodibility Index," for details on how to collect the field information for the input parameters.
2. Use copies of the eight data sheets in appendix 52C for recording field data. The numbers of the tables on the data sheets agree with those in the spreadsheet.
3. Supplemental instructions on how to use this spreadsheet:

Cell	Parameter	Notes
B-7	Exit channel slope	For exit channels with more than one slope, use slope of exit section.
B-8	Spillway flow direction	For curved spillways, use the orientation of exit section.
B-9	Bedrock strike	If the strike of the bedrock varies within the exit channel, measure the strike as it occurs at the exit section.
B-10	Bedrock dip	If the dip of the bedrock varies within the exit channel, measure the dip as it occurs at the exit section.
B-11	Bedrock dip direction	Measure at right angles to the strike and express as an azimuth.
B-12	Apparent dip	The spreadsheet calculates this after all data above it are entered.
B-13	Effective dip	The spreadsheet calculates this after all data above it are entered.
B-14	Is dip direction against or with the flow?	The spreadsheet calculates this after all data above it are entered.
B-15	Ground structure number	The spreadsheet calculates this after all data above it are entered.
B-16	Unconfined compressive strength	If material is rock or cohesive soil, use table 5 to select best value.
B-18	Unconfined compressive strength	If material is cohesionless soil, use table 6 to select best value.
B-20		If table 5 is used, enter **yes**; if table 6 is used, enter **no**. This block must be filled in because it tells the spreadsheet which formula to use to calculate M_s.
B-21		If the material is rock or cohesive soil, the spreadsheet calculates M_s after cell B-16 is filled in.
B-22		If the material is cohesionless soil, the spreadsheet calculates M_s after cell B-18 is filled in. If nothing is entered into cell B-18, **0.000** is shown, indicating the cell is not in use.
B-23	RQD	The three ways to arrive at this value are described on sheet 5. Enter the value derived from either method 1 or 3. If the line survey method (2) is used to calculate mean block diameter, D, based on joint set spacing, enter the average spacing of each of the 3 sets into cells B-42, B-43, and B-44, respectively.

** Notes on Using This Spreadsheet—Continued

Cell	Parameter	Notes
B-24	Joint set number, J_n	Use table 8 to determine J_n.
B-25	Joint roughness number, J_r	If material is rock, use table 9.
B-26		If material is rock, use table 10. For field estimation of J_a for soil material, use column 3 of table 10 (for aperture width > 5 mm).
B-28		If a lab residual shear test is conducted, enter ϕ'_r in degrees in cell B-27. If a lab shear test is unavailable, ϕ'_r can be approximated from liquid limit. See alternative method, cell B-33.
B-30	Headcut erodibility index, K_h	Spreadsheet calculates K_h after all appropriate data above are entered.
B-32	Hydraulic energy, E (kilowatts)	Spreadsheet calculates E after cells B-52 through B-57 are entered.
B-37	Percent clay	Enter clay content (percent finer than 0.002 micron) of soil.
B-38	Liquid limit	Enter liquid limit of soil in percent.
B-39		Once data are entered in cells B-35 and B-36, the spreadsheet calculates residual friction angle. Enter the value obtained in cell B-37 into cell B-27.
B-44	Mean block diameter	Once data are entered into cells B-42, B-43, and B-44, the spreadsheet calculates mean block diameter. If nothing is entered into these cells, **0.000** is is shown, indicating the cells are not in use.
B-45	Joint count	After data are entered into cells B-40, B-41, and B-42, the spreadsheet calculates J_c according to the relationship shown in table 7. If nothing is entered, **33** is shown, indicating the cell is not in use.
B-46	Equivalent RQD	Once the data are entered into cells B-42, B-43, and B-44, the spreadsheet calculates Equivalent RQD. Enter this figure into cell B-23. If this alternative method is not used, **6** is shown, indicating the cell is not in use.
B-52	Peak velocity in exit channel	Use the velocity of flow associated with the peak discharge in the exit channel reach containing the exit section and at a point where the flow is not at critical head.
B-53	Maximum depth of flow in exit channel	Use the maximum depth associated with the peak velocity (used in cell B-52) in the reach containing the exit section and at a point where the flow is not at critical head.
B-54	Elevation of end of exit channel	If the exit channel is constructed all the way to the flood plain, this methodology for calculating a headcut erodibility index does not apply. An overfall condition is one of the necessary assumptions.

**** Notes on Using This Spreadsheet—Continued**

Cell	Parameter	Notes
B-55	Elevation of flood plain	Use the elevation of the flood plain at the base of the hillside in which the spillway is constructed.
B-56	Energy head	The spreadsheet calculates this after cells B-52 through B-55 are filled in.
B-57	Hydraulic energy	The spreadsheet calculates this after cells B-52 through B-55 are filled in.

Notes on significance of chart 1:
1. If the calculated value for K_h plots above the erosion threshold, significant erosion can be anticipated.
2. If the calculated value for K_h plots below the erosion threshold, little to no erosion can be anticipated.
3. Erosion rates are not determined by this method.

NCHRP 24-29 Scour at Bridge Foundations on Rock
Numerical Calculator for Appendix D

Appx_D_KhCalc.xls

APPENDIX E

Erodibility Index Method with Tables

The Erodibility Index Method is similar to the Headcut Erodibility Index (Appendix D). The equations and tables contained in this appendix were adapted from Annandale (2006). The Erodibility Index Method is an empirical threshold-based concept that compares resistance to scour and the stream power of peak discharge. The basic Erodibility Index Method equation, presented below, is followed by descriptions of the terms in the equation and tabulated values of the terms. The applied stream power used in the Erodibility Index Method is based on wall shear stress and Chezy equation. The channel roughness term in the Chezy equation (k) is related to the Manning's roughness term (n) more commonly used in the United States based on calculations described in van Vuuren and Rooseboom (2007), which are described at the end of this appendix.

Rock material resistance to scour is called the Erodibility Index, K, in this method. The basic equation is

$$K = Ms \times Kb \times Kd \times Js$$

where Ms is mass strength number, Kb is block size number, Kd is discontinuity bond shear strength number, and Js is relative ground structure number.

$$Ms = Cr \times 0.78\ UCS^{1.05} \qquad \text{for } UCS \le 10\ \text{MPa}$$

$$Ms = Cr \times UCS \qquad \text{for } UCS > 10\ \text{MPa.}$$

where UCS is unconfined compressive strength of rock material in MPa and Cr is a coefficient of relative density defined as

$$Cr = (g \times \rho r) / (27 \times 10^3)$$

where g is acceleration of gravity (9.807 m/s^2), ρr is mass density of rock (kg/m^3), and 27×10^3 is a reference unit weight in N/m^3. Table E-1 provides values of Ms based on descriptions of physical characteristics.

$$Kb = RQD / Jn \qquad \text{for } 5 \le RQD \le 100 \text{ and } 1 \le Jn \le 5$$

where RQD is rock quality designation using the conventional definition and Jn is the joint set number. Table E-2 provides values of Jn. If RQD is not available, it can be estimated as

$$RQD \approx 105 - (10 / (Jx \times Jy \times Jz)^{0.33})$$

where Jx, Jy, and Jz are average spacing in meters of joint sets in three orthogonal directions.

$$Kd = Jr / Ja$$

where Jr is joint wall roughness and Ja is joint surface alteration. Tables E-3 and E-4 provide values of Jr and Ja.

The relative ground structure number (Js) is provided in Table E-5. It is a function of the orientation of joints that can allow flowing water to enter and the shape of blocks that can facilitate block removal by flowing water.

The Erodibility Index, K, is converted to stream power in kW/m^2 as the threshold for scour by

$$P_{thresh} = K^{0.75}$$

and compared to the available stream power of flowing water by considering the approach flow and turbulence enhanced stream power applied at the rock-bed channel. The stream power of the approach flow is calculated with

$$P_{approach} = \rho \times g \times q \times s$$

where ρ is mass density of water in kg/m^3, g is acceleration of gravity in m/s^2, q is unit discharge in m^3/s/m (= m^2/s), and S is the slope of the energy grade line. The slope of the energy grade line is calculated with

$$S = v^2 / (C^2 \times y)$$

where v is approach flow velocity in m/s, C is Chezy roughness coefficient in $m^{0.5}$/s, and y is approach flow depth in m. The Chezy roughness coefficient is calculated with

$$C = \sqrt{8g}\, 2\log\left(\frac{12y}{k}\right)$$

where g is acceleration of gravity in m/s^2, y is flow depth in m, and k is absolute roughness in m. The absolute roughness term is related to hydraulic radius in m and Manning's n in s/$m^{(1/3)}$ as described in van Vuuren and Rooseboom (2007, p. 4-14). Using the Chezy equation and the Manning's equation, average flow velocity can be equated in terms of absolute roughness, hydraulic radius, and Manning's n value for rough, turbulent flow (Reynold's number > 5000):

$$\bar{v} = 18\log\left(\frac{12R}{k}\right)\sqrt{R\,S} = \frac{R^{2/3}\, S^{1/2}}{n}$$

Solving for absolute roughness, k, in terms of R and n yields the following equation and is shown graphically in Figure E-1.

$$k = \frac{3\,R\,2^{\left(2-\frac{500\,R^{1/6}}{9003\,n}\right)}}{5^{\left(\frac{500\,R^{1/6}}{9003\,n}\right)}}$$

The applied stream power is computed with

$$Pa = 7.853\,\rho\left(\frac{\tau_w}{\rho}\right)^{3/2}$$

where the wall shear stress, τ_w, is $\rho \times g \times y \times S$.

References

Annandale, G.W., 2006, Scour Technology - Mechanics and Engineering Practice: New York, McGraw-Hill, 430 p.

van Vuuren, S.J., and Rooseboom, A., 2007, Hydraulic Calculations, in Kruger, E., ed., Drainage Manual: The South African National Roads Agency Ltd, Pretoria, South Africa, Chapter 4, p. 4-1 to 4-46.

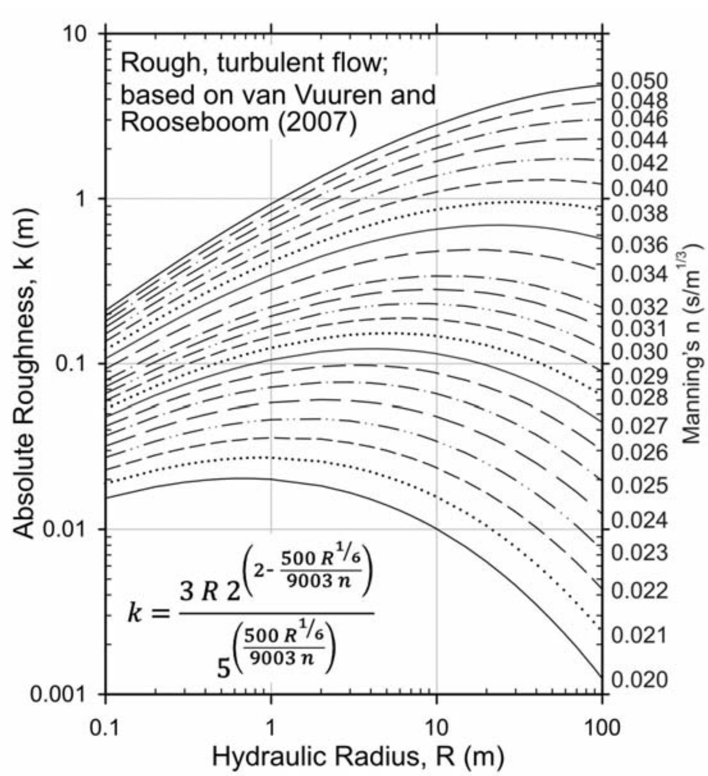

Figure E-1. Absolute roughness in terms of hydraulic radius and Manning's n.

Table E-1 Mass Strength Number for Rock (Ms)

Strength	**Description of Condition**	**Unconfined compressive Strength (MPa)**	**Mass Strength Number (Ms)**
Very Weak Rock	Material crumbles under firm (moderate) blows with sharp end of a geological pick and can be peeled with a knife; too hard to cut triaxial sample by hand	< 1.7 1.7-3.3	0.87 1.86
Weak Rock	Can be just scraped and peeled with a knife; indentations 1 mm to 3 mm show in the specimen with firm (moderate) blows with the pick point	3.3-6.6 6.6-13.2	3.95 8.39
Strong Rock	Cannot be scraped or peeled with a knife; hand-held specimen can be broken with hammer end of geological pick with a single firm (moderate) blow	13.2-26.4	17.70
Very Strong Rock	Handheld specimen breaks with hammer end of pick under more than one blow	26.4-53.0 53.0-106.0	35.0 70.0
	[UCS 106-212 MPa missing from table]	106-212	none listed
Extremely Strong Rock	Specimen requires many blows with a geological pick to break through intact material	> 212.0	280.0

Table 2. Joint Set Number (Jn)

Number of Joint Sets	**Joint Set Number (Jn)**
Intact, no, or few joints/fissures	1.00
One joint/fissure set	1.22
One joint/fissure set plus random	1.50
Two joint/fissure sets	1.83
Two joint/fissure sets plus random	2.24
Three joint/fissure sets	2.73
Three joint/fissure sets plus random	3.34
Four joint/fissure sets	4.09
Multiple joint/fissure sets	5.00

Table 3 Joint Roughness Number (Jr)

Joint Separation	**Joint Surface Condition**	**Joint Roughness Number (Jr)**
Joints, fractures, or bedding tight or closed during turbulent stream flow	Stepped joints./fissures	4.0
	Rough or irregular, undulating	3.0
	Smooth undulating	2.0
	Slickensided undulating	1.5
	Rough or irregular, planar	1.5
	Smooth planar	1.0
	Slickensided planar	0.5
Joints, fractures, or bedding open and remain open during turbulent stream flow	Joints, fractures, or bedding either open or contains relatively soft gouge of sufficient thickness to prevent wall contact during turbulent stream flow	1.0
	Shattered or micro-shattered	1.0

Table 4 Joint Alteration Number (Ja)

Joint Surface Condition	**Joint Alteration Number (Ja) for Joint Separation (mm)**		
	< 1.0	**1.0-5.0**	**> 5.0**
Tightly healed, hard, non-softening impermeable filling	0.75	NA	NA
Unaltered joint wall, surface staining only	1.0	NA	NA
Slightly altered, non-softening, non-cohesive rock mineral or crushed rock filling	2.0	2.0	4.0
Non-softening, slightly clayey non-cohesive filling	3.0	6.0	10.0
Non-softening, strongly over-consolidated clay mineral filling, with or without crushed rock	3.0	6.0	10.0
Softening or low friction clay mineral coatings or small quantities of swelling clays	4.0	8.0	13.0
Softening moderately over-consolidated clay mineral filing, with or without crushed rock	4.0	8.0	13.0
Shattered or micro-shattered swelling clay gouge, with or without crushed rock	5.0	10.0	18.0

Table 5 Relative Ground Structure Number (Js)

Dip Direction of Closer Spaced Joint Set (degrees)	Dip Angle of Closer Spaced Joint Set (degrees)	Ratio of Joint Spacing (1:r) r=y/x where x is short and y is long dimension [use Js for 1:8 if r > 1:8]			
		1:1	**1:2**	**1:4**	**1:8+**
180/0	Vertical 90	1.14	1.20	1.24	1.26
Dip Direction Downstream (With Direction of Water Flow)	89	0.78	0.71	0.65	0.61
	85	0.73	0.68	0.61	0.57
	80	0.67	0.60	0.55	0.52
	70	0.56	0.50	0.46	0.43
	60	0.50	0.46	0.42	0.40
	50	0.49	0.46	0.43	0.41
	40	0.53	0.49	0.46	0.45
	30	0.63	0.59	0.55	0.53
	20	0.84	0.77	0.71	0.67
	10	1.25	1.10	0.98	0.90
	5	1.39	1.23	1.09	1.01
	1	1.50	1.33	1.19	1.10
0/180	Horizontal 0	1.14	1.09	1.05	1.02
Dip Direction Upstream (Against Direction of Water Flow)	-1	0.78	0.85	0.90	0.94
	-5	0.73	0.79	0.84	0.88
	-10	0.67	0.72	0.78	0.81
	-20	0.56	0.62	0.66	0.69
	-30	0.50	0.55	0.58	0.60
	-40	0.49	0.52	0.55	0.57
	-50	0.53	0.56	0.59	0.61
	-60	0.63	0.68	0.71	0.73
	-70	0.84	0.91	0.97	1.01
	-80	1.26	1.41	1.53	1.61
	-85	1.39	1.55	1.69	1.77
	-89	1.50	1.68	1.82	1.91
180/0	Vertical -90	1.14	1.20	1.24	1.26
		Use 1.0 for intact, unjointed rock mass			

REVIEW OF BRIDGE SITES VISITED FOR NCHRP PROJECT 24-29: SCOUR AT BRIDGE FOUNDATIONS ON ROCK

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ABSTRACT

Five bridge sites were visited in 2008 as part of National Cooperative Highway Research Program (NCHRP) Project 24-29: Scour at Bridge Foundations on Rock. I- 10 Chipola River Bridges, Jackson County, Florida, are founded on thick bedded Oligocene marine limestone that shows geologic evidence of dissolution. SR-22 Mill Creek Bridge, Polk County, Oregon, is founded on widely fractured Oligocene marine siltstone prone to slaking in air. I-90 Schoharie Creek Bridge, Montgomery County, New York, that failed in 1987 was founded on Quaternary ice-contact stratified drift armored by hard sandstone boulders and cobbles. The armor layer of boulders over the glacial till in New York provided a threshold control for scour and was used for evaluating excess stream power. Paleozoic marine sandstone is present across the channel at a US Geological Survey stream gage on Schoharie Creek. SR-262 Montezuma Creek Bridge, San Juan County, Utah, is founded on stratified Jurassic sandstone and claystone excavated in 1955 to create a channel which cut off a meander loop. Abrasion pits were observed on sculpted sandstone in Utah, but the primary control on scour was plunge pool excavation of fractured claystone interbedded with the sandstone. SR-273 Sacramento River Bridge, Shasta County, California, is founded on thinly bedded Cretaceous siltstone that slakes in water. Laboratory tests included slake durability, continuous abrasion, Rotating Erosions Test Apparatus (RETA), point load, and specific gravity. Reliable channel cross section data were available for bridges in Oregon, New York, and California for at least two dates several years apart.

INTRODUCTION

National Cooperative Highway Research Program (NCHRP) Project 24-29, Scour at Bridge Foundations on Rock, began in 2006 with objectives of developing a methodology for determining design scour depth and time-rate of scour in rock, and creating design and construction guidelines for application of the methodology. The status of this research in the spring of 2008 was described by Keaton and Mishra (2008), before field visits had been made to bridge sites. The objective of the current paper is to review some geologic and hydraulic conditions of the five sites visited during the summer and fall of 2008 and laboratory test results.

The bridge sites were identified from key reports (OEA, 2001; Dickenson and Baillie, 1999; Resource Consultants and Colorado State University, 1987; Wyss, Janney, Elstner and Mueser Rutledge Consulting Engineers, 1987) and personal information provided by Utah Department of Transportation, California Department of Transportation. Assistance from Florida Department of Transportation, Oregon Department of Transportation, New York State Thruway Authority, and New York State Department of Transportation was instrumental in the success of the research. The field sites visited for NCHRP Project 24-29 are listed in Table 1 and shown on Figure 1. Flood frequency data for the five sites are summarized on Figure 2.

Table 1. List of bridges visited for NCHRP Project 24-29.

River or Stream	Highway	County and State	Drainage Area
Chipola River	Interstate 10	Jackson County, Florida	587 mi^2
Mill Creek	State Route 22	Polk County, Oregon	33 mi^2
Schoharie Creek	Interstate 90	Montgomery County, New York	935 mi^2
Montezuma Creek	State Route 262	San Juan County, Utah	1,153 mi^2
Sacramento River	State Route 273	Shasta County, California	7,560 mi^2

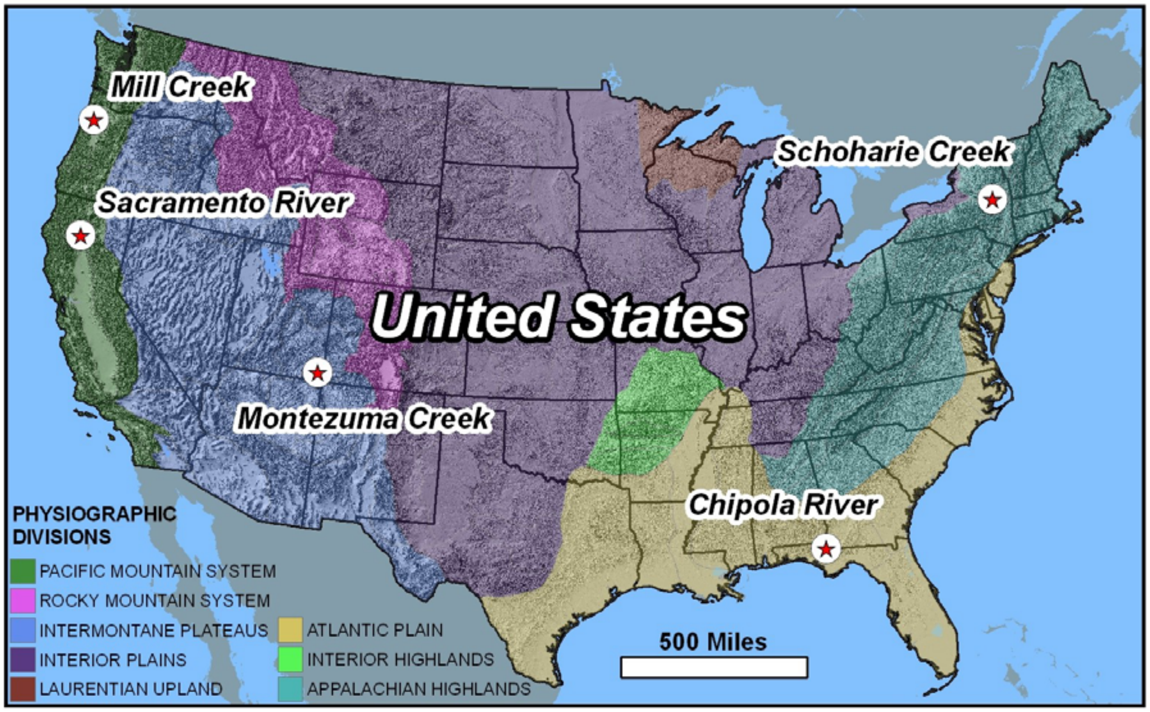

Figure 1. Locations of NCHRP 24-29 field sites. Physiographic divisions from ESRI.

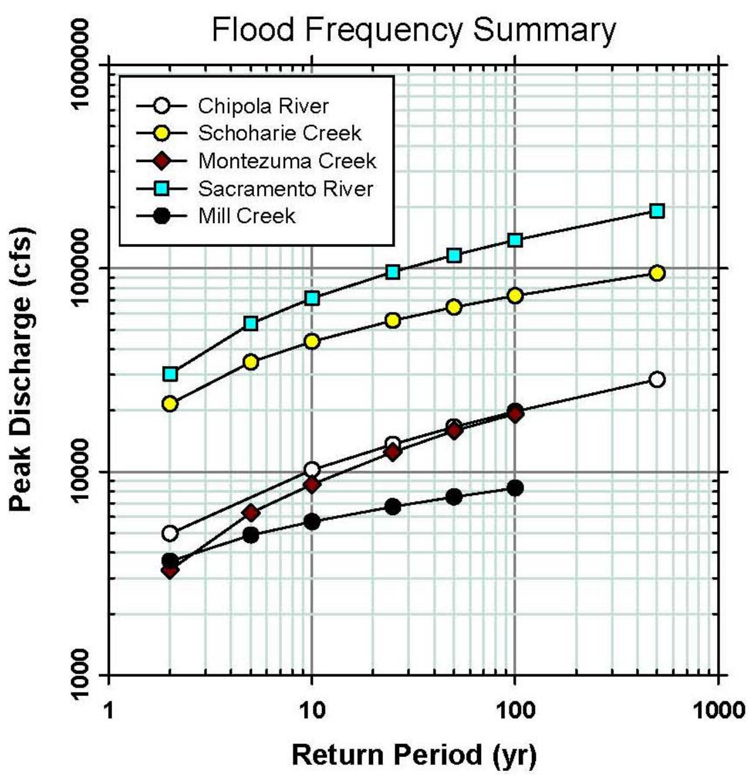

Figure 2. Flood frequency summary. Data from OEA (2001) for Chipola River and from HDR (2004) for Montezuma Creek; other data from nearby USGS stream gages.

SELECTED FIELD DATA FOR BRIDGE SITES

General geologic information and site conditions for the bridge sites are summarized below:

Chipola River – Interstate 10

Interstate 10 crosses Chipola River in the panhandle of Florida approximately 60 miles west of Tallahassee. The drainage basin extends into Alabama, near the Georgia state line (Figure 3). The bridge (Figure 4) is founded on Oligocene Marianna Limestone, white to gray marine limestone that ranges from argillaceous limestone to argillaceous dolostone. The formation contains dissolution features (Figure 5) along the Chipola River. Bedload in this low-gradient stream is fine to medium sand.

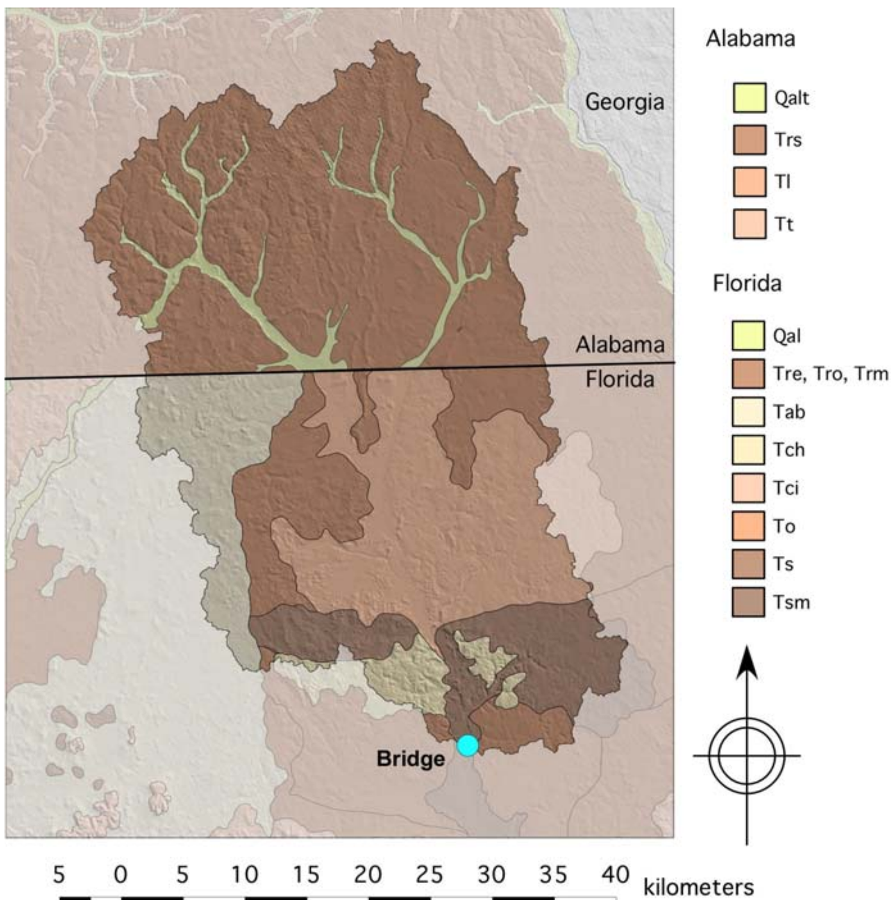

Figure 3. General geologic map of Chipola River drainage basin; geology from Dicken et al., 2007. Map prepared by William C. Haneberg.

Figure 4. I-10 bridges over Chipola River. View is upstream; sample location is in lower right.

Figure 5. Dissolution features on left bank about 1000 feet downstream of bridge.

Mill Creek – State Route 22

State Route 22 crosses Mill Creek in northwest Oregon approximately 20 miles west of Salem. The drainage basin outline and general geologic formations are shown on Figure 6. The bridge (Figure 7) is founded on Eocene Yamhill Formation, gray marine siltstone that ranges from massive to thinly bedded and locally contains interlayered basalt lava flows. The siltstone formation at the bridge site is massive, but it erodes along fractures into cobble- and boulder-sized fragments which, along with basalt boulders, form the bedload (Figure 8); the siltstone slakes in air, as evidenced by boulder-sized mounds of slaked siltstone on the stream bar upstream of the bridge. The Yamhill Formation is sculpted in the rock-bed channel under the bridge (Figure 9).

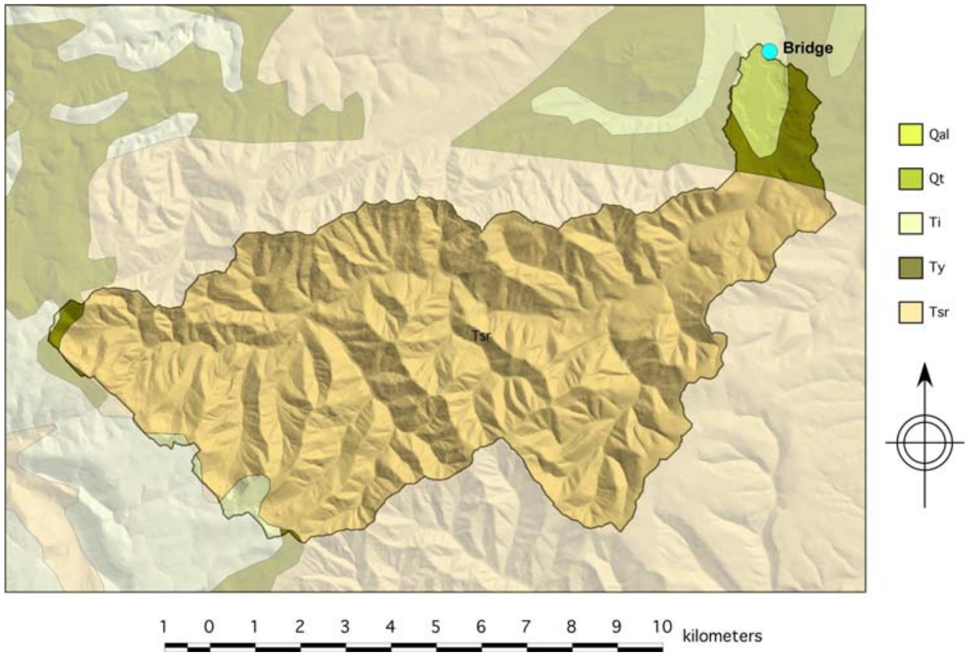

Figure 6. General geologic map of Mill Creek drainage basin; geology from Ludington et al., 2007. Map prepared by William C. Haneberg.

Figure 7. State Route 22 Bridge over Mill Creek. View is downstream; samples taken from stream bed in bottom center of photo.

Figure 8. Boulder bar upstream of bridge. View is upstream. White arrows point to a few of the slaked siltstone boulders.

Figure 9. Sculpted siltstone in rock-bed channel under bridge. View is toward left abutment; flow is left to right.

Schoharie Creek – Interstate 90

Interstate 90 crosses Schoharie Creek in east-central New York about 35 miles northwest of Albany. The drainage basin outline and general geologic formations are shown on Figure 10. The bridge built in 1954 was founded on Quaternary ice-contact stratified glacial till. It failed during a flood in 1987 and was replaced with a bridge (Figure 11) that was founded on bedrock below the glacial till. The Burtonsville gage on Schoharie Creek (USGS 01351500) is about 12 miles

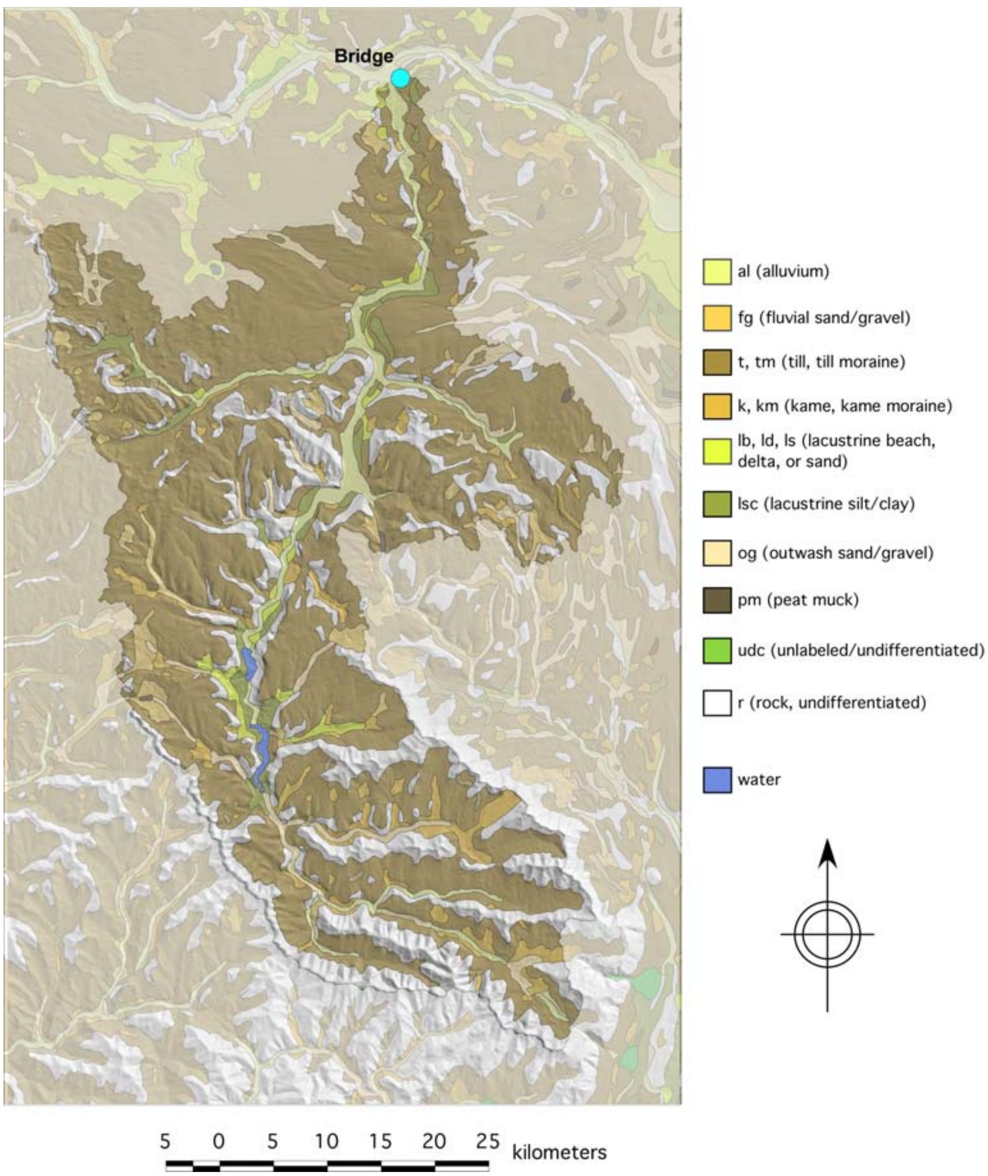

Figure 10. General geologic map of Schoharie Creek drainage basin; geology from Dicken et al., 2008. Map prepared by William C. Haneberg.

upstream of the bridge; bedrock at the gage site is thick-bedded Paleozoic (Devonian) marine sandstone (Figure 12) that is jointed into tabular boulder-size blocks (> 12 inches). The sandstone boulders formed an armor layer on Schoharie Creek (Figure 13), protecting it from exposure to scour at peak discharges less than 20,000 cubic feet per second (cfs) (Resource Consultants and Colorado State University, 1987). Figure 13 shows the August 2008 condition at State Route 161 approximately 4 miles upstream from the I-90 Bridge.

Figure 11. Interstate 90 Bridge over Schoharie Creek rebuilt after 1987 flood. View looking upstream. No samples obtained from bridge site; data from forensic report used.

Figure 12. Thin- to thick-bedded sandstone on left bank of Schoharie Creek at the USGS Burtonsville gage site. Samples taken from the camera position on the right bank.

Figure 13. Schoharie Creek at State Route 161 about 4 miles upstream from I-90. Boulder armor layer here is similar to the channel at I-90 before the bridge failed in 1987.

Montezuma Creek – State Route 262

State Route 262 crosses Montezuma Creek in southeast Utah about 275 miles southeast of Salt Lake City. The drainage basin outline and general geologic formations are shown on Figure 14; the drainage basin extends into Colorado. The bridge (Figure 15) is founded on Jurassic fluvial sandstone with claystone interbeds. Before the bridge was built in about 1960, Montezuma Creek consisted of a large meander bend that defined a narrow peninsula of sandstone and claystone (Figure 16). A narrow channel about 50 feet wide was excavated across the peninsula and an embankment with a culvert was placed across the meander bend. The excavated channel effectively is an unlined spillway; it appears that the initial construction created a knickpoint in the sandstone nearly 200 feet downstream from the bridge. By 2003, the knickpoint had migrated to a point about 15 feet upstream from the bridge (HDR, 2004). In September 2008, the knickpoint was nearly 8 feet high and exposed friable claystone under hard sandstone (Figure 17). Concrete retaining walls were constructed in 2004 to protect exposed claystone interbeds under the bridge foundations from further erosion. Sculpted forms in hard sandstone within about 10 feet of the crest of the knickpoint have pits in downstream-facing sides (Figure 18) that are best explained as abrasion features. Gravel fragments are wedged tightly into vertical joints (Figure 19) and bedding planes. Circular holes with radial fractures in hard sandstone (Figure 20) mark blast holes used for initial excavation of the channel.

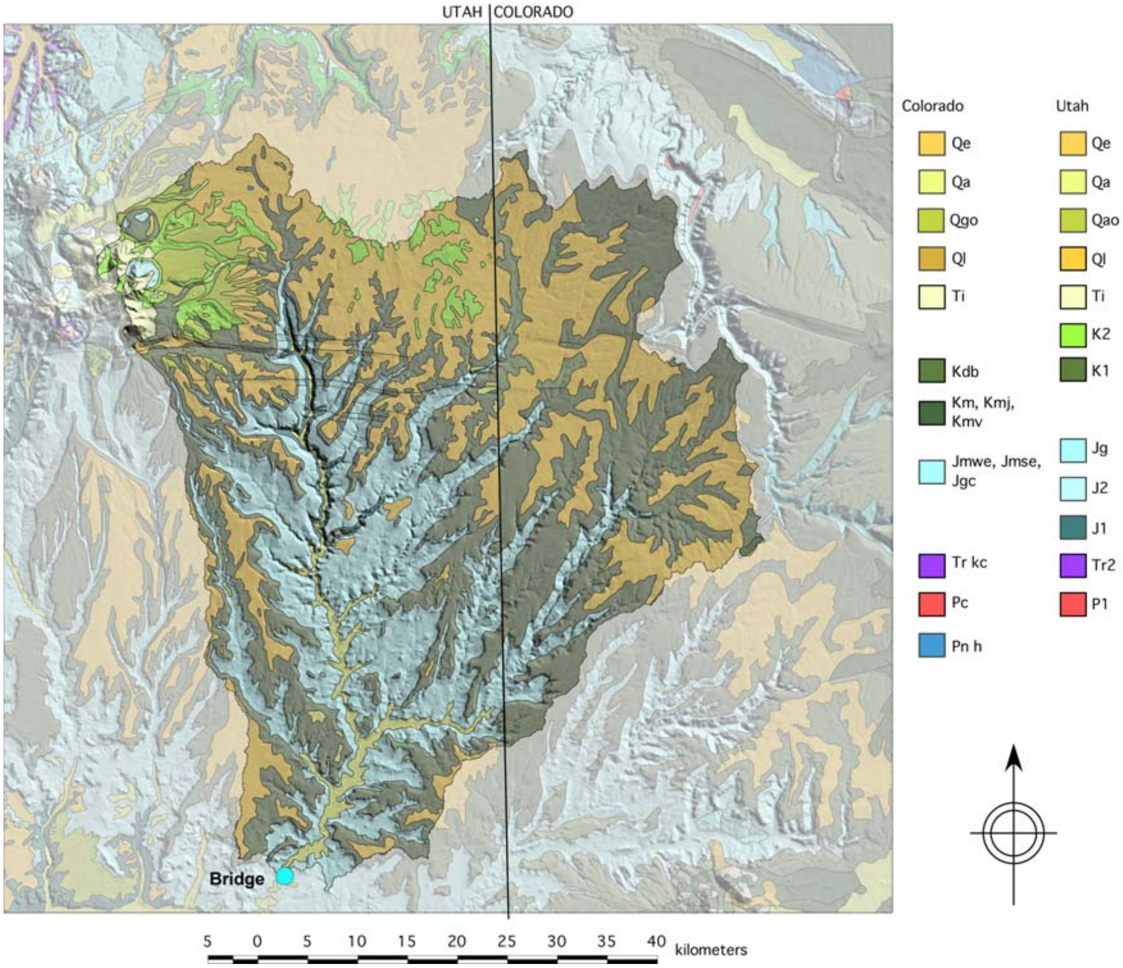

Figure 14. General geologic map of Montezuma Creek drainage basin; geology from Ludington et al., 2007. Map prepared by William C. Haneberg.

Figure 15. State Route 262 Bridge over channel constructed through narrow ridge which became the main channel of Montezuma Creek. View is looking upstream at knickpoint.

Figure 16. Topographic map showing Montezuma Creek channel and cutoff.

Figure 17. Sandstone and claystone exposed in knickpoint about 15 feet upstream from bridge. Orange circles are 1.35m apart on vertical pole.

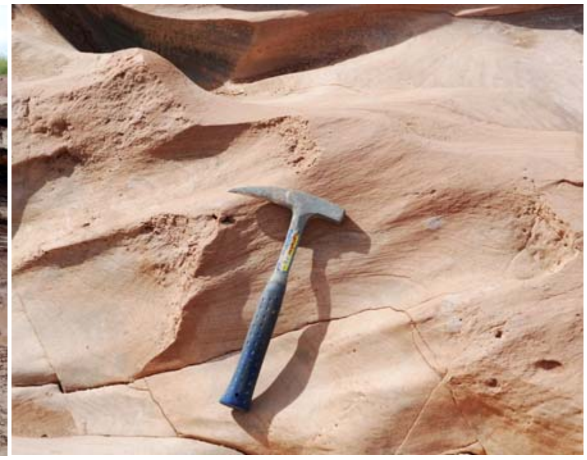

Figure 18. Sculpted and pitted sandstone within 10 feet from crest of knickpoint Water flow is right to left.

Figure 19. Gravel fragments wedged tightly into vertical joint in hard sandstone indicating turbulence-induced opening during flood flow.

Figure 20. Blast hole with radial fractures in hard sandstone. White spots on board are 20 cm and 30 cm apart.

Sacramento River – State Route 273

State Route 273 crosses Sacramento River at Redding in north-central California about 150 miles north of Sacramento. The drainage basin extends into Oregon; the outline and general geologic formations are shown on Figure 21. The bridge (Figure 22) is founded on soft, dark gray, Cretaceous marine siltstone that is thinly bedded and locally fractured (Figure 23). Beds are locally folded and dip toward the left abutment (north) at about 17°; some beds are harder than others (Figure 24). Cobble-sized fragments of hard igneous rocks form the bedload (Figure 25). Shasta Dam, located approximately 10 miles upstream, was closed in 1945.

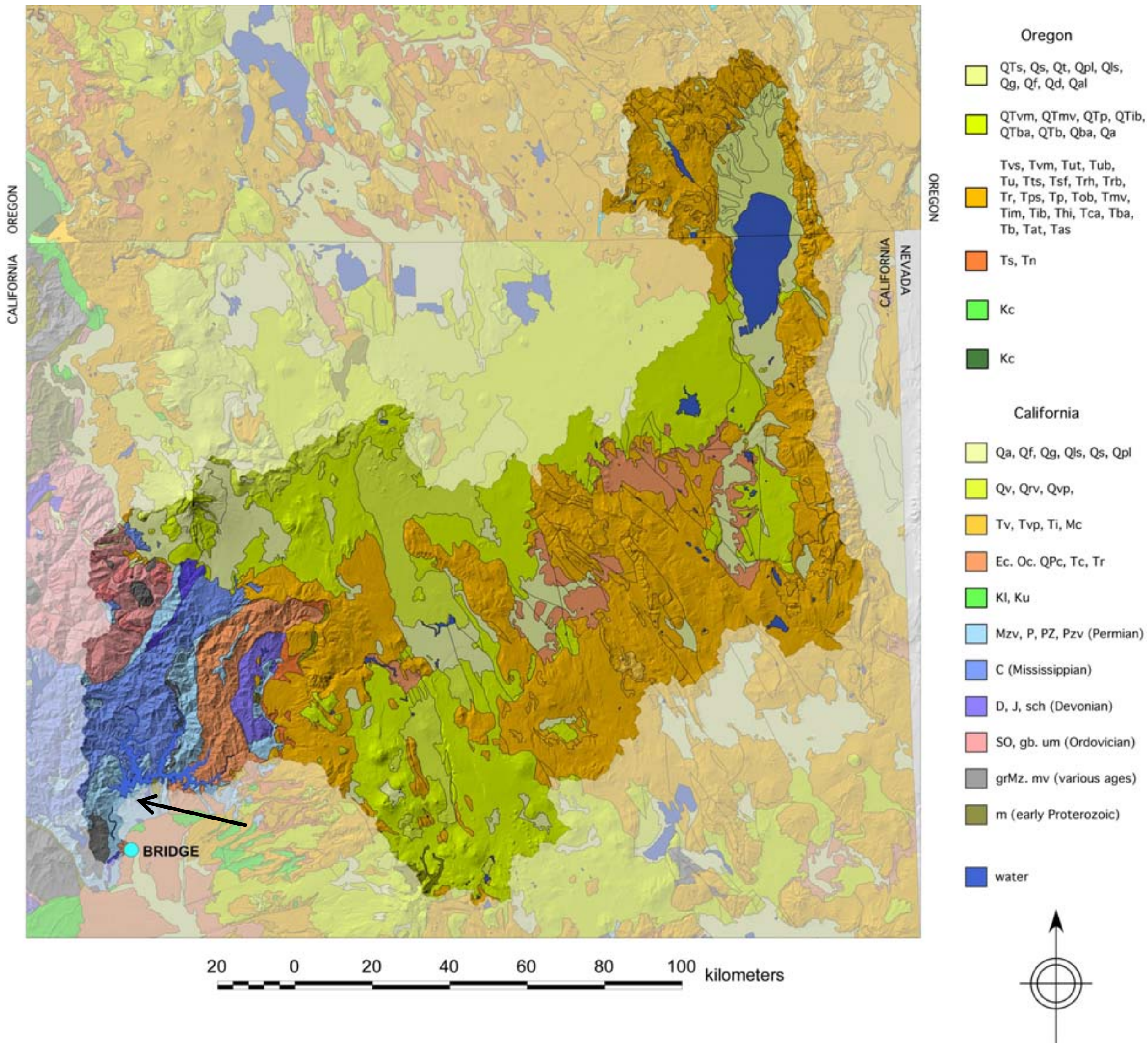

Figure 21. General geologic map of Sacramento River drainage basin; geology from Ludington et al., 2007. Arrow points to Shasta Dam. Map prepared by William C. Haneberg.

Figure 22. State Route 273 Bridge over Sacramento River. View looking toward right abutment.

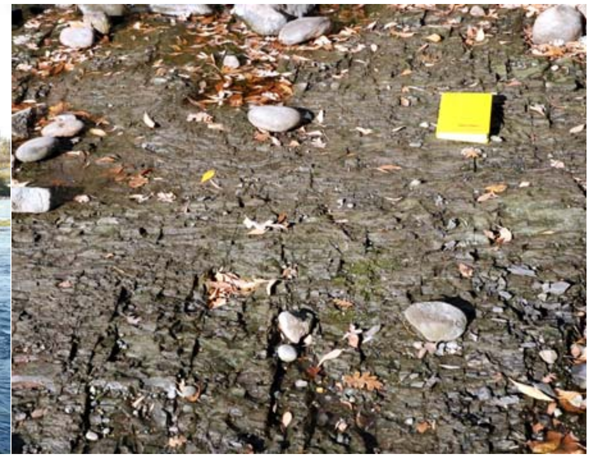

Figure 23. Thinly bedded and locally fractured siltstone. Notebook is 140 mm wide by 192 mm long.

Figure 24. Harder layers in siltstone mark local fold exposed in Sacramento River upstream of SR-273 Bridge. View looking about 45° right of directly upstream; photo taken from bridge.

Figure 25. Rounded cobble-size bed load fragments on bank of Sacramento River near left abutment of SR-273 Bridge. Orange targets are 1.0 m apart.

SELECTED PHYSICAL PROPERTIES FROM LABORATORY TESTS

Laboratory tests included specific gravity, moisture, point load, slake durability, continuous abrasion, and Rotating Erosions Test Apparatus (RETA) tests. Samples collected from bridge sites were supplemented by samples of dolostone from a local quarry (Chipola River), rounded gravel-sized fragments of basalt from a terrace deposit in southwest Utah, and samples of geotechnical grout produced by Moore & Taber Geotechnical Constructors. Selected laboratory test results are summarized in Table 2.

Table 2. Summary of laboratory test results. Test results in the Unconfined Compressive Strength column followed by (T) indicate splitting tension in psi.

Location	Sample	Rock Type	Specific Gravity	Unit Weight (pcf)	Moisture (%)	Point Load Is(50) MPa	Unconfined Compressive Strength (psi)	Slake Durability Index Id(2)	Abrasion Number
Chipola River	Bank	Limestone	2.16	134.8	11.0	1.097	3500	93.1	27.2
	Quarry	Dolostone 1	2.02	125.7	16.0	1.149	3650	98.8	31.4
	Quarry	Dolostone 2	2.31	144.1	3.9	4.736	15100	92.9	8.2
Mill Creek	Bank	Siltstone	2.26	141.1	16.8	0.264	850	2.4	27.4
	Core (OSU)	Siltstone	2.27	141.5	6.0	2.627	8380	23.4	23.7
	Core (RETA)	Siltstone	2.23	139.3	13.1	---	203, 67 (T)	---	---
Schoharie Gage	Bank	Sandstone	2.66	166.0	1.0	14.090	44950	---	4.6
Montezuma Creek	Head Cut	Sandstone	2.60	161.9	1.4	10.629	33900	---	13.6
	Head Cut	Claystone 1	2.50	156.3	14.3	1.176	3750	35.8	23.8
	Head Cut	Claystone 2	2.30	143.7	16.7	---	---	---	63.5
Sacramento River	Bank	Siltstone	2.31	144.1	7.2	4.202	13400	0.7	43.1
	Core	Siltstone	2.36	147.2	13.5	0.690	2200	5.3	33.3
Basalt gravel	Terrace	Basalt	2.54	158.6	1.5	---	---	---	8.9
Grout	1 sack mix	Sand-cement	2.10	130.9	16.2	1.299	4150	88.3	51.2
	1/2 sack mix	Sand-cement	2.06	128.7	17.0	0.169	540	22.3	> 51.2
	1/2 (RETA)	Sand-cement	1.92	119.8	12.3	---	40 (T)	---	---

Specific gravity tests were performed on bulk samples using ASTM method C127-07. Point load index tests were performed using ASTM method D5731-08. Continuous abrasion tests were modified from the Slake Durability Test, ASTM method D4644-08, using the general procedure described by Dickenson and Baillie (1999). The ASTM slake durability procedure calls for oven drying and two 10-minute-long cycles of tumbling; the Slake Durability Index ($Id_{(2)}$) is the percentage of initial sample mass retained in the basket after the second cycle. The modified procedure eliminates the oven drying part and changes the tumbling and weighing increments to 30 minutes or 60 minutes for a number of hours. Weighing is done on 'drip dry' samples that have most of the free water off of the sample fragments, but without letting them dry for substantial amounts of time. The sample fragments are left in the basket during weighing.

The 'continuous abrasion' test of Dickenson and Baillie (1999) expresses sample loss as a function of accumulated time during the test (Figure 26). The abrasion number is defined as the slope of the abrasion loss rate curve for that part of the test beyond 120 minutes on a semi log plot of the data (lower graph on Figure 26). The first 60 to 120 minutes of the test display a sample loss rate that is controlled by rounding of angular fragments, whereas sample abrasion is occurring after rounding is complete (Figure 27). The samples demonstrate a wide range of results.

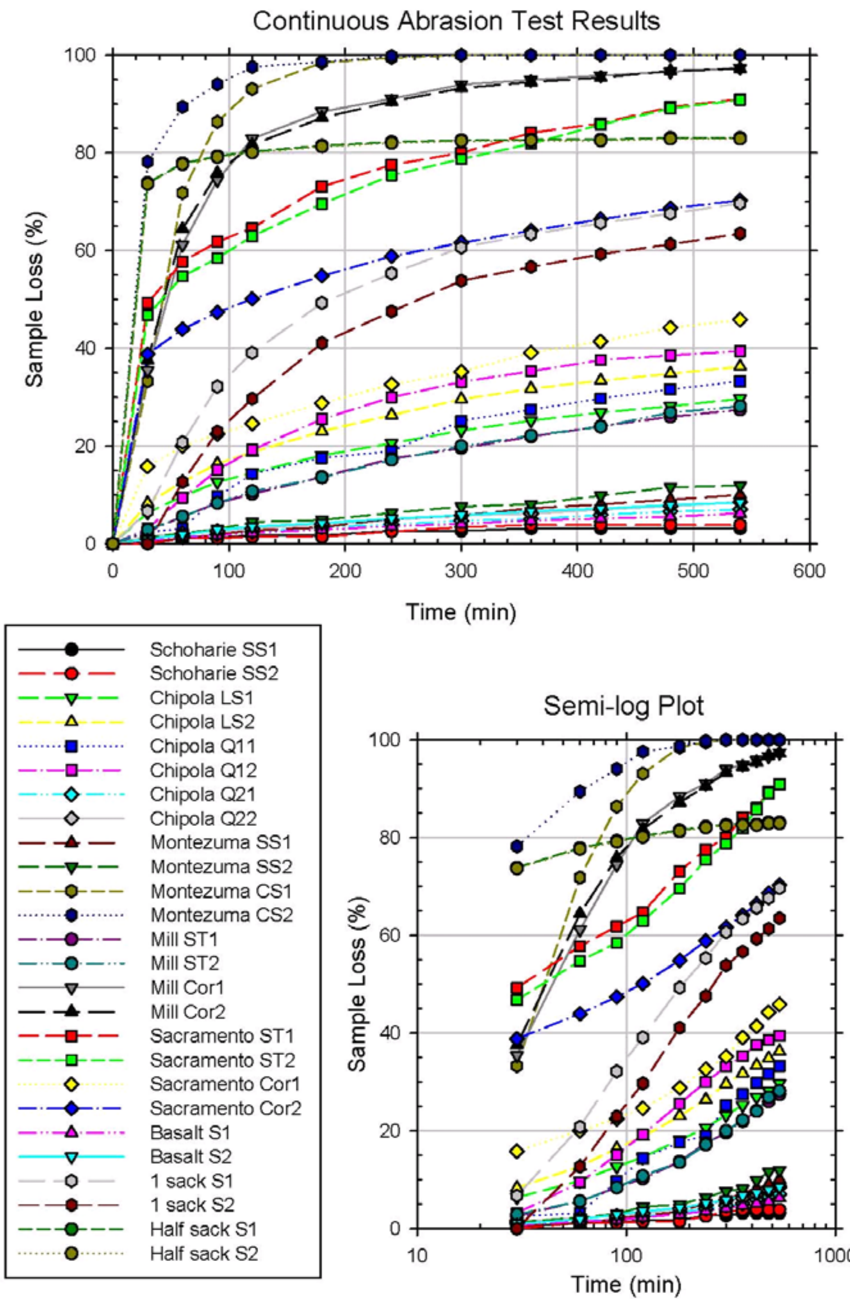

Figure 26. Continuous abrasion test results. Notations: SS – sandstone; LS – limestone; Q1, Q2 – quarry; CS – claystone; Cor- Core; S - sample.

Sacramento River Siltstone Core Sample | Geotechnical Grout 1-Sack Mix Sample

Figure 27. Comparative photographs showing two samples at 0, 60, and 300 minutes during the continuous abrasion test

The wide range of sample loss (very little loss of resistant samples compared to complete loss of nonresistant samples) suggested that the continuous abrasion test results might not be directly comparable. At some degree of sample loss, nonresistant sample fragments are abrading only against the wire mesh of the basket, whereas resistant sample fragments are abrading against each other as well as the wire basket. Therefore, energy was calculated as sample mass × distance traveled (Newton-meters or Joules) and plotted against the equivalent cumulative distance that the samples traveled during the test. The distance was calculated from the rate of basket rotation (20 rpm) and the basket circumference (0.44 m). The equivalent relative velocity of the sample is 0.1467 m/s. The samples travel an equivalent distance of 4752 m during a 9-hr test. Resistant samples exhibit more constant energy during the continuous abrasion test than nonresistant samples. Figure 28 shows cumulative energy for eight samples with resistant samples plotting as straight lines and nonresistant samples exhibiting nonlinear behavior.

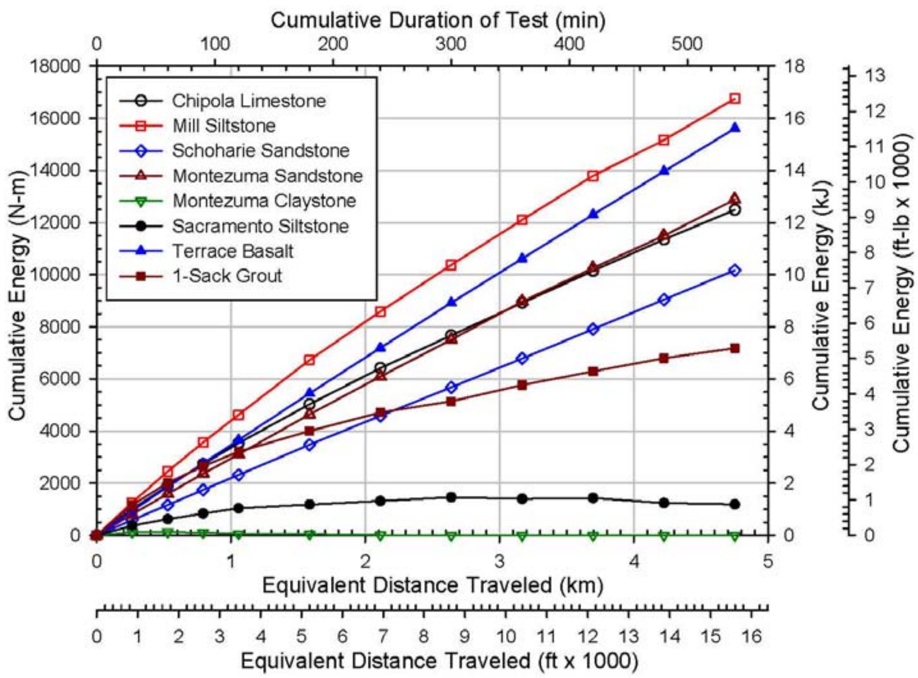

Figure 28. Cumulative energy plotted against equivalent distance traveled during a 9-hr continuous abrasion test using standard slake durability test equipment.

Energy dissipation can be expressed in terms of Newton-meters per second or foot-pound per second, which are the units of stream power (1 N-m/s = 1 J/s = 1 W). Unit stream power is stream power normalized per area of channel cross section, expressed as W/m^2. The continuous abrasion test results were converted to equivalent power or unit energy dissipation by dividing the incremental energy by the number of seconds between measurements and assuming that the sample fragments remain in the lower 45° of the slake durability basket during the test. The basket circumference is 0.44 m and its length is 0.10 m; therefore, the area of a 45° sector of the basket is 0.0055 m^2. Figure 29 shows the first 3 hours of the test data plotted in Figure 28 with the results normalized as percentages of initial sample mass and initial equivalent power. The values progress from right to left, starting with 100% of the equivalent power.

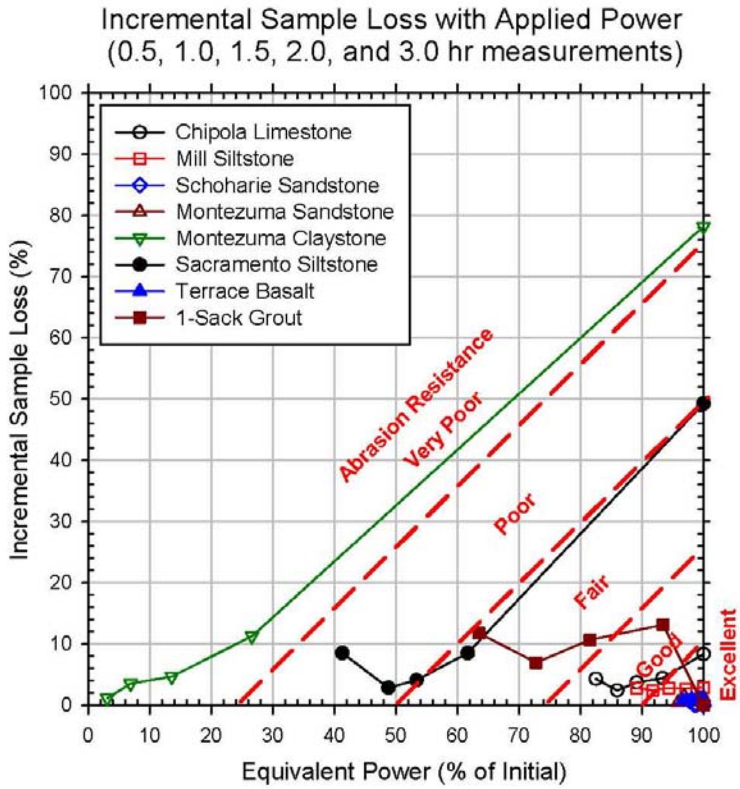

Figure 29. Incremental sample loss plotted against equivalent power.
Abrasion resistance field boundaries are arbitrary.

It can be seen in Figure 29 that samples with linear trends in Figure 28 retain at least 95% of the initial power during the first 3 hours of the continuous abrasion test. Samples with strongly nonlinear trends in Figure 28 (Montezuma claystone and Sacramento siltstone) exhibit large sample loss in the initial test increment. Samples with mild nonlinear trends in Figure 28 (Chipola limestone, Mill siltstone, and 1-sack grout) exhibit modest sample loss in the initial test increment, with continuing loss in subsequent test increments. Samples with linear trends in Figure 28 exhibit high equivalent power (>95%) and low incremental sample loss (<5%) during the 3 hours of test data plotted on Figure 29. It should be noted in Figure 27 that coarse sand grains (>2 mm) abrading from the 1-sack grout sample are retained in the basket and contribute to incremental sample mass; therefore, the continuous abrasion test results for the geotechnical grout samples do not represent actual abrasion loss.

Florida DOT tested four samples in their Rotating Erosion Test Apparatus (RETA) (Figure 30): Siltstone core samples from Mill Creek obtained with drilling donated by Oregon DOT and geotechnical grout samples donated by Moore & Taber. Siltstone samples were tested at field moisture and saturated. Grout samples were sand-cement slurry mixed with ½ sack of cement per 8 cubic feet of grout and cast in standard plastic tubes 3 inches in diameter and 6 inches long. The exterior surface of the grout cylinders were as smooth as the inside of the plastic tube in which they were cast. The RETA results show negligible erosion rate on the smooth sample, but a rough sample showed a higher erosion rate. Testing of several other samples was attempted, but the samples were too fragile to survive handling during preparation.

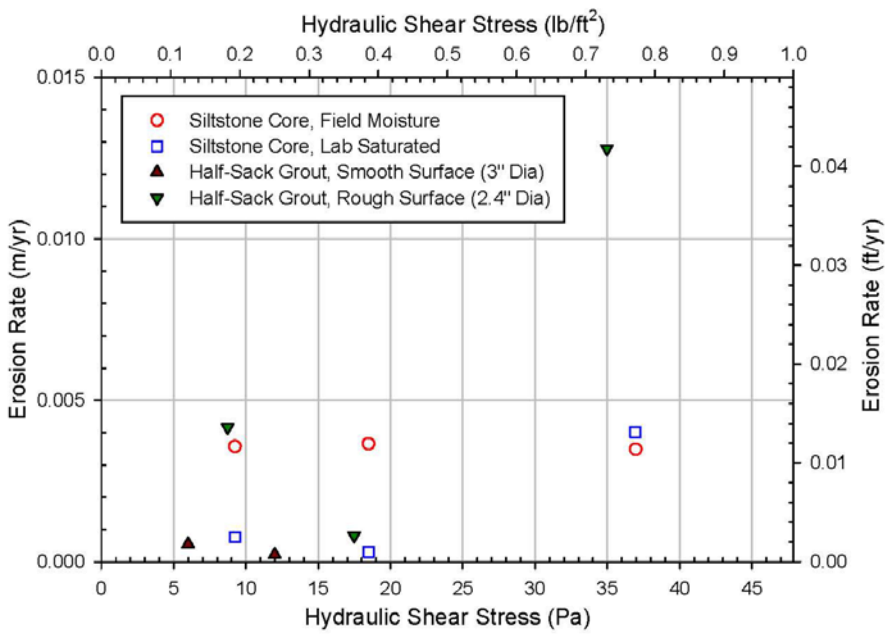

Figure 30. Rotating Erosion Test Apparatus (RETA) test results

CONCLUSIONS

The five bridge sites described above demonstrate a wide range of field conditions (e.g., drainage basin area, geologic setting, elevation, and climate) and tests results. Using test results to predict scour depths and rates continues to be a challenge. Bridge sites for which multiple cross sections are available provide a basis for determining scour rates empirically if stream flow data are available or can be estimated. Sites of proposed bridges and existing bridges for which repeated cross sections are not available require geotechnical characterization as well as stream flow data for predicting scour depth and time rate of scour.

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EVALUATING SCOUR AT BRIDGE FOUNDATIONS ON ROCK: NCHRP PROJECT 24-29

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National Cooperative Highway Research Program (NCHRP) Project 24-29 is geotechnical site characterization in scour-relevant terms for use by hydraulic engineers. The goal of this project is to develop procedures for evaluating scour at bridge foundations on rock that can be integrated with Federal Highway Administration (FHWA) Hydraulic Engineering Circular No. 18 (HEC-18).

All rock materials will erode over geologic time. Some rock materials erode during engineering time whereas other rock materials do not. Some erodible rocks wear away gradually, whereas other rock materials erode as blocks defined by joint and bedding planes. Scour holes in rock develop progressively and may be filled with sand between flood events. Bridges are not founded on rock materials that dissolve in engineering time (e.g., halite) and cavitation is unlikely on most natural channels. Some bridges are founded on soluble rocks, such as limestone, that can have cavities filled with complex mixtures of intact rock blocks in a clay matrix, the scour response of which cannot be generalized.

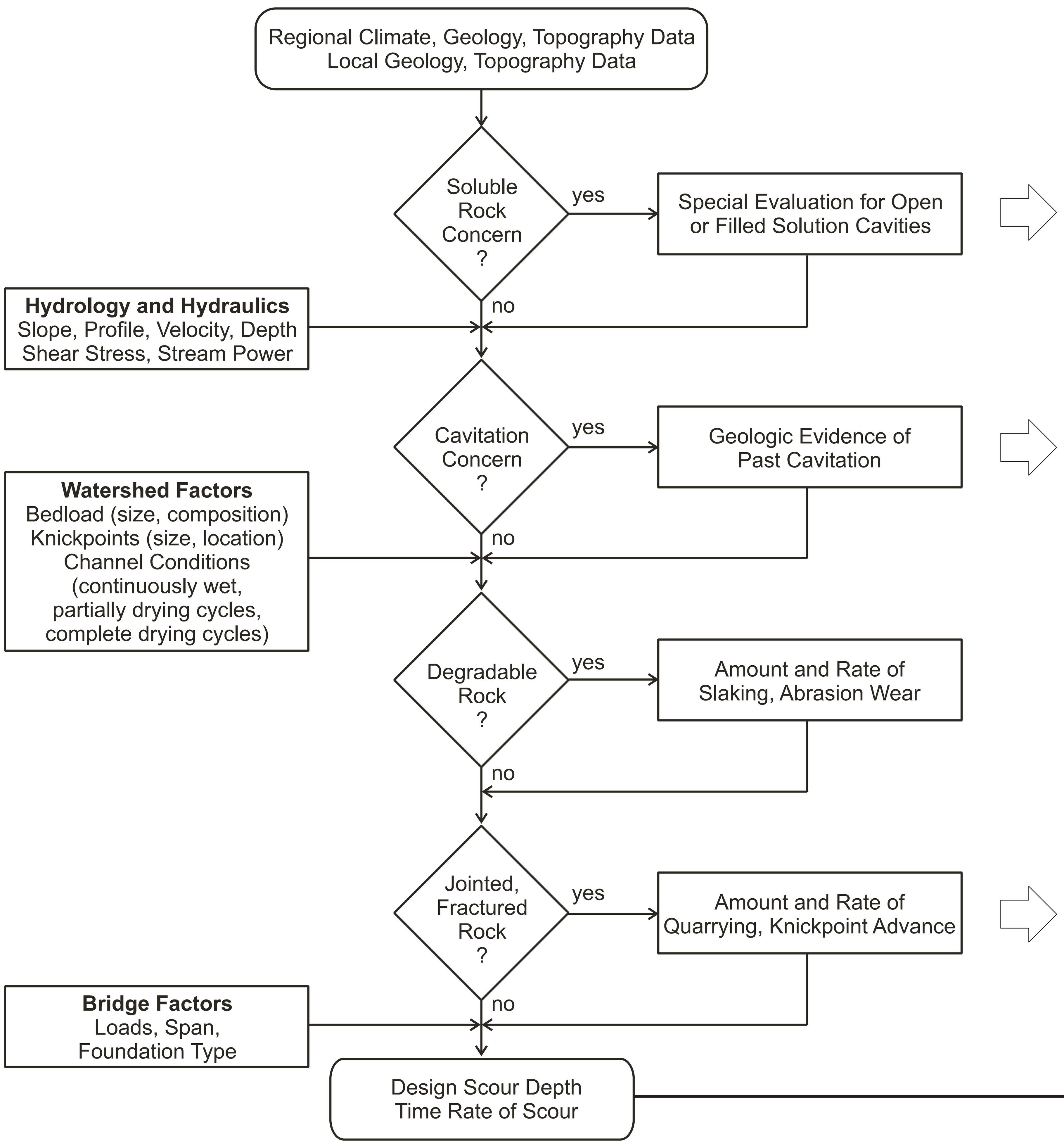
The progressive nature of rock scour requires hydraulic forces to be described in terms that can be accumulated over time. Stream power is such a term and is used in our method. Time rate of scour can be estimated from repeated channel cross sections at existing bridge sites and the excess stream power accumulated during the time interval between cross sections. Probability weighted average annual scour is calculated from the stream power generated by traditional flood events times the empirically determined scour number (scour depth per unit of power) from repeated cross sections.

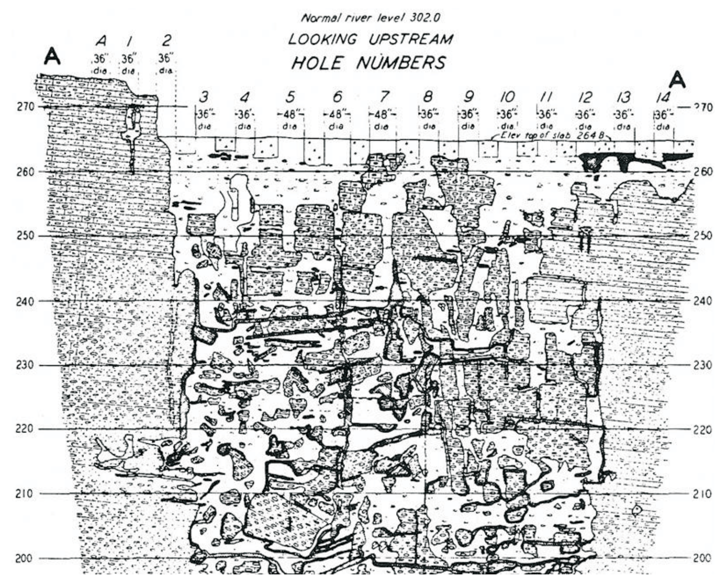
A modified slake durability test procedure is used to determine rock material abrasion resistance in terms expressed as equivalent scour rate and stream power from which a geotechnical scour number is obtained. Numerical modeling of open channel flow over durable rock blocks was used to determine threshold conditions for quarrying and plucking.

For sites where repeated cross sections are not available, such as sites for new bridges, the geotechnical scour number is used to develop the average annual scour depth. Design scour depth is the product of the average annual scour depth and the life of the bridge.

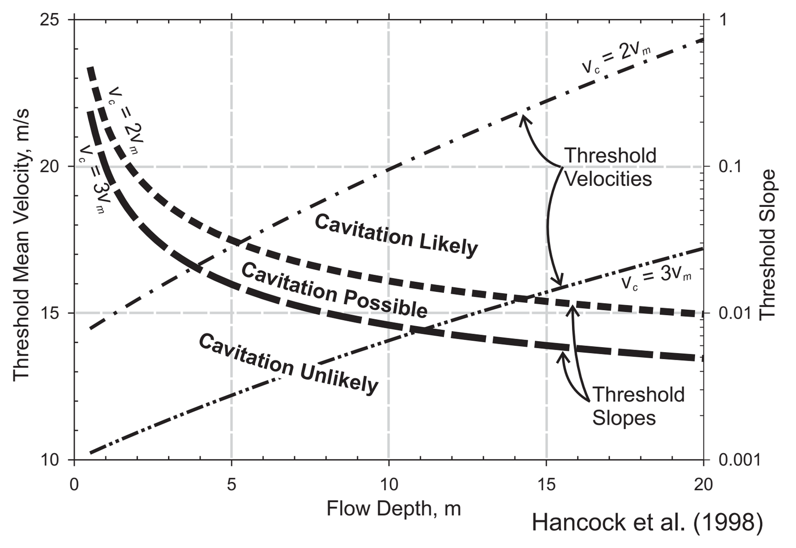
Rock Scour Processes

Potential Rock Scour Process	General Observations	Recommended Phase II Approach
Preparation of Rock for Subsequent Scour	Physical and chemical weathering processes, such as wetting and drying, freezing and thawing, and salt crystallization, weaken rock material over periods of time when stream discharge is low.	Field observation of rock surface weathering and gravel fragments wedged into fractures in blocky rock. Identify reference points for future observations to characterize rate of rock condition deterioration.
Dissolution of Soluble Rocks	Probably dealt with at initial bridge planning or foundation design stage. General dissolution is a rate problem; ancient solution cavities filled with rubble and soil are local scour problems.	Identify susceptible rock types and filled or unfilled cavities reported in the literature. Field observations of active and paleo-karst-like features. Use solubility tables for susceptible rock types.
Abrasion	Rock material hardness and toughness in relation to amount and hardness of sediment load particles sliding, rolling, or saltating in the flow.	Field observation of bedload deposits; evaluation of watershed for sources of hard bedload materials. Laboratory measurements of abrasion rates.
Quarrying or Plucking	Rock mass discontinuities; orientation and roughness of joints and fractures; block sizes and shapes; general blocky or smooth shape of channel in jointed rock formations.	Field observations and examination of core from borings; measurement of joint spacing and orientation; examination of fracture conditions and filling materials for pre-conditioning for block removal.
Cavitation	Rare in natural channels; requires very steep, narrow rock channels in which high velocities can occur with deep flows. Probably no bridges will be exposed to cavitation processes.	Check hydraulic parameters against threshold conditions in plot of mean velocity versus mean flow depth and slope.

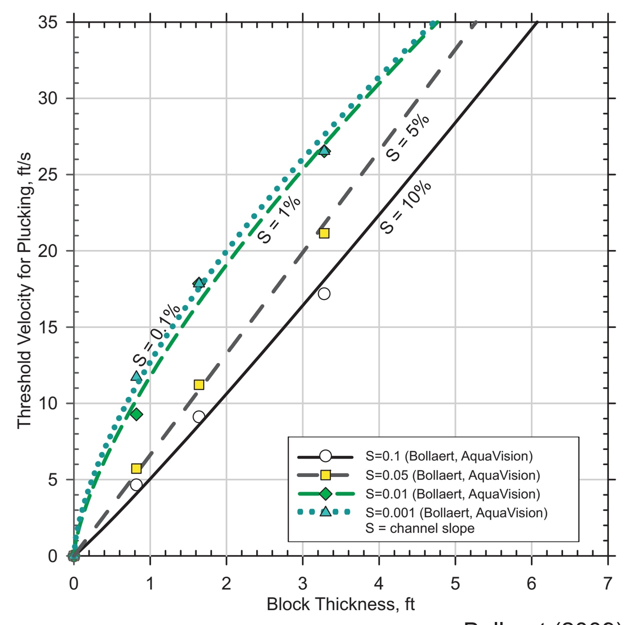




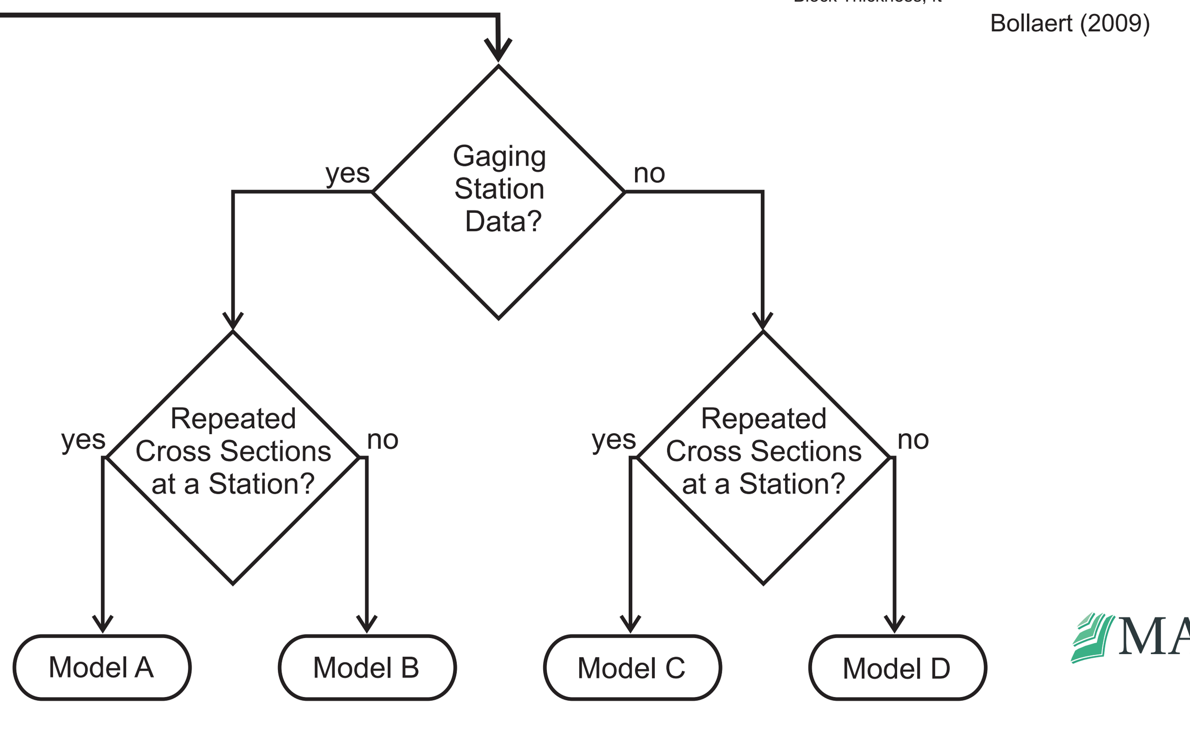
Burwell and Moneymaker (1950)



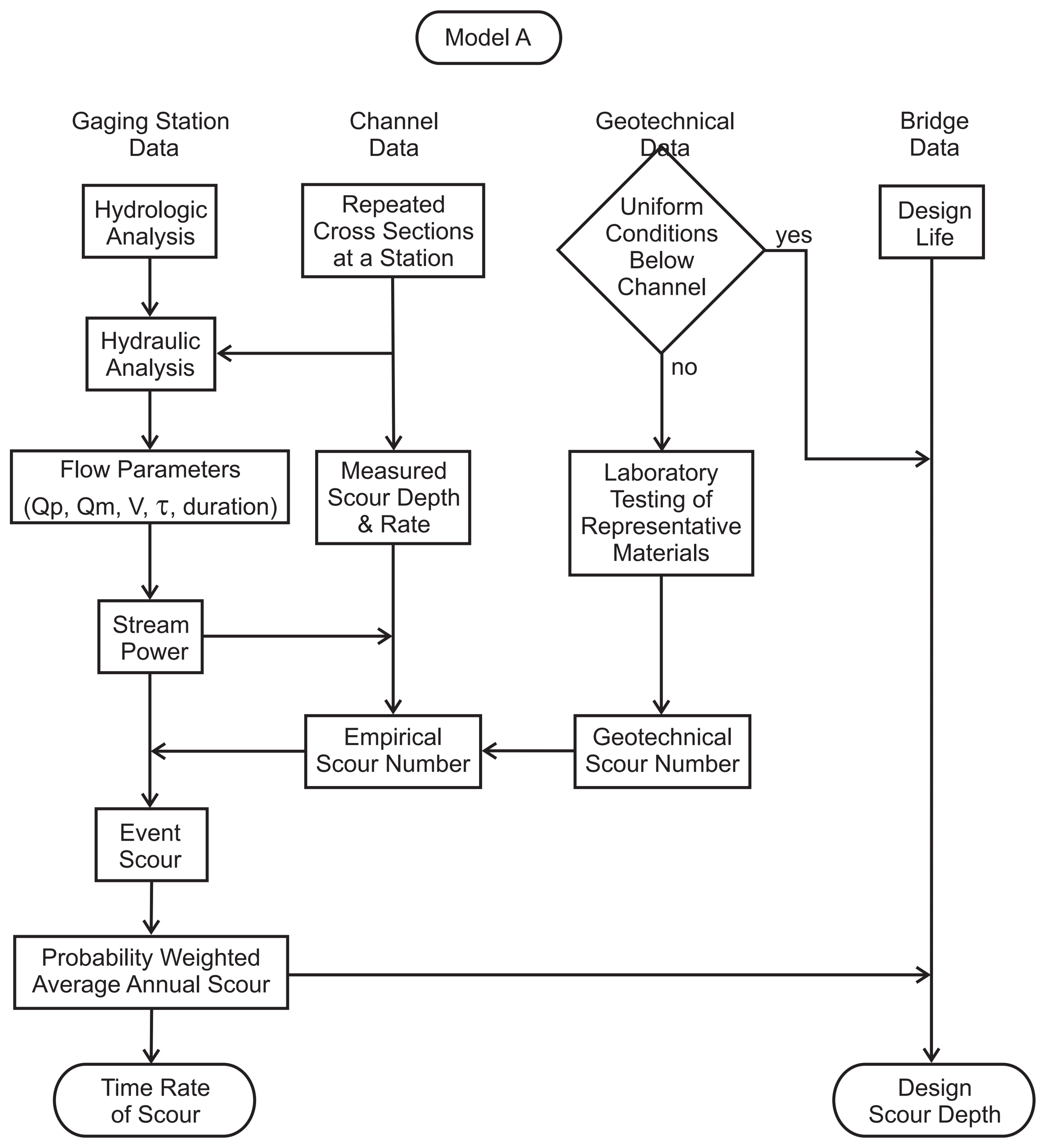
Hancock et al. (1998)

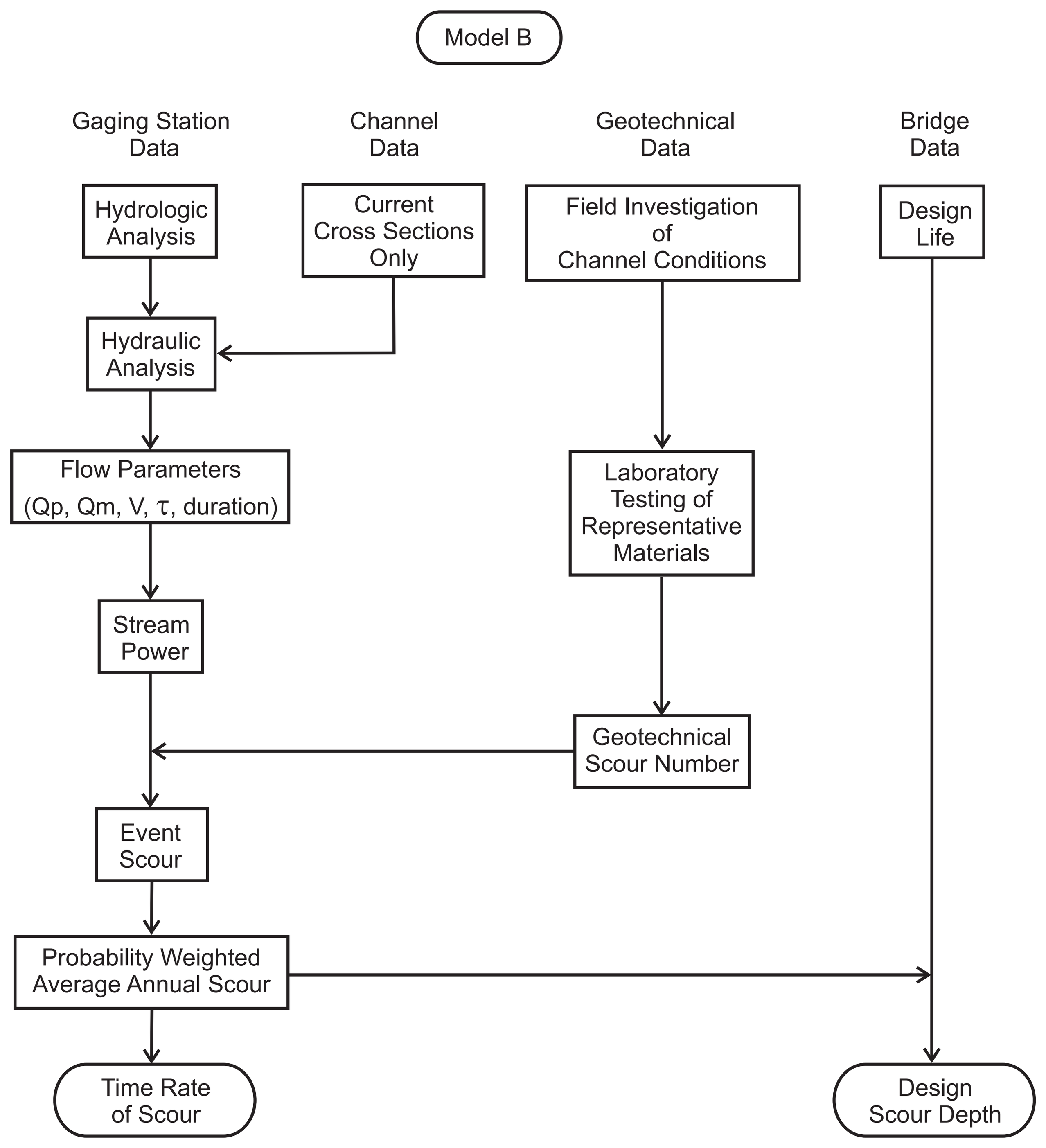


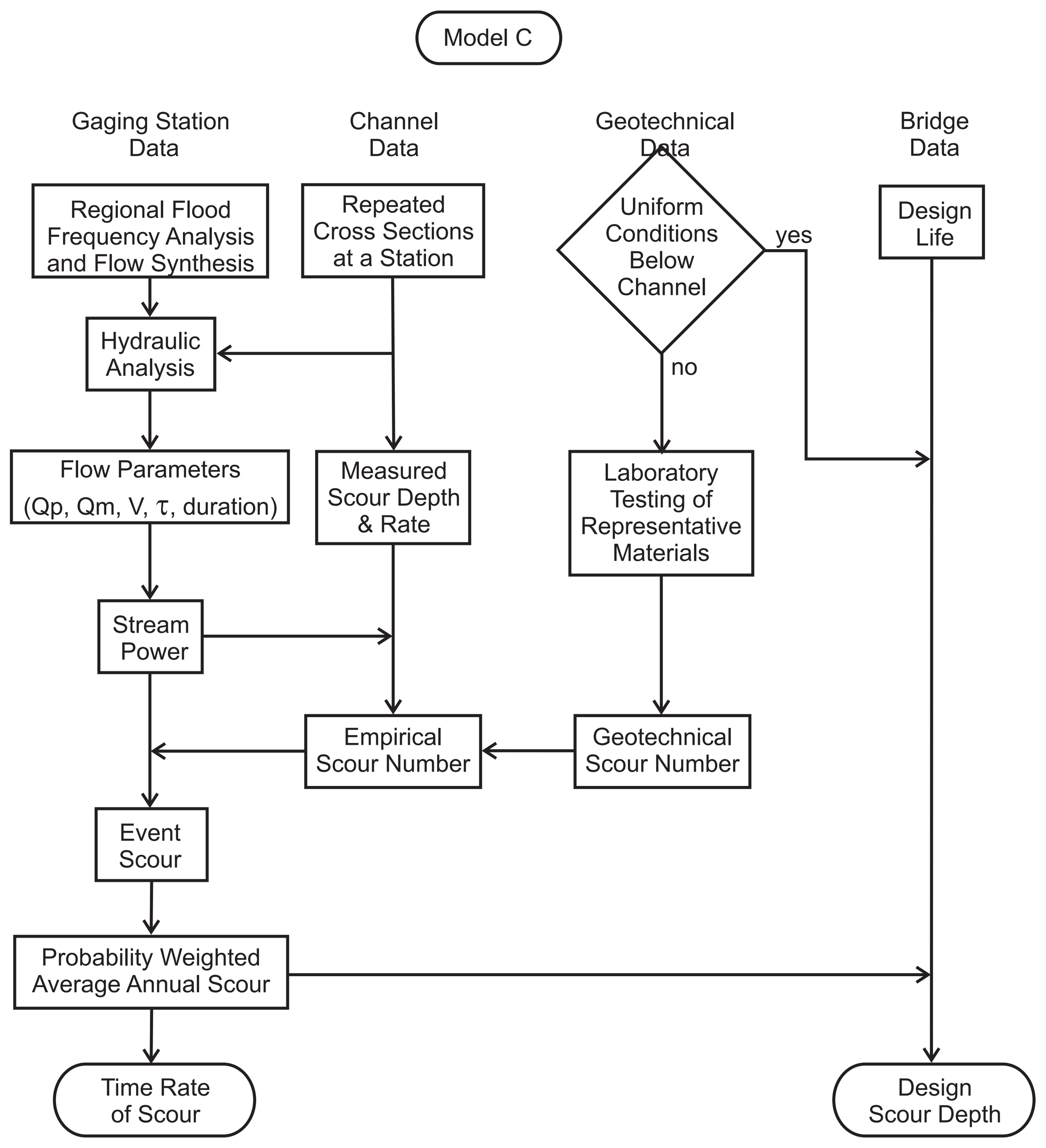
Bollaert (2009)

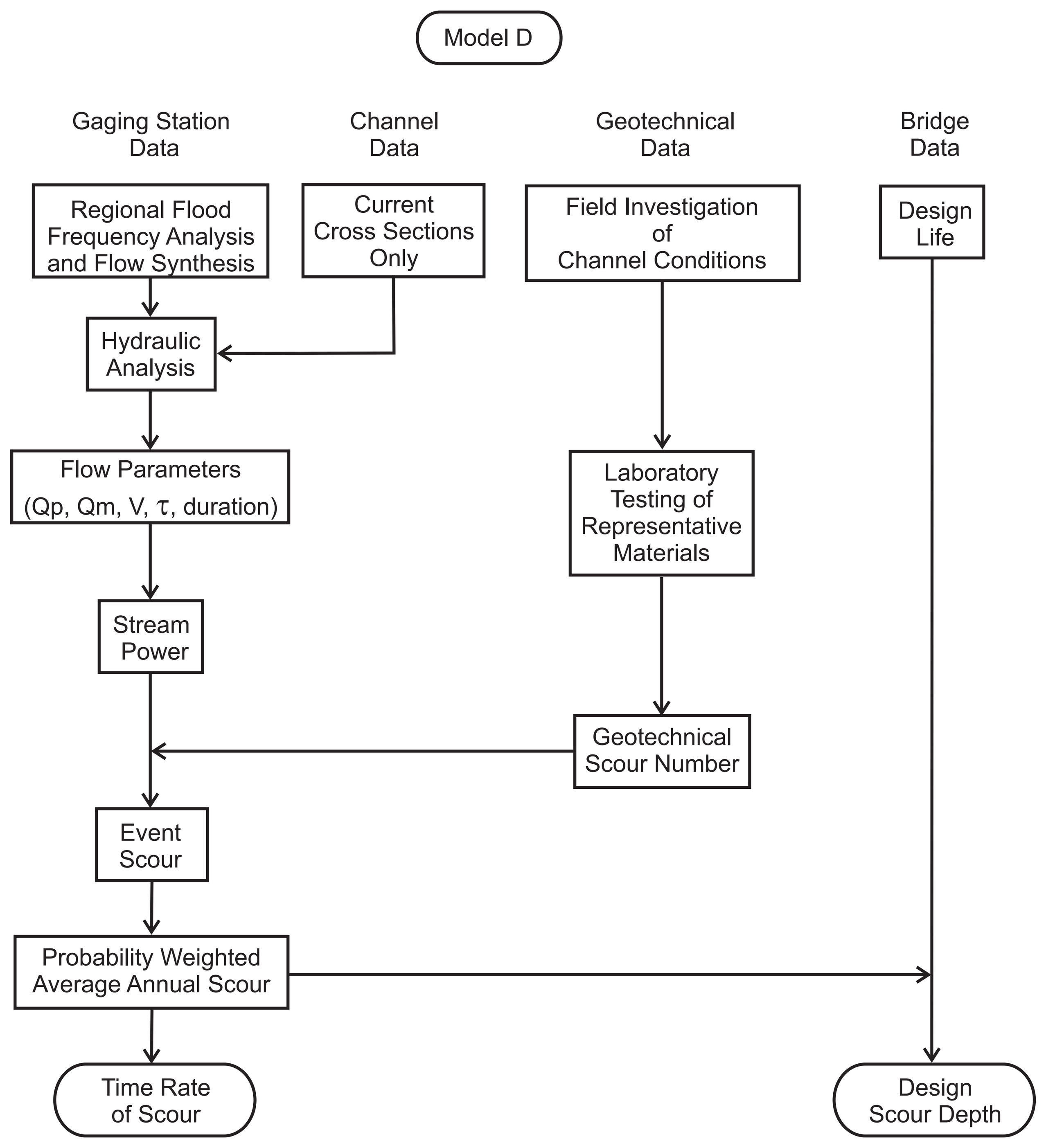


Flow Diagram of Rock Scour Processes and Rock Scour Model Framework

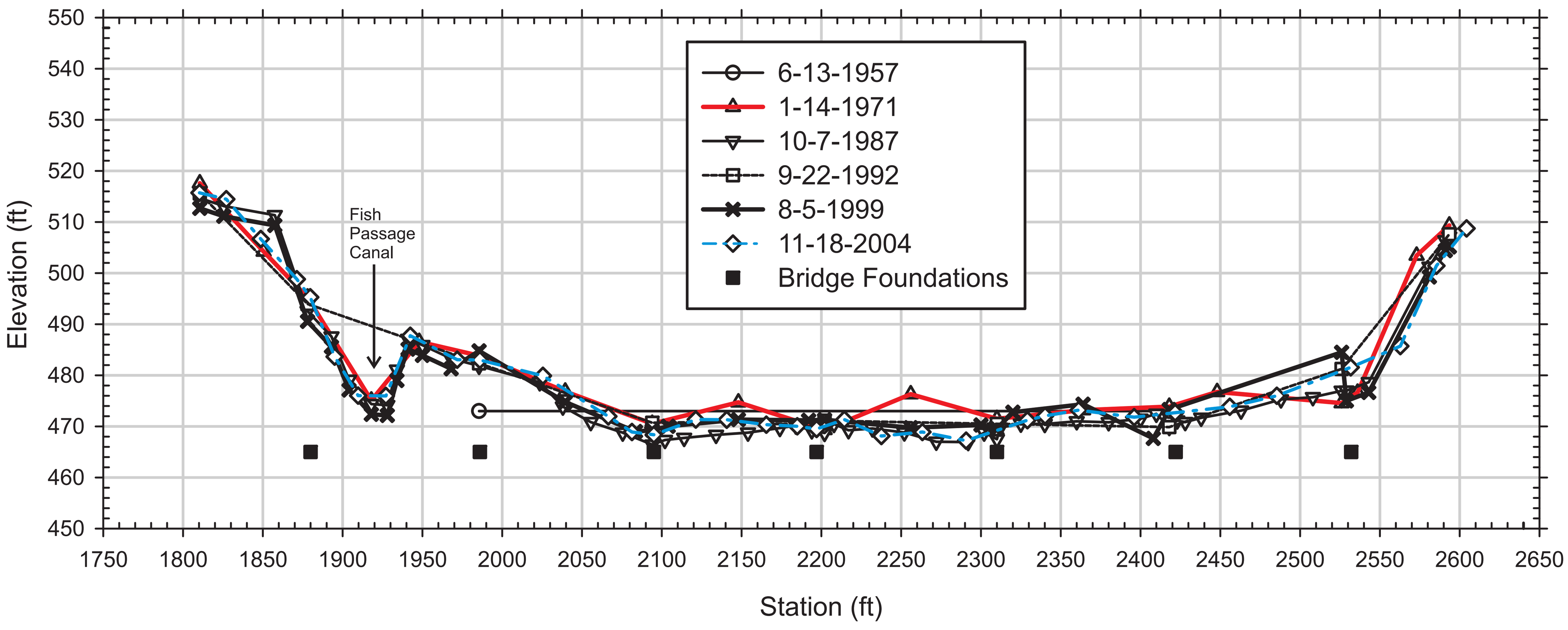






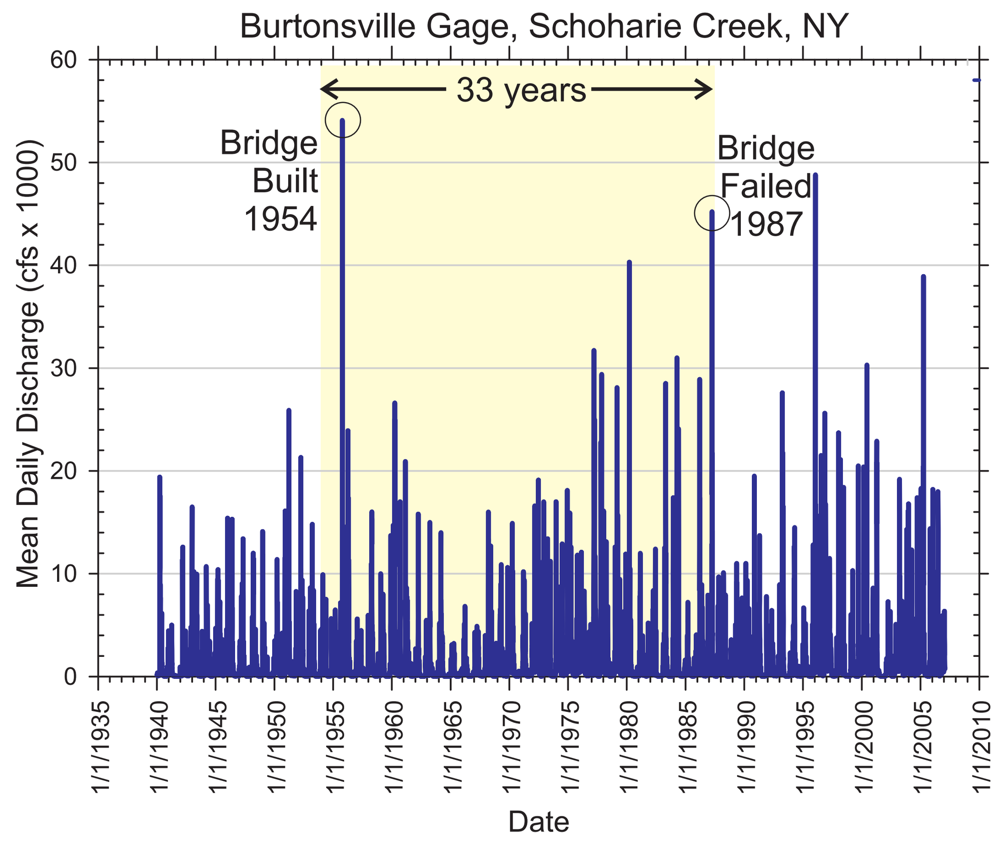


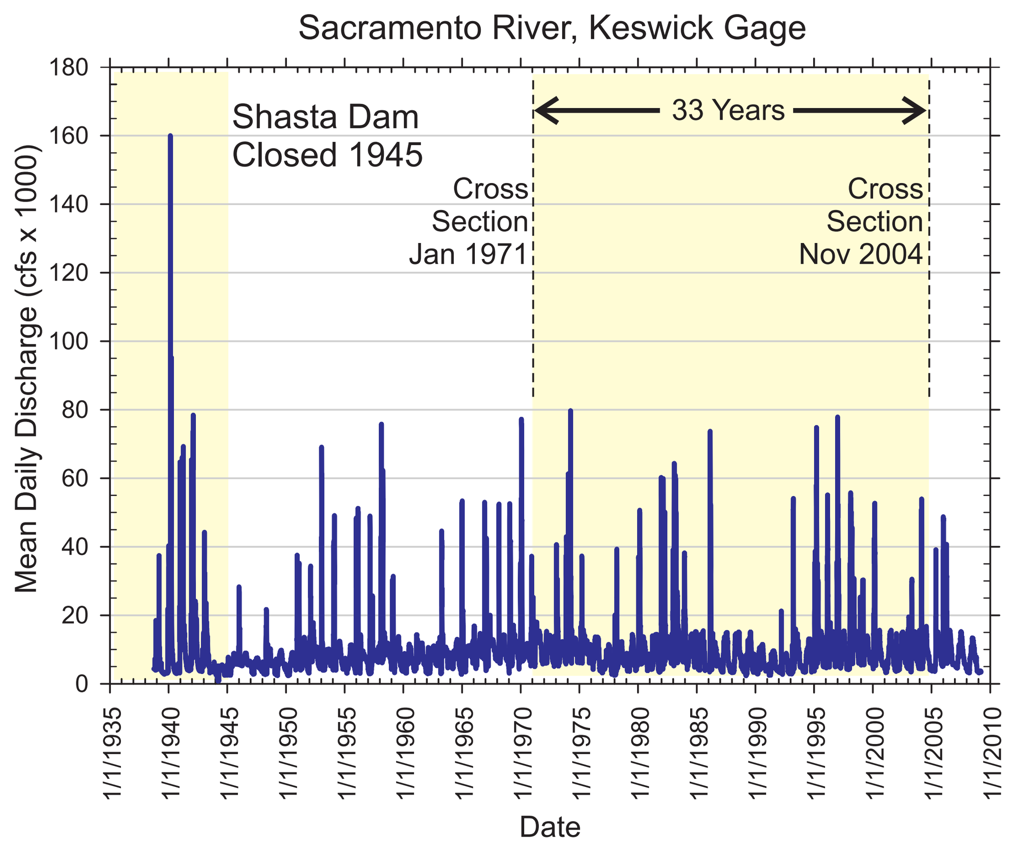
Sacramento River Cross Sections At Market Street (SR-273), Redding, CA

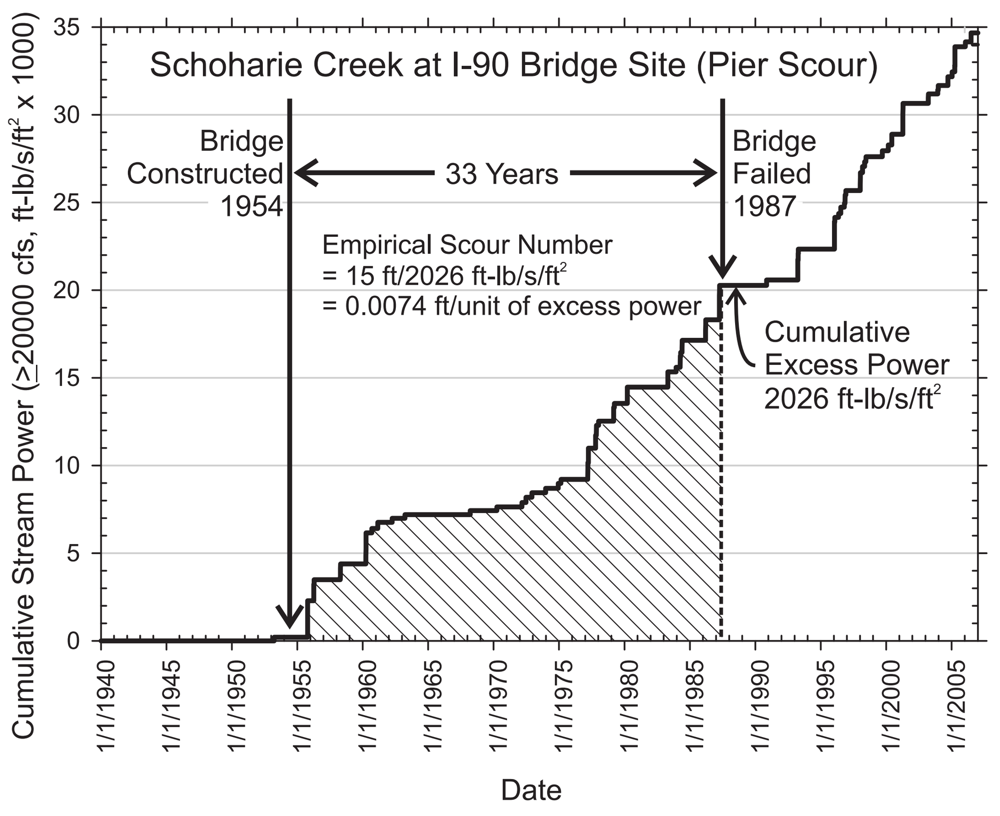


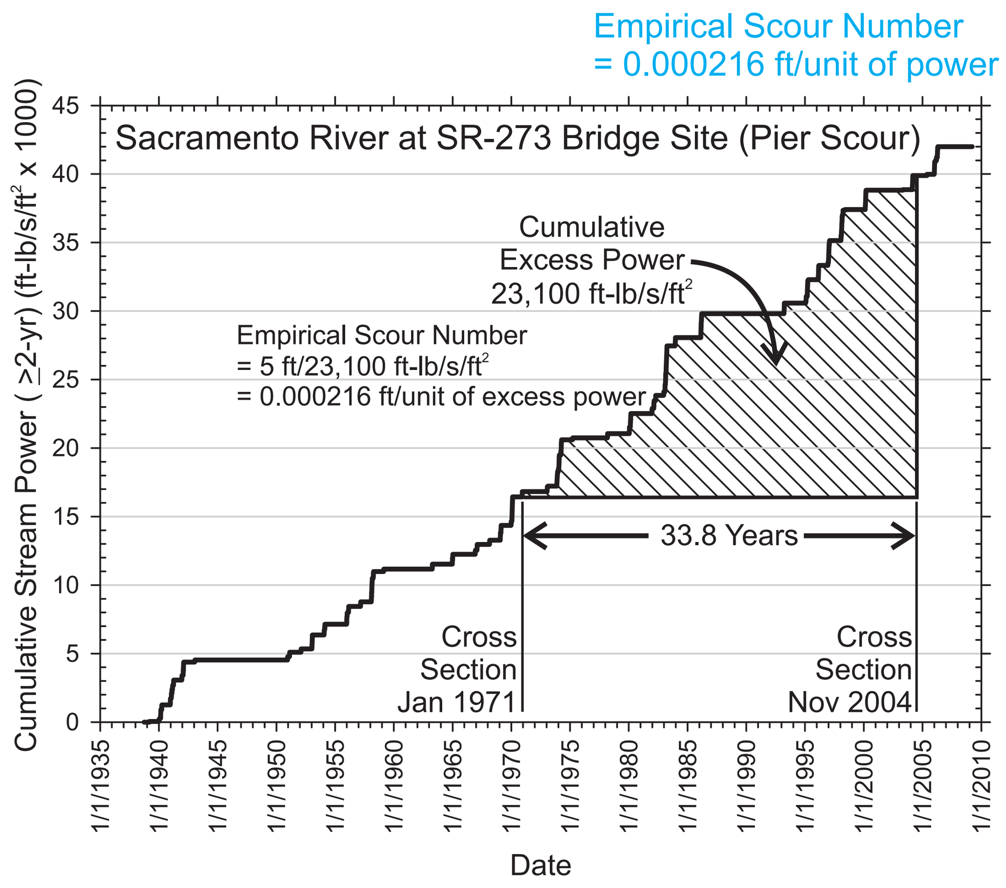
Interstate Highway 90 Bridge
over Schoharie Creek
Montgomery County, New York

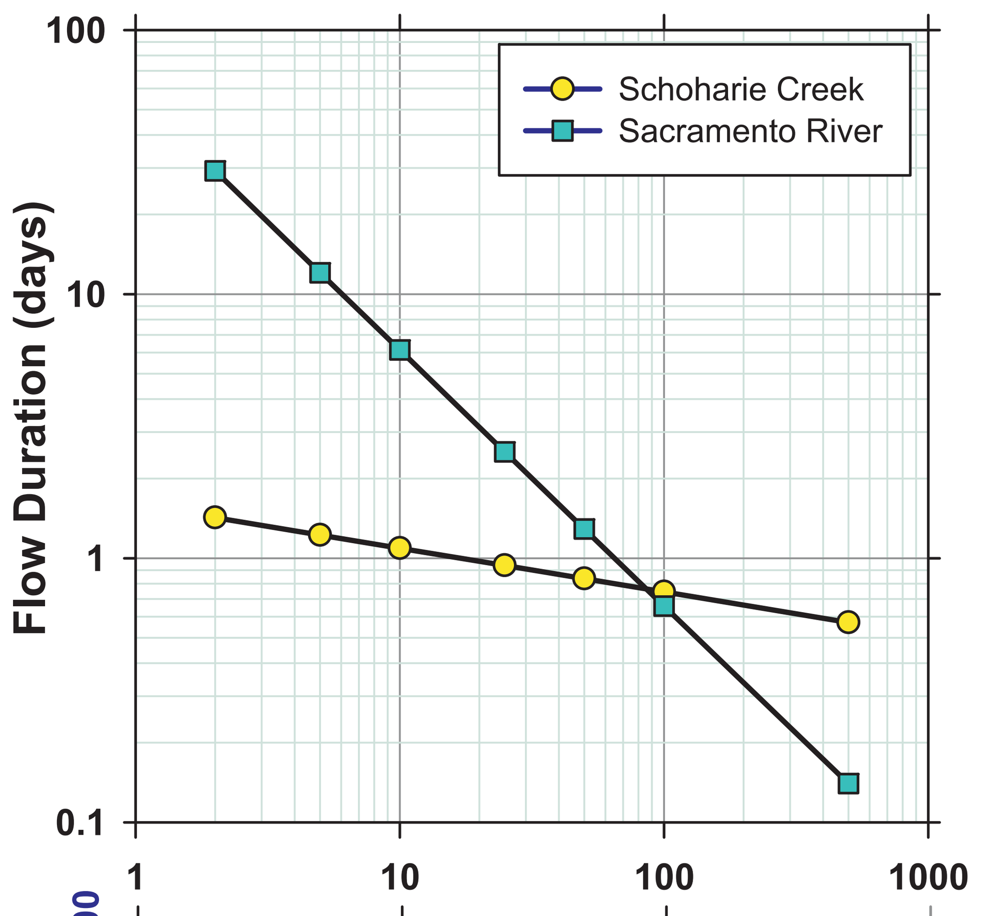
Market Street Bridge (SR-273)
over Sacramento River
Redding, Shasta County, California

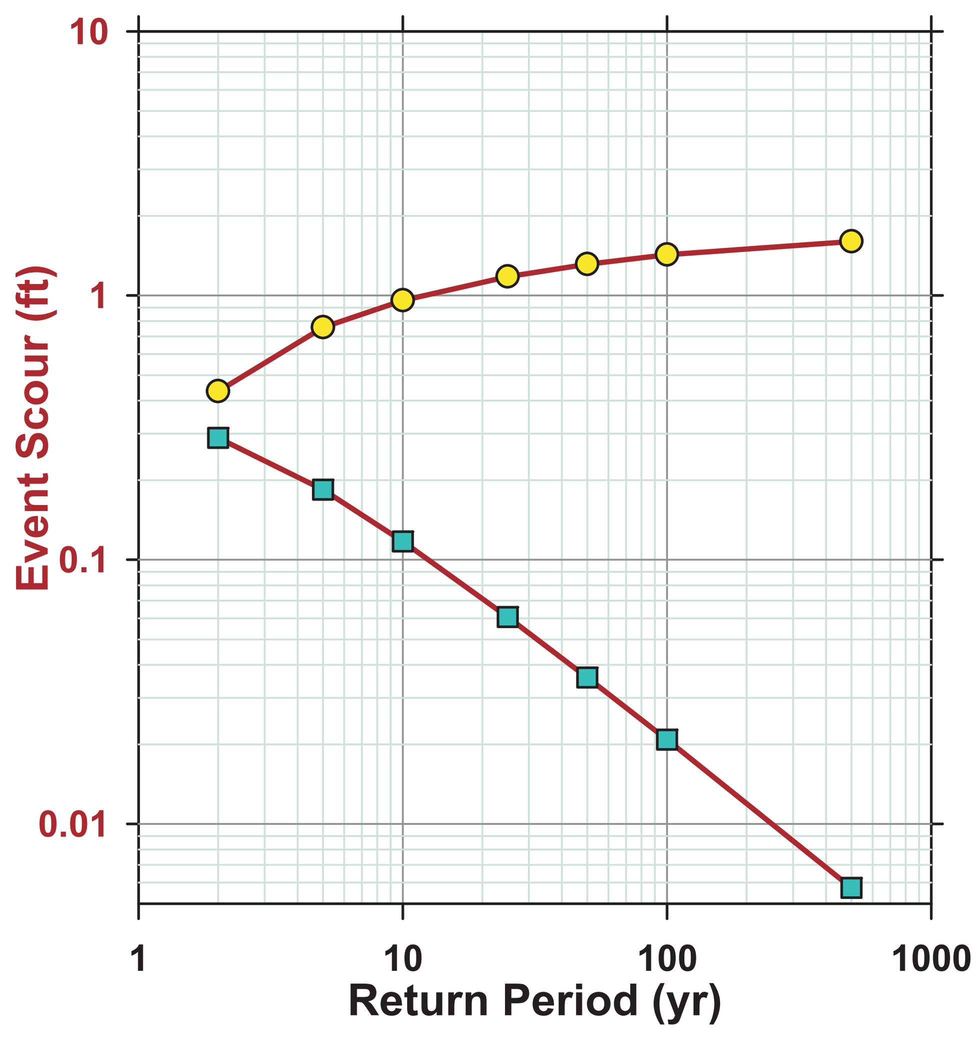


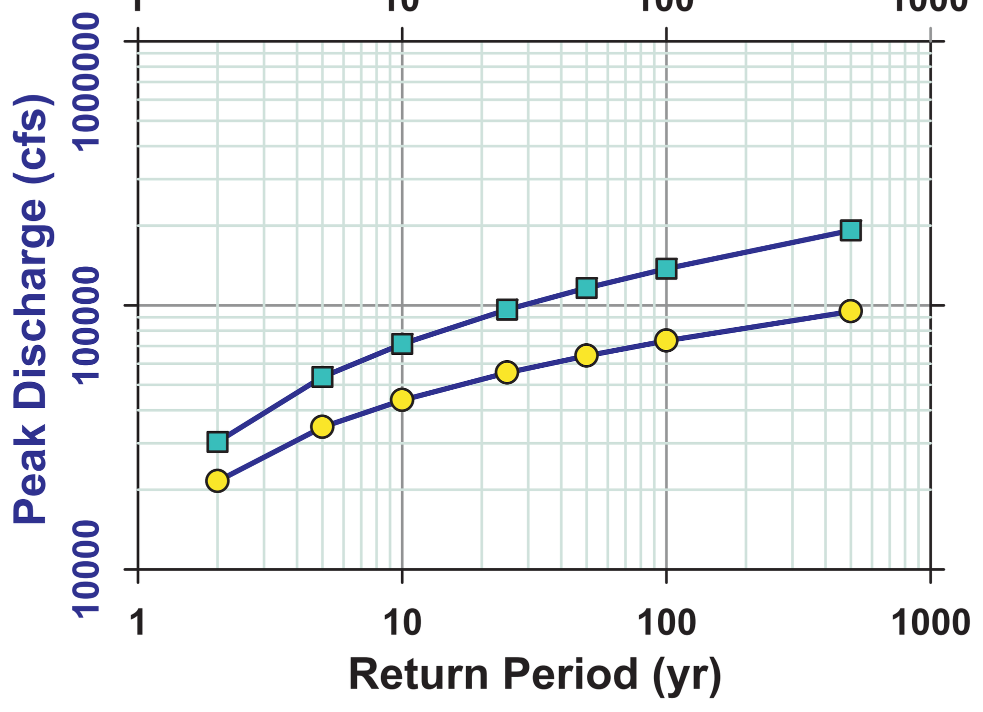


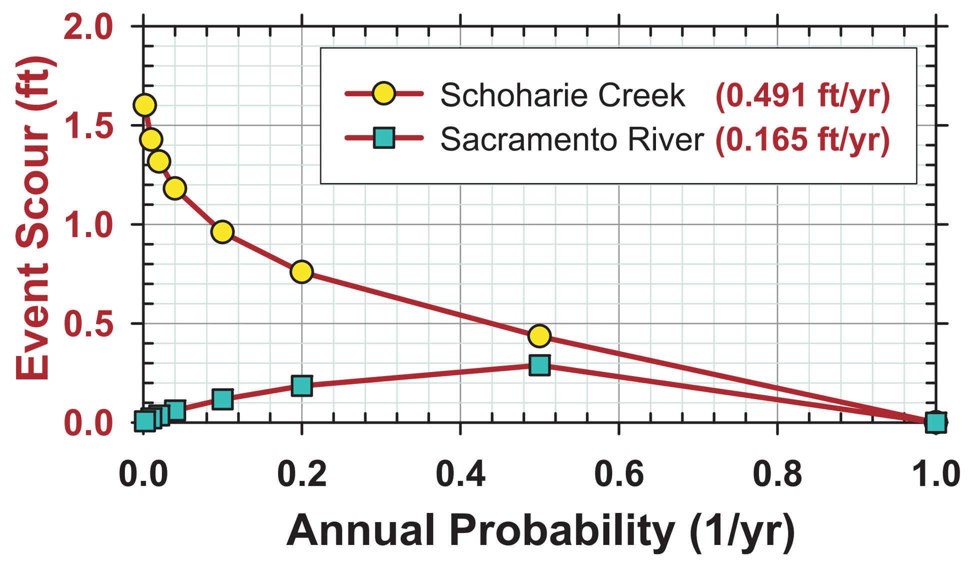












Schoharie Creek at I-90 Bridge Site

Flood Event Return Period (yr)	Annual Frequency (1/yr)	Peak Discharge (cfs)	Mean Daily Discharge (cfs)	Flow Velocity (fps)	Velocity at Pier (fps)	Flow Depth (ft)	Shear Stress (psf)	Excess Stream Power (ft-lb/s/ft^2)	Event Duration (d)	Event Scour (ft)
1	1.0	--	--	--	--	--	--	0	--	0
2	0.5	21544	15841	7.30	12.42	9.94	2.925	36.32	1.42	0.43
5	0.2	34588	25432	9.47	16.10	12.23	4.589	73.87	1.22	0.76
10	0.1	43691	32126	10.76	18.30	13.55	5.731	104.85	1.09	0.96
25	0.04	55481	40795	12.27	20.86	15.04	7.192	150.02	0.94	1.18
50	0.02	64404	47356	13.32	22.64	16.06	8.288	187.61	0.84	1.31
100	0.01	73376	53953	14.30	24.31	17.00	9.383	228.13	0.75	1.43
500	0.002	94628	69579	16.44	27.95	19.00	11.950	334.05	0.57	1.60

Sacramento River at SR-273 Bridge Site

Flood Event Return Period (yr)	Annual Frequency (λ, 1/yr)	Peak Discharge (cfs)	Mean Daily Discharge (cfs)	Flow Velocity (fps)	Velocity at Pier (fps)	Flow Depth (ft)	Shear Stress (psf)	Excess Stream Power (ft-lb/s/ft^2)	Event Duration (d)	Event Scour (Se, ft)
1	1.0	--	--	--	--	--	--	0	--	0
2	0.5	30340	29126	8.52	14.48	14.63	2.969	43.00	29.25	0.289
5	0.2	53510	51370	10.11	17.19	18.41	3.873	66.56	12.03	0.184
10	0.1	71320	68467	11.02	18.74	20.67	4.430	83.03	6.14	0.117
25	0.04	96220	92371	12.07	20.51	23.33	5.097	104.55	2.53	0.061
50	0.02	116300	111648	12.78	21.72	25.19	5.570	120.98	1.29	0.036
100	0.01	137600	132096	13.44	22.85	26.96	6.027	137.70	0.66	0.021
500	0.002	192000	184320	14.86	25.26	30.85	7.044	177.95	0.14	0.006

"Time Rate of Scour" (Probability Weighted Average Annual Scour Depth)

$$\overline{Sa} = (\lambda_1-\lambda_2)\frac{(Se_1+Se_2)}{2} + (\lambda_2-\lambda_5)\frac{(Se_2+Se_5)}{2} + (\lambda_5-\lambda_{10})\frac{(Se_5+Se_{10})}{2} + (\lambda_{10}-\lambda_{25})\frac{(Se_{10}+Se_{25})}{2} + (\lambda_{25}-\lambda_{50})\frac{(Se_{25}+Se_{50})}{2} + (\lambda_{50}-\lambda_{100})\frac{(Se_{50}+Se_{100})}{2} + (\lambda_{100}-\lambda_{500})\frac{(Se_{100}+Se_{500})}{2} + \ldots$$

$$\overline{Sa} = 0.25\, Se_1 + 0.4\, Se_2 + 0.2\, Se_5 + 0.08\, Se_{10} + 0.04\, Se_{25} + 0.015\, Se_{50} + 0.009\, Se_{100} + 0.004\, Se_{500}$$

$\overline{Sa}_{Schoharie} = 0.491$ ft/yr $\qquad \overline{Sa}_{Sacramento} = 0.165$ ft/yr

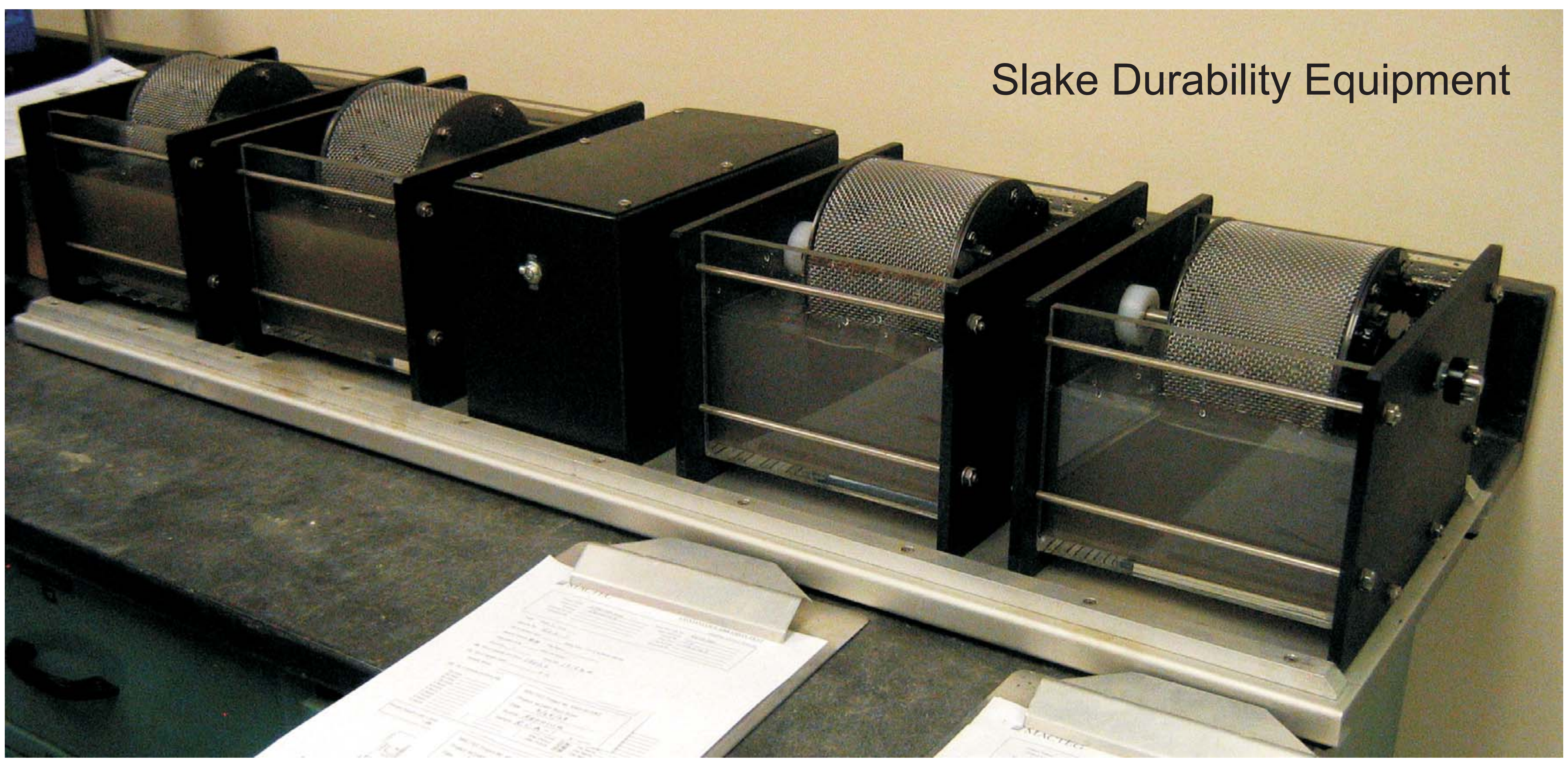
Scour Depth From Repeated Cross Sections

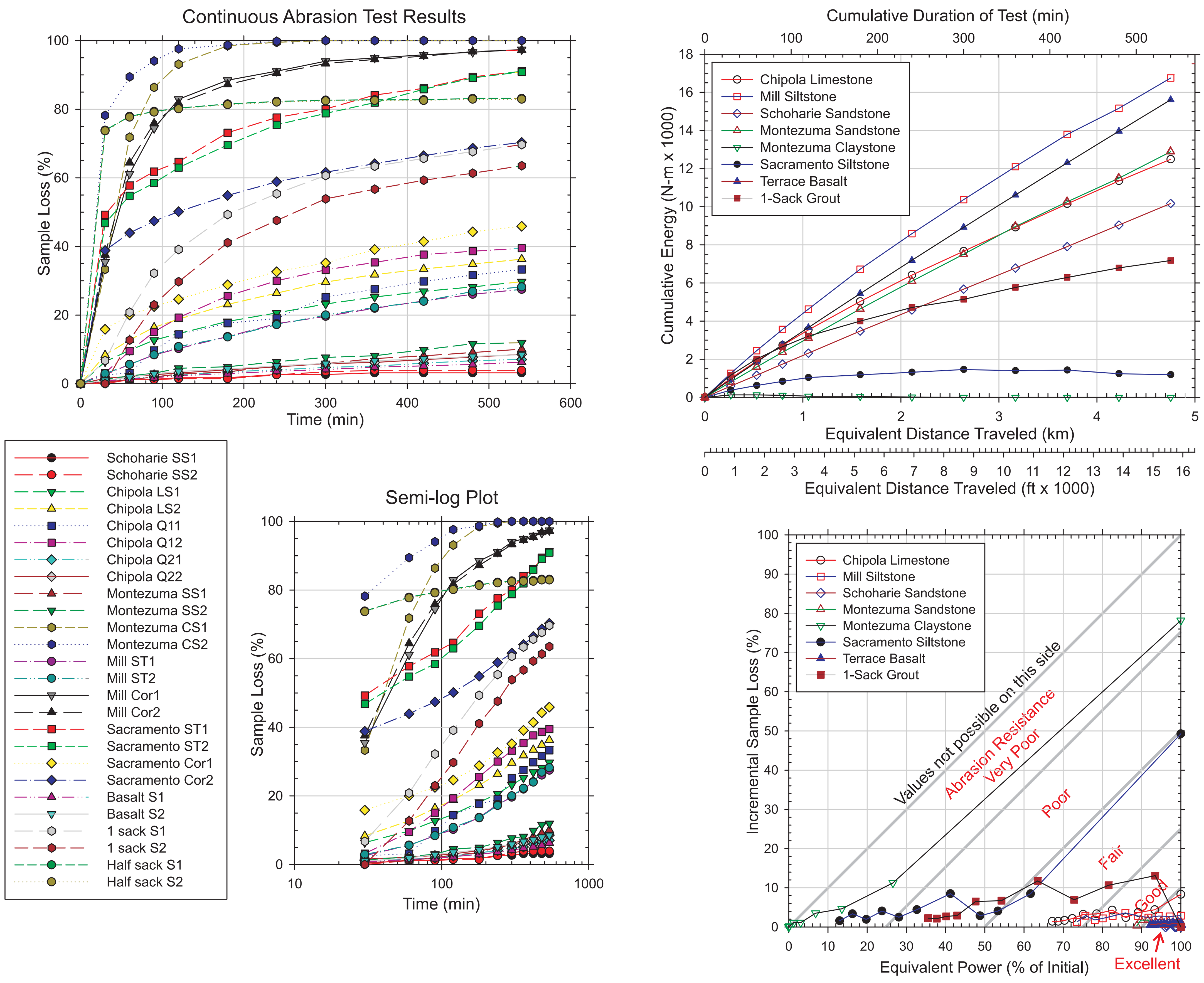
$Sd_{Schoharie} = 15$ ft $\qquad Sd_{Sacramento} = 5$ ft

"Design Scour Depth"

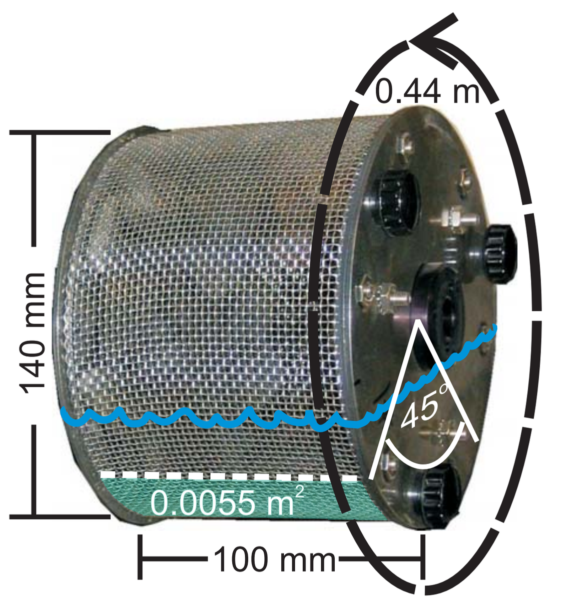
$Sd_{Schoharie} = 0.491$ ft/yr x 33 yr = 16.2 ft $\qquad Sd_{Sacramento} = 0.165$ ft/yr x 33.8 yr = 5.6 ft

$Sd_{Schoharie}$ = 8% overpredicted $\qquad Sd_{Sacramento}$ = 11% overpredicted

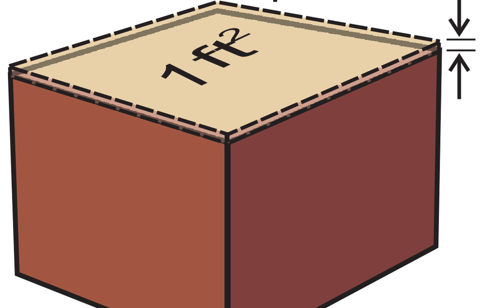




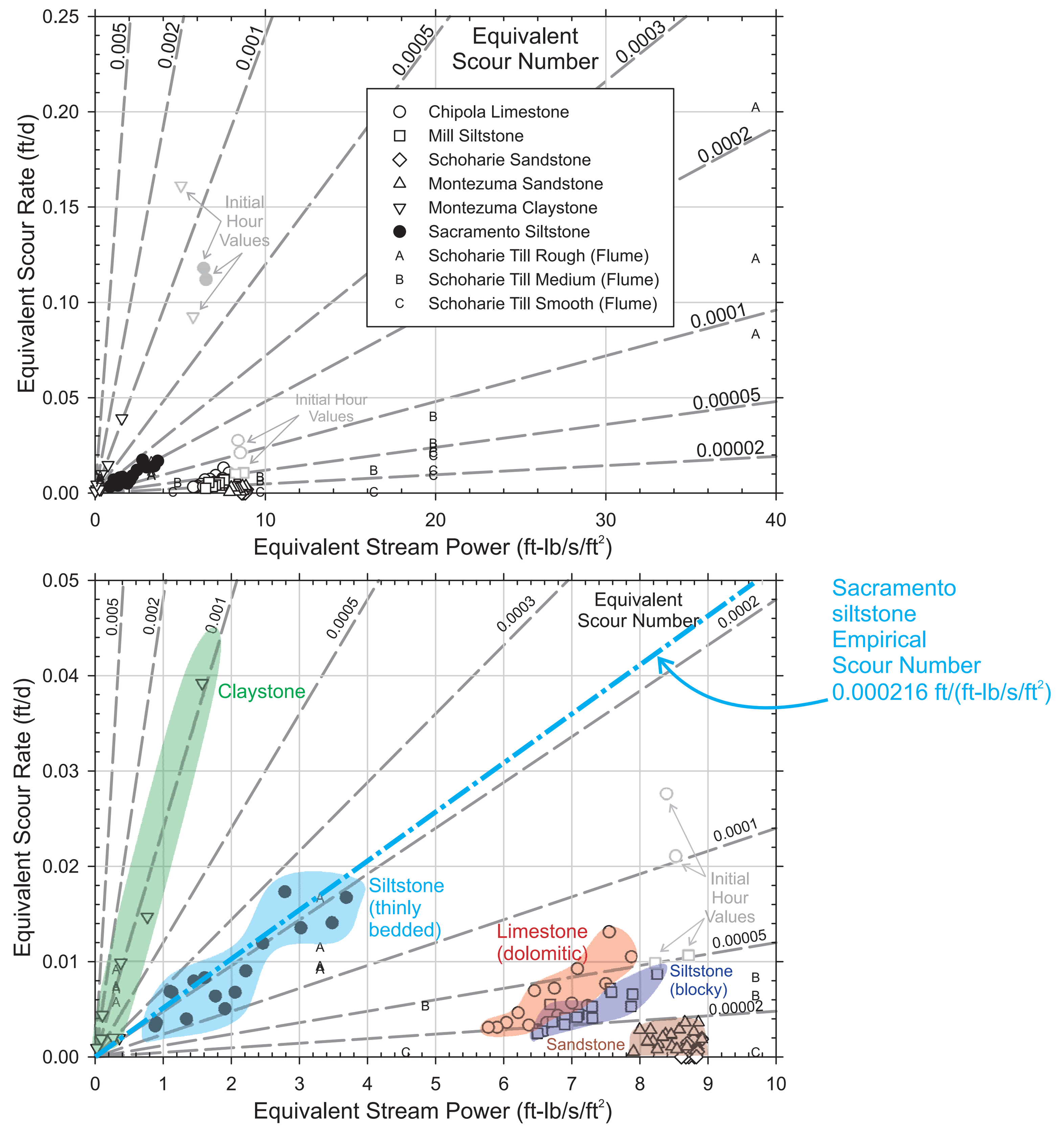
Continuous Abrasion Test Results



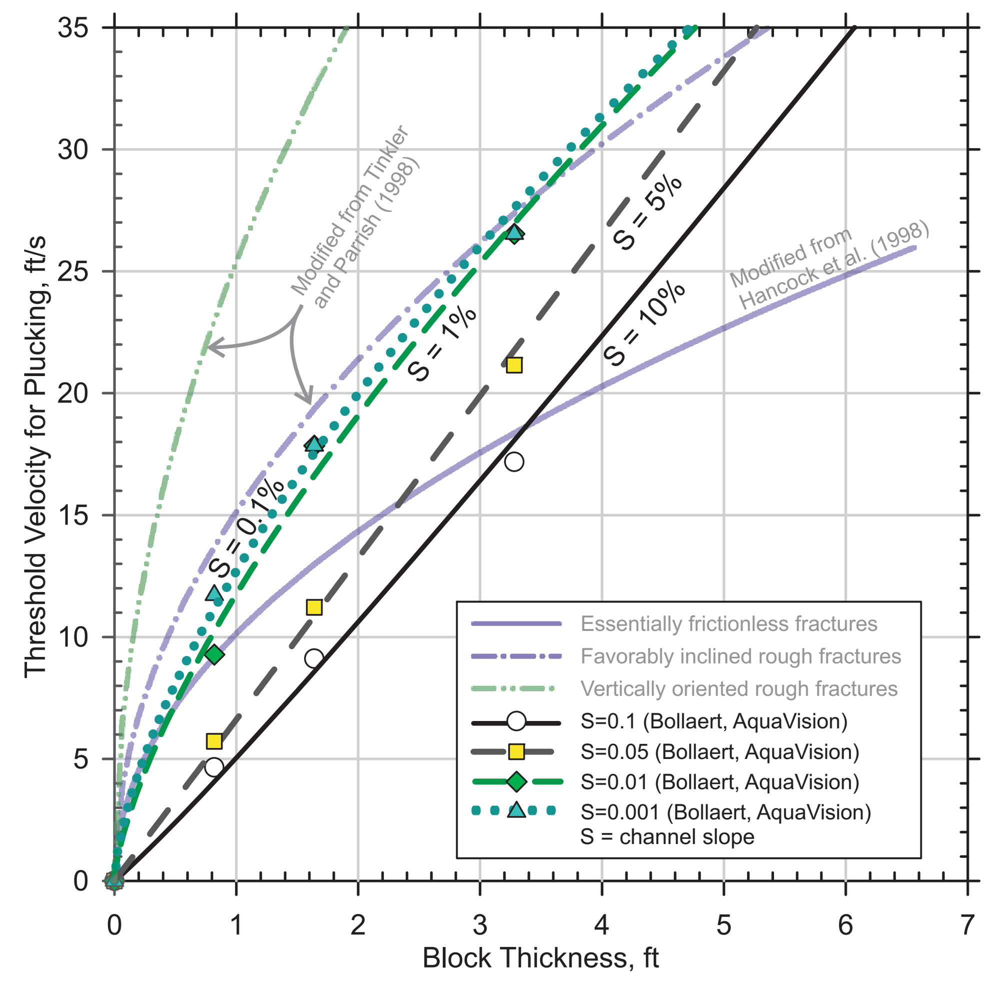
"Scour Depth" from sample loss



Notes:
1. Flume test data from Cornell University reported in Wyss, Janney, Elstner Associates and Mueser Rutledge (1987);
2. Other data points are test values at hourly increments with samples normalized to initial weight of 500 gm;
3. Equivalent scour number calculated from equivalent scour rate times test increment in days divided by equivalent stream power
4. Initial test values are shaded because they reflect wear associated with rounding of sharp edges, whereas later values are comparable sample response



Continuous Abrasion Test Results Expressed as Equivalent Scour Rate and Stream Power



Threshold of Durable Block Plucking
Calculated by Dr. Erik Bollaert,
AquaVision Engineering, Lausanne, Switzerland

Improved Optimization and Visualization of Drilling Directions for Rock Mass Discontinuity Characterization

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Key Terms: Discontinuity, Sampling Bias, Borehole, Directional Drilling, Rock Mass Characterization, Fractured Rock, Jointed Rock, Linear Sampling Bias Index

INTRODUCTION

Characterization of planar discontinuities such as bedding, joints, and faults is an essential element of successful rock engineering. Discontinuities exert considerable influence over the shear strength and permeability of rock masses, which are important considerations in the evaluation of slope or tunnel stability, groundwater flow, and contaminant transport problems in rock. Discontinuities also control *in situ* block sizes that can be important when assessing the adequacy of potential riprap or armor-stone sources, the susceptibility of bridge foundations to scour during floods, and the sizes of rock blocks susceptible to sliding or falling along steep slopes.

The bias introduced by sampling discontinuities along lines and planes has been investigated by such authors as Terzaghi (1965), Kulatilake and Wu (1984), Priest

(1994), Martel (1999), Park and West (2002), and Zhou and Maerz (2002). As shown by Terzaghi (1965), discontinuities separated from boreholes by angles of 30° or less fall into a blind zone and are likely to be statistically under-represented or completely missed in subsurface exploration programs. Subsequent authors confirmed her conclusion while investigating complications such as the effects discontinuities with finite, rather than infinite, extent.

In situations where there is no knowledge of the discontinuities to be encountered during subsurface exploration, the best strategy is to select a combination of different borehole orientations that minimize the chances that the average orientation of any discontinuity set falls into a Terzaghi (1965) blind zone. This is illustrated in Figure 1, which shows a lower hemisphere equal area projection with 30° shadow zones for three inclined boreholes. Discontinuities for which dip-lines (defined by a dip and dip direction, as opposed to a strike and dip) fall into the shadow zone for a particular borehole are unlikely to be encountered in that borehole. Those discontinuities will, however, be encountered in other boreholes as long as the shadow zones do not overlap.

In situations where there exists some *a priori* knowledge of discontinuity orientations, for example from published reports, existing geologic maps, or site reconnaissance, it is possible to use that information to optimize drilling directions. Zhou and Maerz (2002), for example, developed a linear sampling bias index (LSBI) that can be minimized in order to optimize drilling directions. Although the LSBI minimization approach produces correct results, it suffers from some shortcomings that inhibit its utility. First, the approach developed by Zhou and Maerz (2002) treats the two components of discontinuity orientation (strike and dip in their case) separately by using projections onto horizontal and vertical planes. Thus, two graphs are required to represent the degree of bias associated with different borehole orientations, and users must interpret the meaning of minima in the two graphs in terms of a non-standard set of sign conventions. In particular, they allow dip angles to range across an entire hemisphere from 0° to 180° rather than the 0° to 90° customary in geology. Second, the LSBI proposed by Zhou and Maerz (2002) is based upon the reciprocal of the sine of the separation angle between a hypothetical borehole and a discontinuity. The advantage of a reciprocal approach is that it strongly penalizes the most unfavorable borehole orientations when optimizing the drilling direction. The disadvantage is that as the denominator approaches zero—as it does when the borehole and discontinuities are nearly parallel—the LSBI grows asymptotically large and, in the limit, becomes non-numeric. This makes it difficult to numerically evaluate and graph the results without truncating the LSBI function. Third, the strike-and-dip based formulation of Zhou and Maerz (2002) does not work for horizontal planes because the strike angle is undefined, and they suggest that horizontal discontinuities be disregarded when optimizing the drilling direction. Fourth, the LSBI of Zhou and Maerz (2002) is unit-less and its geometric significance can therefore be difficult to comprehend.

This technical note presents a method that builds upon the approach taken by Zhou and Maerz (2002) by incorporating changes that make it potentially more useful and geometrically meaningful. The new method treats both orientation components simultaneously using a measure akin to the standard deviation of the angles between a potential borehole orientation and the lower hemisphere poles to discontinuities to calculate a linear sampling angular deviation (LSAD). Thus, the results can be shown in a single graph (either in Cartesian coordinates or a lower hemisphere projection) with physically meaningful units of ±degrees, do not become asymptotically large or non-numeric, and penalize the most unfavorable orientations by summing the squares of angular deviations.

THEORY

The direction cosines or unit vector components of a borehole described by plunge δ_b and azimuth θ_b are (*e.g.*, Priest, 1994; Pollard and Fletcher, 2005)

$$\mathbf{b} = \begin{Bmatrix} b_x \\ b_y \\ b_z \end{Bmatrix} = \begin{Bmatrix} \cos\delta_b \, \sin\theta_b \\ \cos\delta_b \, \cos\theta_b \\ -\sin\delta_b \end{Bmatrix} \tag{1}$$

In this note, the *z*-axis is taken to be positive upwards; hence, a downward directed borehole has a negative *z* component. The direction cosines for the lower hemisphere pole to a discontinuity with dip δ_d and dip direction θ_d are, in comparison,

$$\mathbf{d} = \begin{Bmatrix} d_x \\ d_y \\ d_z \end{Bmatrix} = -\begin{Bmatrix} \sin\delta_d \, \sin\theta_d \\ \sin\delta_d \, \cos\theta_d \\ \cos\delta_d \end{Bmatrix} \tag{2}$$

Because real discontinuities are never perfectly parallel, the values used in practice will most likely be vector means calculated for each set (*e.g.*, Cronin, 2008), which the practitioner should ensure are representative of the data. The angle α between unit vectors **b** and **d** is, from basic vector analysis, given by the dot product of the two vectors (*cf.*, Zhou and Maerz, 2002)

$$\cos\alpha = \mathbf{b} \cdot \mathbf{d} = b_x d_x + b_y d_y + b_z d_z \tag{3}$$

Borehole sampling bias is minimized when the borehole is normal to a discontinuity (Terzaghi, 1965; Zhou and Maerz, 2002), in which case the borehole and pole coincide and $\alpha = 0$. Vertical planes require special consideration because the concepts of downward- and upward-directed poles become meaningless. For vertical discontinuities, equation (3) should be evaluated using both **d** and –**d** and the smaller of the two α-values retained.

Estimation of the optimal drilling direction in a situation where several discontinuity sets exists requires that some measure of angular dispersion of discontinuity sets around the borehole be minimized. One such angular measure is the normalized sum of the squared angular differences between the borehole and the poles to $i = 1 \ldots n$ discontinuity sets, which is (*cf.* Zhou and Maerz, 2002)

$$\sigma_\alpha^2 = \frac{1}{n} \sum_{i=1}^{n} \arccos\left(\mathbf{b} \cdot \mathbf{d}_i\right) \tag{4}$$

in which $\mathbf{d}_i$ contains the direction cosines for the ith of n discontinuity sets. Equation (4) is similar in form to the angular variance of vectors with respect to their mean (Borradaile, 2003) and has units of degrees or radians squared depending on the input units. Taking the square root of equation (4) yields a quantity analogous to an angular standard deviation, which has units of degrees or radians and is therefore a physically sensible measure of dispersion that is likely to be conceptually familiar to most users. The standard deviation-like measure is herein named the linear sampling angular deviation (LSAD). The optimum drilling direction is found by either plotting σ_α over the ranges $0° \leq \delta \leq 90°$ and $0° \leq \theta < 360°$ and visually identifying minima or, in simple cases, using a mathematical minimization algorithm.

Plotting the results in Cartesian coordinates is straightforward. One simply evaluates equation (4) on a grid ranging over $0° \leq \theta_b < 360°$ and $0° \leq \delta_b < 90°$ using whatever computational software is convenient (converting the angles to radians if necessary), takes the square root of the results, and contours them. Mapping results onto a spherical projection, in this case an equal area projection, requires additional effort. One solution is to establish a Cartesian grid ranging over $-1 \leq x \leq 1$ and $-1 \leq y \leq 1$, then calculate the plunge and azimuth of each point on the grid for which $x^2 + y^2 \leq 1$ using the expressions

$$
\begin{aligned}
r &= \sqrt{x^2 + y^2} \\
\delta_b &= \tfrac{1}{2}\left[180° - 4\arcsin\left(r/\sqrt{2}\right)\right] \\
\theta_b &= 90° - \arctan\left(y/x\right)
\end{aligned}
\qquad (5\text{ a, b, c})
$$

For each calculated plunge and azimuth pair, calculate a σ_α value using equation (4) and contour the results. The examples shown in this paper were produced using a series of functions written for the computer program Mathematica (Haneberg, 2004) , which are available from the author.

Numerical algorithms may also be used to find LSAD minima; however, they should always be used with caution. Users should take care to understand whether the algorithm is intended to find global or local minima, and also that not all minima may be found if more than one minimum exists. If a minimization algorithm is to be used, the recommended approach is to graphically estimate the location of each minimum in terms of δ_b and θ_b using a Cartesian plot or spherical projection, and then quantitatively search for local minima using that estimate as a starting point with the constraints $0° \leq \theta_b < 360°$ and $0° \leq \delta_b < 90°$.

EXAMPLES

The application of equation (4) to estimate optimal drilling directions can be illustrated using several simple examples involving one, two, three, and seven discontinuity sets.

One Discontinuity Set.– The most straightforward example involves a single discontinuity set. Although the solution is trivial, it serves to illustrate and verify the approach. Figures 2 and 3 show the LSAD plotted in Cartesian coordinates and on a lower hemisphere equal area projection, respectively, for a single discontinuity set with a dip/dipline of 45°/045°. In both cases, the LSAD minimum of $\sigma_\alpha = 0$ occurs for borehole with a plunge/azimuth of 45°/225°, which is also the lower hemisphere pole to the discontinuity set.

Two Discontinuity Sets.— This example uses the same orientations as the two discontinuity set example in Zhou and Maerz (2002), one horizontal set and one vertical set striking north-south. The results, illustrated in Figures 4 and 5, show that two LSAD minima at 45°/090° and 45°/270° arise as consequence of the vertical set. Because the two LSAD minima are equal in value, drilling in either of those directions should produce statistically identical results. A vertical borehole, which is the default choice in many geotechnical exploration programs, would result in an LSAD value of $60° < \sigma_\alpha < 65°$ compared to the LSAD minimum values of $\sigma_\alpha = 45°$.

Three Discontinuity Sets.— A third example involves three sets of mutually orthogonal discontinuities, one horizontal and two vertical, as are typically present in flat lying sedimentary rocks that have been subjected to minor deformation. The example discontinuity sets have orientations of 0°/000°, 90°/000°, and 90°/090°. As shown in Figures 6 and 7, the two sets of vertical discontinuities give rise to four LSAD minima with σ_α = ±54.7° at borehole orientations of 35°/045°, 35°/135°, 35°/225°, and 35°/315°. Because LSAD the minima are equal in value, boreholes in each of the four directions should yield similar results and, in practice, only one of the directions would need to be chosen. The existence of two sets of vertical discontinuities further compounds the sampling bias that would be introduced by choosing vertical boreholes, which would completely ignore two of the three discontinuity sets and in this case produce LSAD values in the range of $70° < \sigma_\alpha < 75°$ compared to the minima of σ_α = 54.7°. Small LSAD maxima also exist for borehole orientations of 00°/000°, 00°/090°, 00°/180°, and 00°/270°.

Seven Discontinuity Sets.— Zhou and Maerz (2002) included in their paper a real data set consisting of the average dips and dip directions of seven discontinuity sets encountered along a 58 m (190 ft) long borehole in fractured argillite. LSAD contour plots in Figures 8 and 9 show a minimum centered approximately about a vertical borehole orientation. Figure 9 also includes the poles to the seven discontinuity sets, illustrating that the LSAD minimum is close to the centroid of the pole locations. In other words, minimizing the LSAD is a process akin to determining the borehole orientation that is simultaneously as parallel as possible all of the discontinuity poles. The graphical estimate of a nearly vertical borehole was further refined using the FindMinimum function in the computer program Mathematica, which yielded a minimum LSAD value of $\sigma_\alpha < 42.3°$ for a vertical borehole. This compares to the optimal orientation of approximately 86°/140° estimated graphically by Zhou and Maerz (2002) and converted to the standard geologic sign conventions used in this note. Thus, the optimal directions predicted by the two methods differ by only 4° (Figure 9).

SUMMARY

The linear sampling angular dispersion (LSAD) approach described in this note provides a method to optimize drilling directions for geotechnical exploration programs in cases where there is *a priori* knowledge of discontinuity orientations. By using a measure of angular dispersion that simultaneously considers both dip and dip direction, does not become asymptotic or non-numerical, and is quantified using geometrically sensible units, the LSAD method builds upon and increases the utility of concepts developed by such authors as Zhou and Maerz (2002). Contouring LSAD values, either in Cartesian coordinates or on a lower hemisphere projection, allows optimal drilling directions corresponding to LSAD minima to be easily visualized and exploited when planning geotechnical exploration programs.

If more than one LSAD minimum exists, drilling in any of the directions defined by the minima should yield statistically similar results. Thus, the choice of drilling direction among multiple minima can be dictated by secondary constraints such as drilling rig accessibility or site topography. The use of contour plots also helps to identify secondarily favorable orientations in the event that project details prevent drilling in directions defined by the minima. Just as importantly, the contour plots can help to identify the most unfavorable directions that should be avoided. For example, Figures 6 and 7 show that in the case of two vertical and one horizontal discontinuity set, a vertical borehole—which is the default orientation for most geotechnical exploration programs—

would be the worst possible choice. In the case of one horizontal and one vertical set, Figures 4 and 5 show that a vertical borehole would be far from optimal but not the worst choice (the worst choice would be a horizontal borehole parallel to both of the discontinuity sets, which would intersect neither set). It must also be remembered that if more than one set of discontinuities exists, optimization relative to all of the sets is always a form of compromise. In some situations it may be prudent to avoid compromises and plan the drilling program with a variety of orientations each optimized to the orientation of a single discontinuity set.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1. Lower hemisphere equal area plot illustrating a drilling strategy as outlined by Terzaghi (1965) for situations in which discontinuity orientation is unknown. The black dots represent boreholes and the gray circles represent 30° cones defining the shadow zone around each borehole.

Figure 2. Cartesian contour plot of LSAD for a single discontinuity set with 45°/045°, with a single minimum at 45°/225°. The contour interval is 10°.

Figure 3. Lower hemisphere equal area contour plot of LSAD for a single discontinuity set with 45°/045°, with a single minimum at 45°/225°. The contour interval is 10°.

Figure 4. Cartesian contour plot of LSAD for two discontinuity sets: one horizontal (00°/000°) and one vertical with a north-south strike (90°/90°). This configuration produces two minima at 45°/090° and 45°/270°. The contour interval is 5°.

Figure 5. Lower hemisphere equal area contour plot of LSAD for two discontinuity sets: one horizontal (00°/000°) and one vertical with a north-south strike (90°/90°). This configuration produces two minima at 45°/090° and 45°/270°. The contour interval is 5°.

Figure 6. Cartesian contour plot of LSAD for three discontinuity sets: one horizontal (00°/000°), one vertical with a north-south strike (90°/90°), and one vertical with an east-

west strike (00°/000°). This configuration produces four minima at 35°/045°, 35°/135°, 35°/225°, and 35°/315°. The contour interval is 5°.

Figure 7. Lower hemisphere equal area contour plot of LSAD for three discontinuity sets: one horizontal (00°/000°), one vertical with a north-south strike (90°/90°), and one vertical with an east-west strike (00°/000°). This configuration produces four minima at 35°/045°, 35°/135°, 35°/225°, and 35°/315°. The contour interval is 5°.

Figure 8. Cartesian contour plot of LSAD for the seven discontinuity sets used by Zhou and Maerz (2002), which shows a single minimum for a vertical borehole. Contour interval is 1°.

Figure 9. Lower hemisphere equal area contour plot of LSAD for the seven discontinuity sets used by Zhou and Maerz (2002), which shows a single minimum for a vertical borehole. The gray circles are the poles to the seven discontinuity sets, the black circle is the optimal orientation predicted using the LSAD approach described in this note, and the open circle is the optimal orientation predicted using the LSBI method by Zhou and Maerz (2002). The contour interval is 2°.

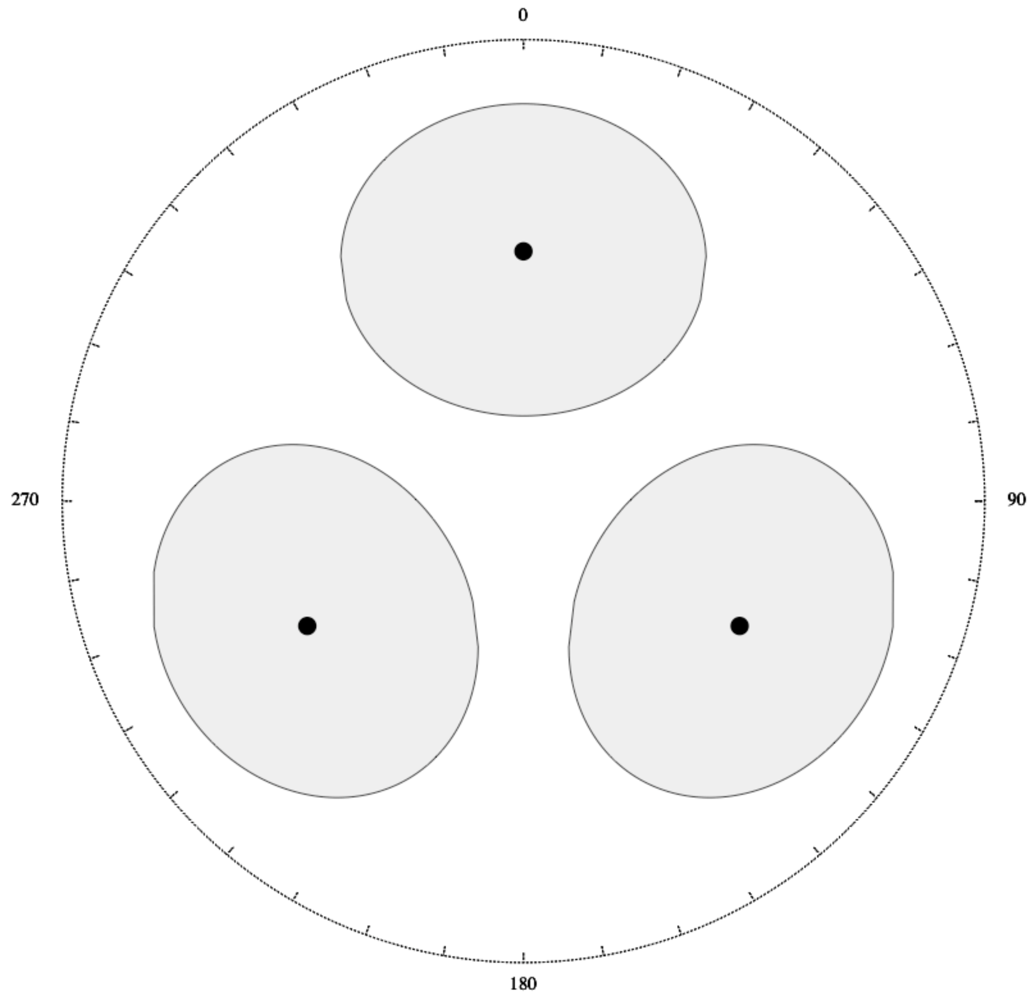
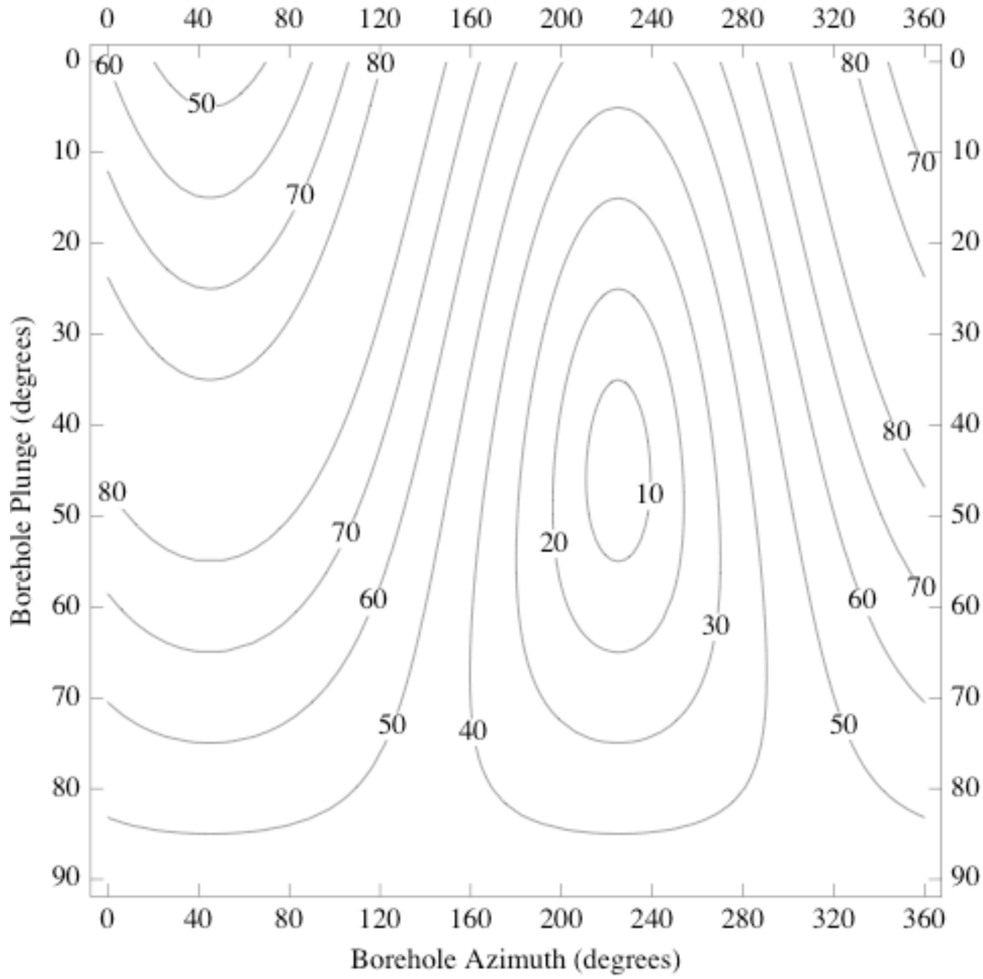


Figure 1


Borehole Plunge (degrees)
Borehole Azimuth (degrees)
0 40 80 120 160 200 240 280 320 360
0 10 20 30 40 50 60 70 80 90
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50

Figure 2

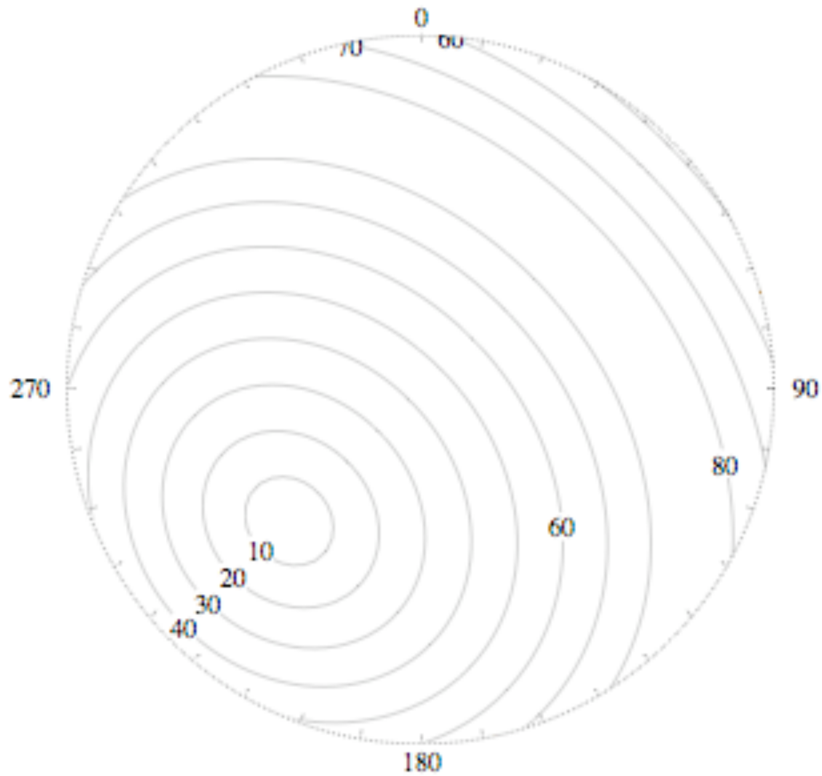


Figure 3

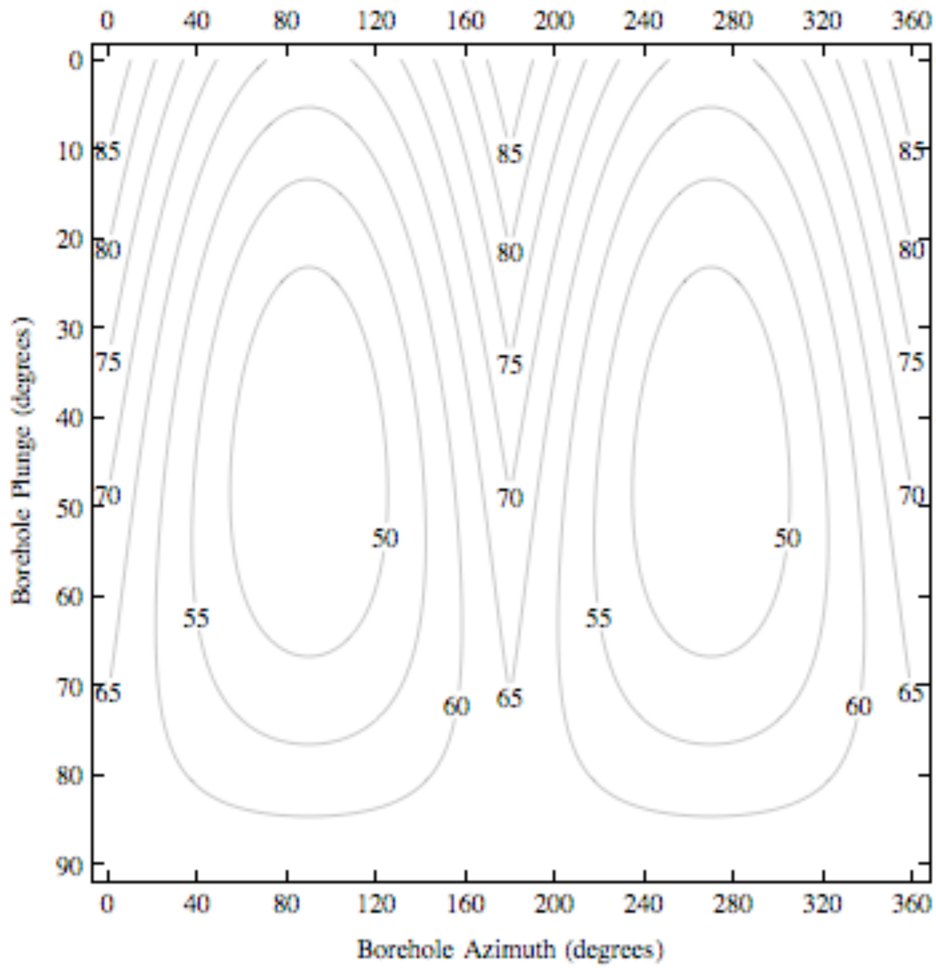

0 40 80 120 160 200 240 280 320 360
Borehole Plunge (degrees)
0 10 20 30 40 50 60 70 80 90
85 80 75 70 65
85 80 75 70 65
85 80 75 70 65
50 55 60
50 55 60
Borehole Azimuth (degrees)

Figure 4

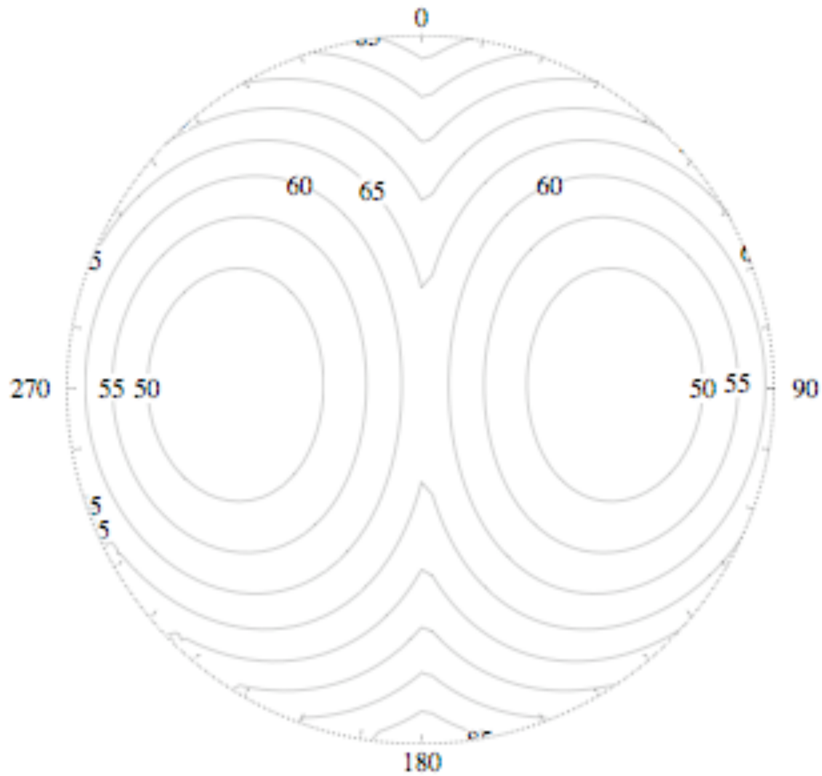
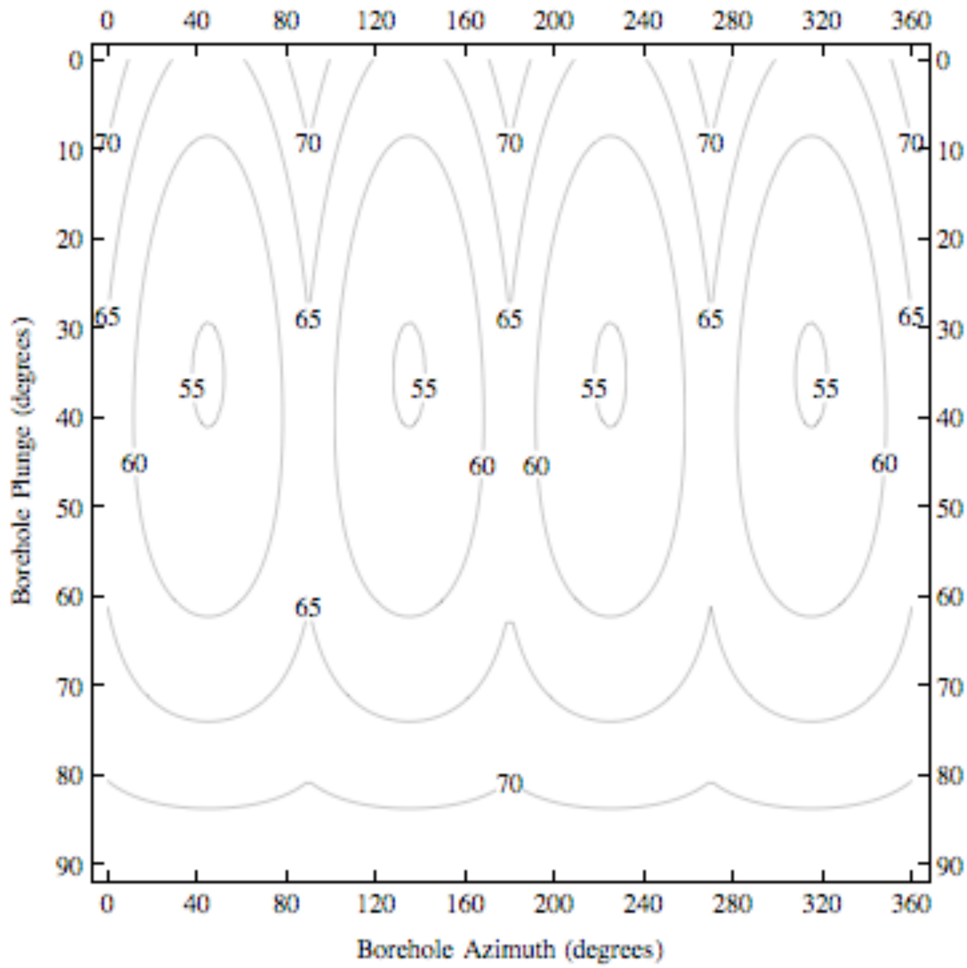


Figure 5


0
40
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Borehole Plunge (degrees)
Borehole Azimuth (degrees)
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Figure 6

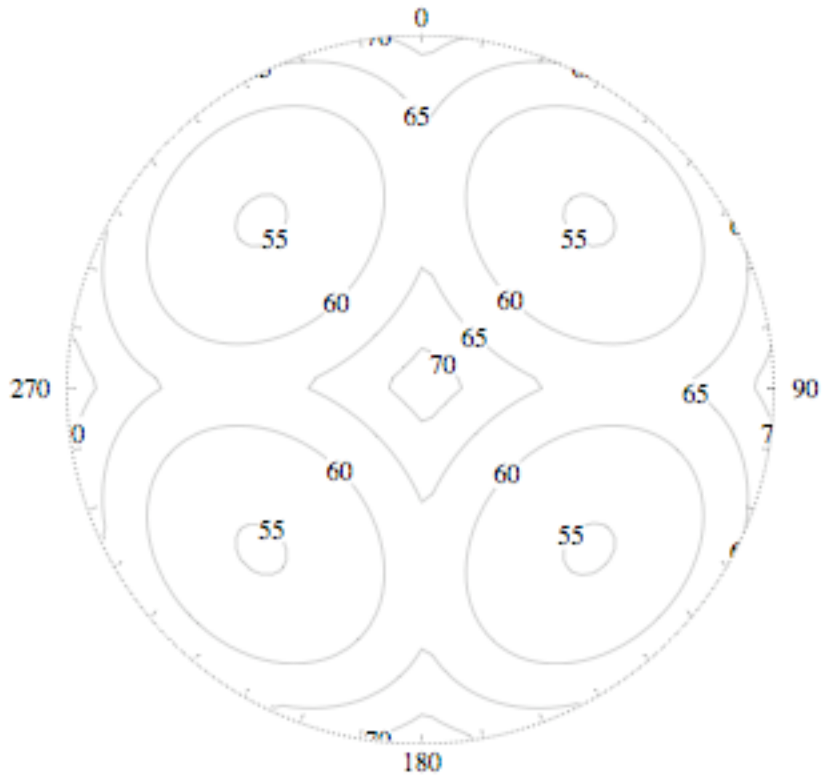
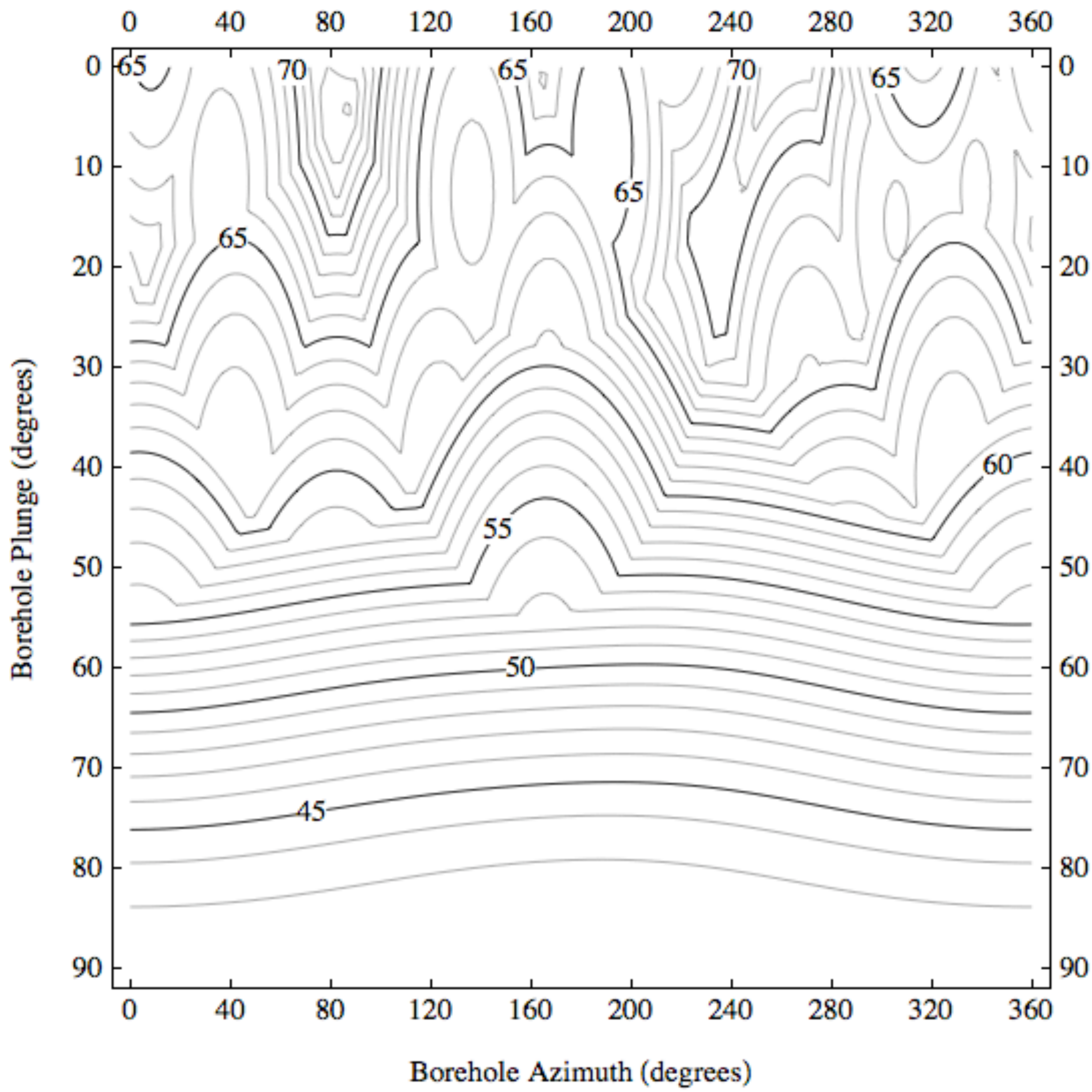


Figure 7


Borehole Plunge (degrees)
Borehole Azimuth (degrees)
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40
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Figure 8

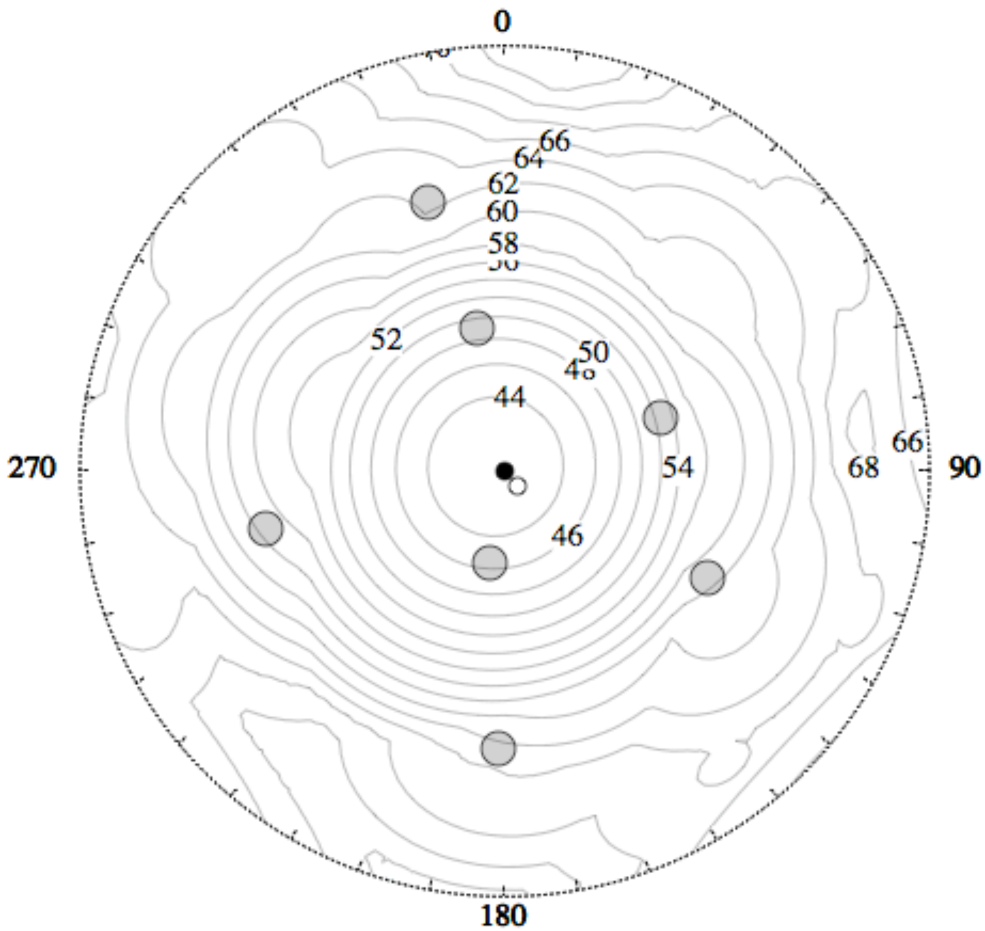

Figure 9

IN SITU BLOCK SIZE AND REPRESENTATIVE DISCONTINUITY SET ORIENTATION CALCULATION FOR SCOUR SUSCEPTIBILITY ESTIMATION

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Introduction

Estimation of in situ rock block sizes and average orientations for scour susceptibility evaluation requires the collection and analysis of 3-D rock mass discontinuity data. In some cases surface data can be collected from outcrops—for example, exposures along riverbanks and in channels during times of low flow. In most cases, however, block size estimation will require the practitioner to work with borehole data that will always provide an incomplete, and in some cases biased, representation of actual geologic conditions. Estimation of block size would require simplifying assumptions even if the supporting data were complete. Applying simplifying assumptions to incomplete data compounds the uncertainties involved in the process. Thus, it is imperative that sound geologic insight be used when designing geotechnical exploration programs and interpreting their results.

Although there is commercial software available that will estimate block sizes from discontinuity data using sophisticated approaches such as stochastic simulation of discrete fracture networks, for example as described by Rogers et al (2007), it is expensive, highly specialized, not likely to be available to geologists or geotechnical engineers engaged in typical bridge scour evaluations. The method described in this section is an adaptation of published analytical and empirical methods that can be applied using simple graphical and/or computational tools available to most practicing geologists. It assumes a working knowledge of structural geology stereographic projection techniques as described in, for example, Marshak and Mitra (1988) or Lisle and Leyshon (2004). Hemispherical projection techniques (this document uses equal area rather than stereographic projections) discussed in this section can generally be implemented using various commercial computer programs that are well known among practicing geologists and geological engineers. No particular program is recommended or endorsed here,but most of the examples in this appendix were created using a suite of freely available add-on functions for the commercial computational software Mathematica (version 7).

Site Geologic Model

Borings should not be planned or made without first developing a conceptual geologic model of the site, and should never be relied upon as the sole means of inferring geologic conditions at any site. There may be non-geologic factors that limit boring locations, for example inadequate drilling rig access or property restrictions. Insofar as possible, however, borings should be make in locations and directions chosen to most effectively validate or refine the conceptual geologic model rather than on a uniform grid or line generated without consideration of the site geology. Attempts to elucidate the site geology on the basis of borings alone constitute poor practice and should be avoided.

The conceptual geologic model can be textual or graphical, but in either case must include information about anticipated rock and soil types as well as discontinuities relevant to scour calculations. Examples of simple textual conceptual models include "Flat lying interbedded sandstone and shale with two orthogonal sets of nearly vertical joints and well-defined inter-formational contacts" and "Granitic gneiss with multiple generations of folds, non-systematic joints, and small faults dipping about 30° with displacements on the order of several feet and a consistent strike of 045°." Graphical conceptual site models consist of interpretive geologic cross sections or block diagrams that convey the same kinds of information as textual conceptual models. Sources of information for conceptual geologic models include published or open-file geologic maps and reports, state geological survey libraries and core repositories, field reconnaissance, and local experience.

The anticipated orientations of discontinuities such as joints, faults, and bedding planes are a critical component of conceptual geologic models because they are necessary to assess the adequacy of boreholes for design-level site characterization. Reliance on vertical borings without ancillary information can, depending on the geology of the site, produce results that range from biased to completely unrepresentative of actual subsurface conditions.

If bedrock exposures are available at the site or nearby, for example in road cuts or riverbanks, their rock type(s), stratigraphic sequence, and structural geology should be described and discontinuity orientations measured, and the results incorporated into the site conceptual model. As many nearby exposures as practical should be described in order to adequately characterize the spatial variability of discontinuity orientations.

INDIVIDUAL DISCONTINUITY PROPERTIES

Individual discontinuities encountered in cores should be described using standard nomenclature (ISRM, 1978; USBR, 2001; Priest, 1993) and as outlined below.

Discontinuity Type

To the extent that it can be determined from the cores or outcrops, the type of discontinuity should be identified. Common discontinuity types include joints (cracks with little or no shear displacement), faults (cracks with appreciable shear displacement), and depositional contacts between different rock types (for example, bedding planes or unconformities). The relatively small diameter of most cores makes it difficult to positively identify faults unless they juxtapose two different rock types; however, in some cases faults can be tentatively distinguished by the presence of sheared fault gouge or breccia even if they do not separate different rock types (see Filling). In areas underlain by folded or thrust faulted sedimentary rocks, shearing can occur along bedding planes to produce bedding plane faults. In some cases, bedding plane faults can be distinguished from un-faulted bedding planes by the presence of sheared gouge, slickensides, and/or mechanical separation.

It is important to distinguish discontinuities of geologic origin from those created by coring (Kulander et al, 1990). In general, coring induced fractures will have fresh and unaltered (or unweathered) surfaces with no fracture filling. These indications are not unambiguous and it is possible that geologically induced fractures may share some of the same properties. Coring induced fractures should be oriented parallel to the maximum compressive stress at the project site. In deep drilling, therefore, knowledge of regional stress orientations can help to distinguish coring induced fractures. The shallow depth of geotechnical boreholes relative to topographic features such as river valleys perturb regional stress fields and can make it difficult to make inferences about the local state of stress from regional data (e.g., Haneberg, 1999). Therefore, regional stress maps should not be relied upon to identify coring-induced discontinuities.

Discontinuity Filling

The nature and consistency of any material preserved along discontinuities should be described. In particular, is the filling soft material such as clayey fault gouge that might be eroded or hard crystalline material such as calcite or quartz that is likely to be resistant to erosion if submerged in flowing water?

Discontinuity Aperture

It is generally impossible to measure the aperture of discontinuities in cores unless they are filled by calcite, quartz, or other cementing agents that hold the rock together during core extraction and handling. It may be possible to measure *in situ* apertures of discontinuities in nearby outcrops or, if the apertures are large, on borehole televiewer logs. Care should be taken when measuring discontinuity apertures in outcrop because the apertures may have been widened by weathering. Aperture should always be measured perpendicular to the discontinuity walls, which may be difficult in outcrops.

Discontinuity Roughness

The area of discontinuity surface available for roughness estimation will depend on the orientation of the discontinuity relative to the core. Horizontal or nearly horizontal discontinuities will present only a small cross sectional area in a vertical core. Steeply dipping discontinuities, however, may present large cross sectional areas adequate for roughness profiles over short distances. In those cases, standard measures such as the joint roughness coefficient (*JRC*) or asperity angle (*i*) should be used (Barton and Choubey, 1977; Patton, 1966).

Discontinuity Orientation

The true orientations of discontinuities can be measured in oriented cores (only the dip magnitude can be measured in un-oriented cores), in borehole televiewer logs, and in outcrops. If the core is vertical, the dip of a discontinuity measured relative to the core axis will be its true dip but its dip direction is unknown unless the core is oriented. Dip direction can be estimated using stereographic projections, however, if the same discontinuity can be identified in three or more boreholes with different orientations. If the core is not vertical, the dip will be relative unless it is corrected to true dip using information about core orientation. For the methods of block size estimation outlined in this section, it is imperative to obtain true dip angle and dip direction measurements using oriented cores, borehole televiewer logs, or outcrops.

The orientation of an individual discontinuity can be specified using strike and dip angle, dip angle and dip direction (also known as the dip vector orientation), or the plunge and azimuth of the pole to the discontinuity (Table 1). Because strike is the bi-directional line of intersection between a dipping plane and an imaginary horizontal plane, and the dip angle contains no information about dip direction, strike and dip measurements must include information to specify the dip direction. It can therefore be convenient to use the so-called right-hand notation to specify strikes and dip angles, in which the dip direction is always 90° clockwise from the strike direction and therefore unambiguous. The disadvantage of right-hand notation is that it requires the strike direction to be calculated either in the field or the office, which is a potential source of error.

An alternative to strike and dip, which is preferred by some practitioners, is to avoid the use of strike and dip notation and instead express discontinuity orientation in terms of a single unambiguous vector defined by the dip angle and the dip direction, also known as the dip vector. In terms of traditional structural geology nomenclature, the dip and dip direction are the plunge and azimuth of a line defining the true or maximum dip of a plane. Thus, dip vector data are plotted and analyzed as lines rather than planes.

Strike can be described using either a compass quadrant bearing (e.g., N30°E) or an azimuth (e.g., 030°), although non-numerical compass quadrants data can pose problems for computer programs and should be avoided. Azimuths, which can range from 0° to 360°, are conventionally written using three digits with a leading zero if necessary. Dip angles, which can range from 0° to 90°, are conventionally written using two digits. The nature of orientations can be further clarified by adopting notation that distinguishes between strike and dip — which consists of partial information about two lines that define a plane— and dip and dip direction — which consist of information about a single line that defines a plane by virtue of its geometric relationship to the plane. One approach, which is used in Table 1, is to signify a strike and dip notation by writing the strike (in either azimuth or compass quadrant bearing) first and separating it from the dip using a dash. A plunge and azimuth, in contrast, can be signified by writing the two-digit plunge first and separating it from the accompanying three-digit azimuth with a forward slash. Other conventions can be used, but they should remain consistent within an organization and clearly defined in project reports, maps, and borehole logs so that the data are useful to others.

Table 1. Alternative notations for the orientation of a discontinuity.

Notation	Orientation
Strike and dip (compass quadrant bearing)	N30°E – 40° NW
Strike and dip (strike azimuth – dip angle)	030° – 40° NW
Right hand rule (strike azimuth – dip angle)	210° – 40°
Dip vector (dip angle / dip direction)	40°/300°
Pole to plane (plunge / azimuth)	50°/120°

Orientation Measurement Using Cores

In core from a vertical borehole, the complement of the dip angle, α, is measured between the borehole axis and the long axis of the ellipse formed by the intersection of a discontinuity and the borehole (Figure 1). The dip angle is $\delta = 90^{\circ} - \alpha$, in which δ is the dip angle and α is the maximum angle between the core axis and the discontinuity plane (i.e., the complement of the dip angle). The relative dip direction, β, is measured clockwise from the reference line (BOC in Figure 1) on the core and rotated as necessary to reference the dip direction to north. This correction can be accomplished either by rotating the discontinuity around a vertical axis on a stereo or equal area net until the orientation line is oriented north, or by simple subtraction. Wrap-around protractors (Holcombe Coughlin & Associates, 20005) can be used to simplify measurement of the relative $\alpha-$ and β–angles of discontinuities in cores, and commercial software is available to aid in oriented core calculations.

For example, if the direction from the core axis to the orientation line is 135°, α = 45°, and β = 60°, the discontinuity dip vector is oriented 45°/195° (Figure 2). This is determined by first plotting a dip vector oriented 45°/090° and then rotating it clockwise β = 60° beyond 135°, to obtain an orientation of 45°/195°.

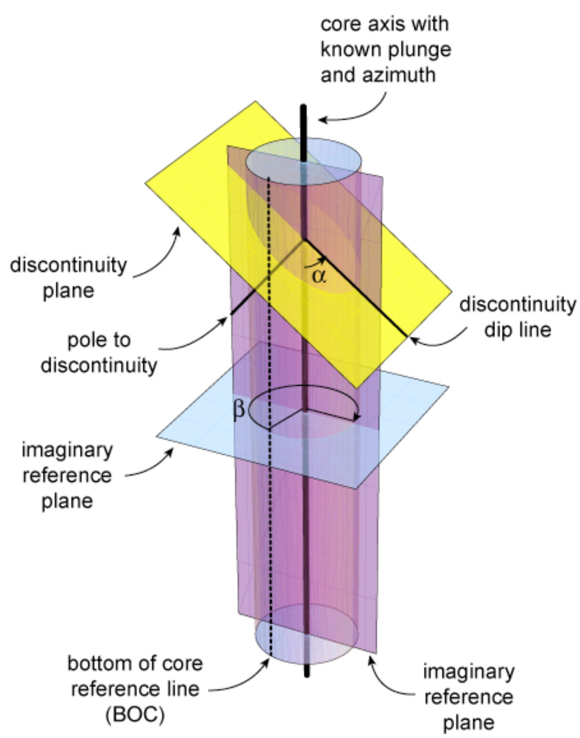

Figure 1. Illustration of variables necessary to calculate the true orientation of a discontinuity intersected by an oriented core.

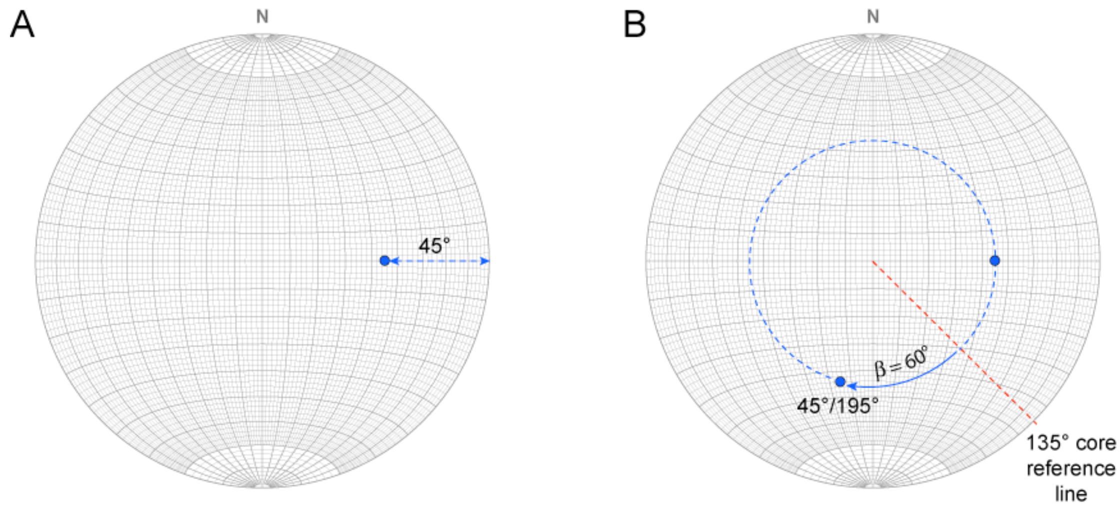

Figure 2. Determination of discontinuity orientation using data from an oriented vertical core with a reference line oriented 135°, $\alpha = 45°$, and $\beta = 60°$

Determination of discontinuity orientations in a non-vertical core is more complicated because two rotations must be performed. The first rotation is around a vertical axis, similar to that performed for a vertical core. The second rotation is around a horizontal axis normal to an imaginary vertical plane containing the core axis (Figure 1). In addition to the α and β angles, the plunge and azimuth of the borehole must be known in order to perform the two rotations. The angle β is conventionally measured clockwise from a bottom of core (BOC) reference line and the α is measured as above.

The steps necessary to determine the orientation of a discontinuity from non-vertical oriented core are illustrated in Figure 3. Majoribanks (1997, Appendix B) describes an alternative method that produces identical results and commercial software is also available. For this example, the borehole axis is oriented 40°/220°, $\alpha = 20°$, and $\beta = 290°$. First, plot the known plunge and bearing of the borehole axis, which is identical to the orientation of the bottom of core (BOC) reference line, on a stereo or equal area net (Figure 3A). Also, plot a vertical plane passing through the borehole axis for future reference. Second, plot the discontinuity dip vector using a relative dip of 90° – α and dip direction β measured clockwise from the borehole azimuth (Figure 3B). Note that β defines the angle between the borehole azimuth and the discontinuity dip direction and not its strike. Also plot the pole to the discontinuity, which at this point has an orientation of 20°/330°, and if desired the great circle arc representing the discontinuity. The great circle arc is not necessary for the calculations but may help with visualization of the problem. Third, rotate the existing lines and planes so that the vertical plane passing through the borehole is oriented east-west (Figure 3C). This will facilitate rotation around a horizontal axis normal to the vertical plane. Perform the rotation by moving the pole to the discontinuity 50° in a clockwise direction along the small circle upon which it lies. The resulting new point is the pole to the rotated discontinuity. Fourth, rotate the existing points and lines so that the new pole (green) falls along the E-W small circle, measure 90° in either direction along the small circle, and plot the resulting point as the dip vector of the rotated plane (Figure 3D). While the points are in the same position, measure the plunge of the dip vector (62° in this case). Fifth, rotate the existing points and lines until the borehole axis is in its original orientation of 40°/220° and measure the dip vector direction and/or strike (Figure 3E). The dip vector orientation of the discontinuity is 62°/128° and the strike and dip, in right-hand notation, is 038°-62°.

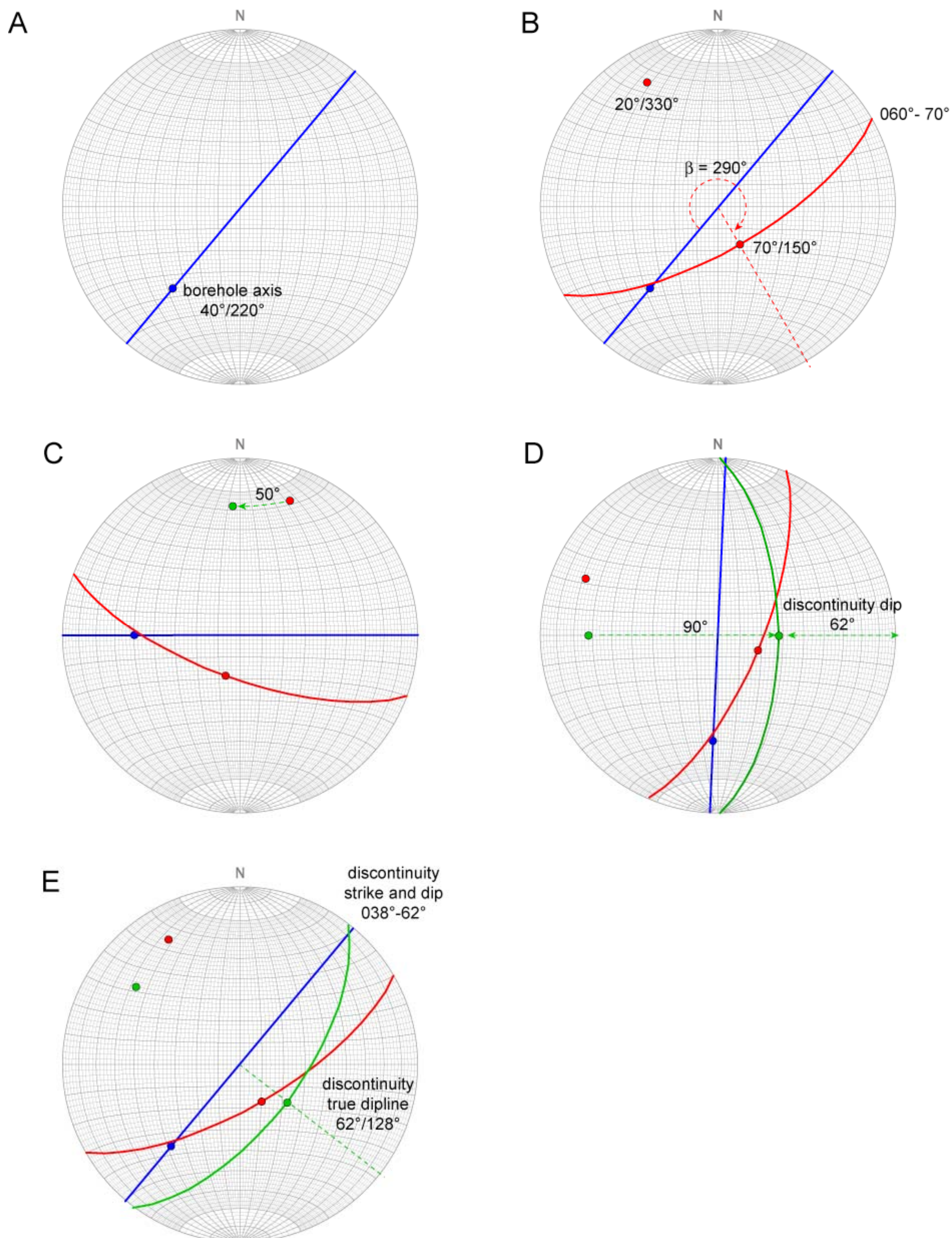

Figure 3. Steps in the determination of discontinuity orientation from a non-vertical oriented core. The core orientation is 40°/220°, $\alpha = 20°$, and $\beta = 290°$.

Orientation Measurement Using Borehole Televiewer Logs

Borehole televiewers provide scaled and oriented images of the borehole wall produced using data from either optical or acoustic instruments. In the case of an optical borehole televiewer, the log is a digital photograph of the borehole wall. In the case of an acoustic borehole televiewer, the shades or colors of the image represent the acoustic impedance of the surrounding rock and not the true colors of the rock. Image processing techniques such as contrast stretching, histogram equalization, and edge detection can be employed to accentuate subtle changes representing changes in rock type, degree of weathering, or discontinuities.

Figure 4 shows a typical acoustic televiewer log with depths indicated in feet. The first graphical column shows a caliper log superimposed on a colored sonic travel time image. Comparison of the travel time colors with the caliper measurement shows that the brighter yellow areas correspond to slightly wider parts of the borehole. The second column is the acoustic televiewer image, which depicts the acoustic impedance of the borehole wall. The sinusoidal features are dipping discontinuities, which form an elliptical trace where they intersect a circular borehole (Figure 5A). When the borehole image is unrolled, the ellipses become sinusoidal curves (Figure 5B) from which the dip angle and dip direction can be easily calculated. The third column contains a tadpole plot in which the dip angle is shown by the horizontal position of the colored dot and the dip direction is shown by the direction of the tail, with north towards the top. The fourth column is a slab plot showing the discontinuities as they would appear in a vertical slice through a core and the fifth column shows the televiewer image as it would appear wrapped around a cast of the borehole (with borehole diameter variations as indicated by the caliper log). In most cases, discontinuities can be identified and their orientations calculated automatically using image processing techniques, which allows large numbers of discontinuity measurements to be quickly generated. It is also possible, however, to manually calculate the orientations of individual discontinuities as shown in Figure 6. The trough of the sine curve is at an azimuth of approximately 152°; hence, this is the dip direction. The dip angle is calculated using the vertical distance between the trough and crest (which is twice the amplitude of the sine curve) and the borehole diameter, which is in this example a standard HX or HQ borehole with a diameter of 3.78 inches. The dip angle is thus

$$\delta = \arctan\left({}^{4.8\text{ inches}}\!\big/_{3.78\text{ inches}} \right) = 52^\circ \qquad (1)$$

This result, 52°/152°, is within a few degrees of the automatically generated orientation for the same discontinuity shown on the tadpole plot in Figure 4. If orientations are measured manually, care must be taken to ensure that the units of measurement are consistent because in the United States the depth scale will be in feet but the borehole diameter will likely be given in inches.

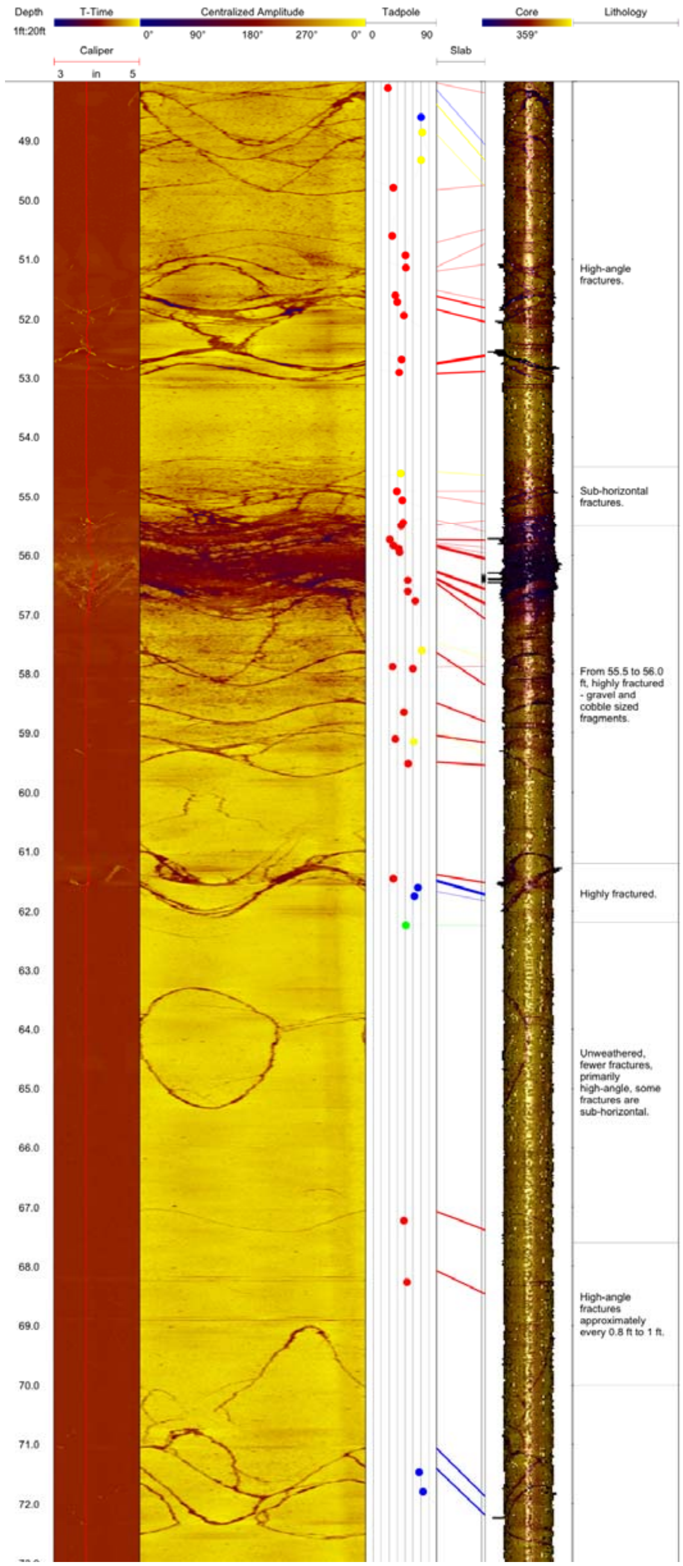

Figure 4. Portion of a typical borehole acoustic televiewer log through discontinuous rock (image courtesy of Pacific Surveys, LLC).

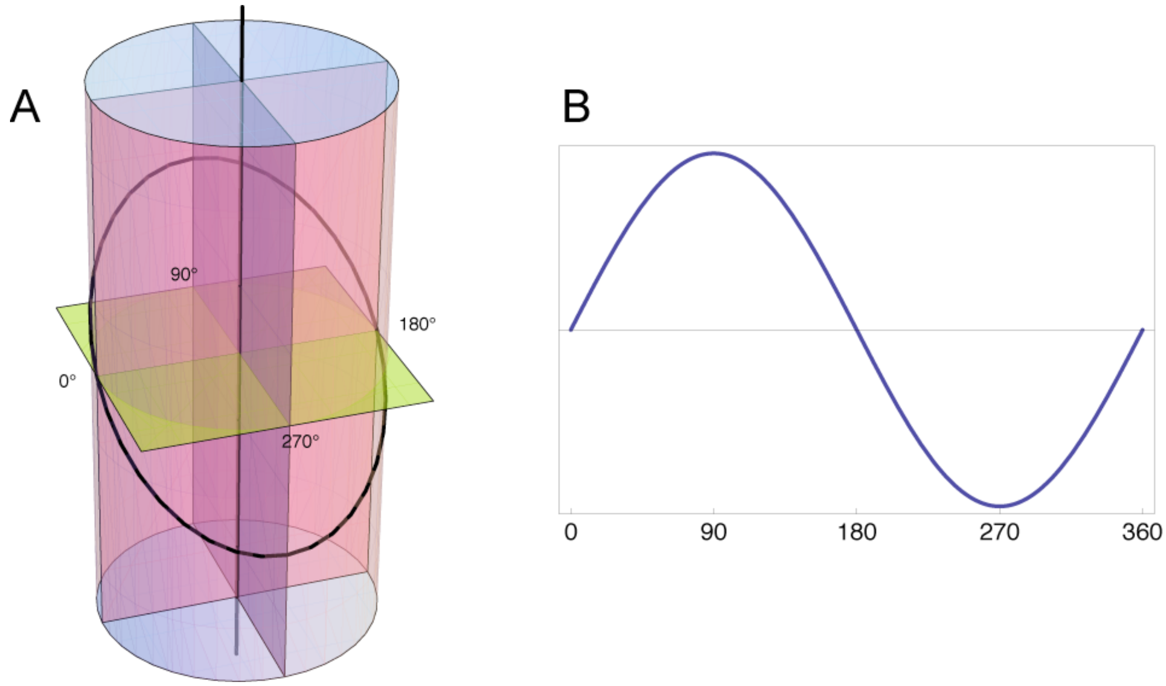

Figure 5. Schematic illustration of an inclined planar discontinuity intersecting a circular borehole. The trace of the borehole-discontinuity intersection is an ellipse in three dimensions, but becomes a sine curve when the borehole televiewer image is unrolled to show the discontinuity elevation as a function of azimuth.

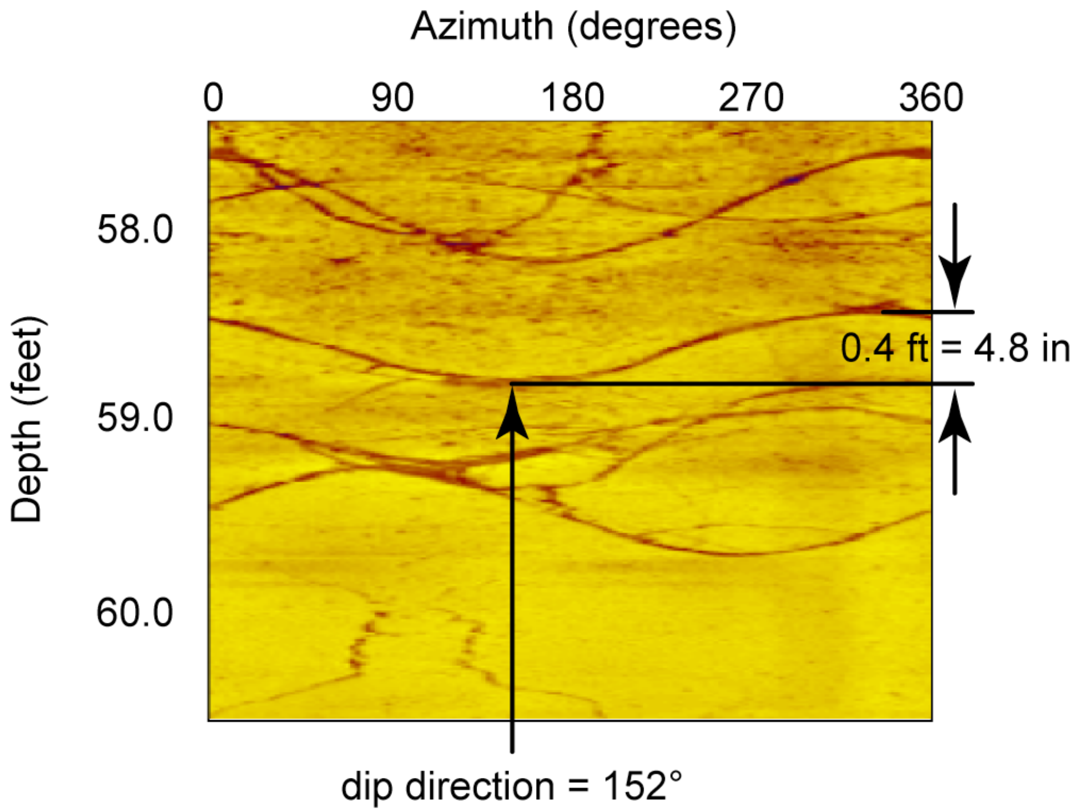

Figure 6. Portion of the acoustic televiewer log from Figure 4, illustrating the procedure for manual calculation of discontinuity orientation. The dip vector orientation is 52°/152°.

Other Properties

Properties such as discontinuity length, termination type, and crack tip interaction generally cannot be inferred from cores or televiewer logs.

DISCONTINUITY SYSTEMATICS

Vocabulary

When describing discontinuities in rock engineering projects, it is useful to extend the vocabulary that is universally used by geologists to describe joints in rock, as illustrated in Figure 7. Discontinuities that possess a regular geometric relationship to each other are *systematic*, whereas those that possess no regular geometric relationship (*i.e*,, they appear to be randomly oriented) are *non-systematic*. Groups of discontinuities that are parallel or sub-parallel to each other should be referred to as a *discontinuity sets*, and groups of sets should be described to as *discontinuity systems*.

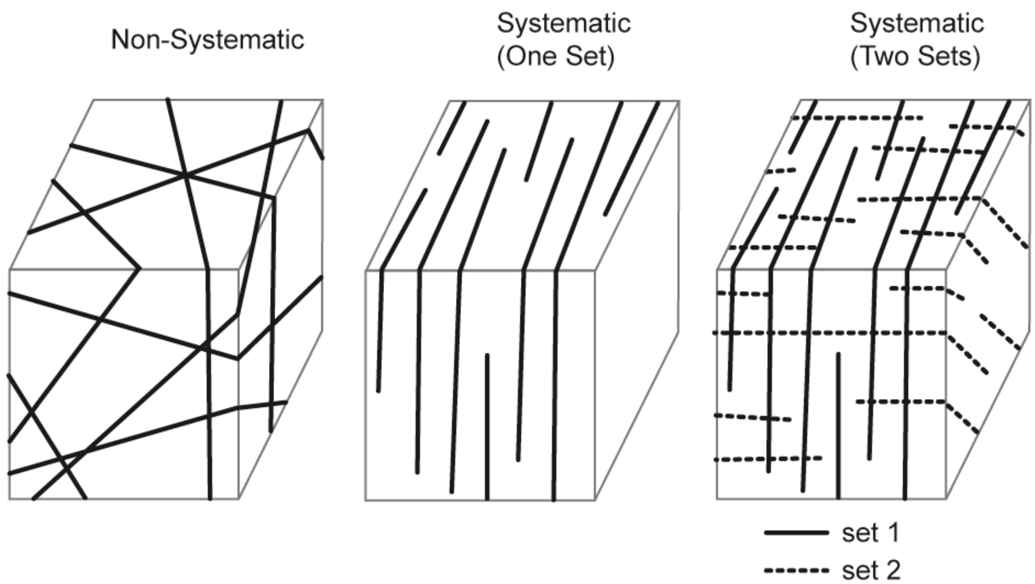

Figure 7. Block diagrams showing non-systematic discontinuities, one set of systematic discontinuities, and two sets of systematic discontinuities.

BOREHOLE ORIENTATION AND SAMPLING BIAS

Vertical borings, the most common method of subsurface geotechnical site characterization, are useful for determining soil or rock type but are inadequate for discontinuity orientation and spacing characterization in many geologic settings. This is because soils or rocks occupy volumes that can be intersected by carefully located boreholes with a wide range of orientations, including vertical boreholes. Discontinuities, however, are planar or nearly planar elements that are likely to be intersected by favorably oriented boreholes but may be completely missed by unfavorably oriented boreholes, which may introduce significant bias into the data available to constrain scour potential evaluations. Discontinuities that are nearly parallel to boreholes have a low probability of being intersected, particularly in boreholes of limited depth. If nearly parallel discontinuities are detected, they are likely to be too few in number to yield statistically reliable information (Figure 8). If the angle between a discontinuity set and a boring is less than about 30°, the set lies in a blind zone that cannot be adequately characterized (Terzaghi, 1965). For vertical borings, discontinuity sets with dips greater than 60° fall within the blind zone.

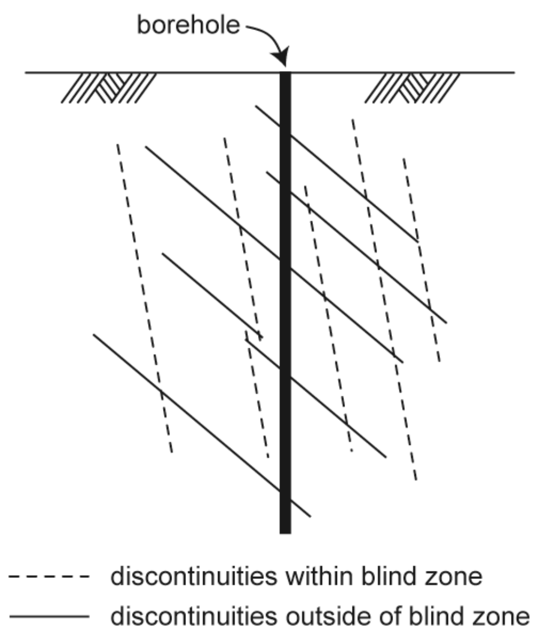

Figure 8. Schematic illustration of borehole orientation bias. Steeply dipping discontinuities are much less likely than gently dipping discontinuities (typically bedding planes) to be intersected by a vertical borehole.

If there is *a priori* knowledge of the orientations of discontinuity sets likely to be encountered at a site, then it is possible to use that information to optimize drilling directions. Building upon a method proposed by Zhou and Maerz (2002), the direction cosines or *x*-*y*-*z* components of a borehole with plunge δ_b and azimumth θ_b are given by (e.g., Priest, 1993; Pollard and Fletcher, 2005; Haneberg, in review):

$$\mathbf{b} = \begin{Bmatrix} b_x \\ b_y \\ b_z \end{Bmatrix} = \begin{Bmatrix} \cos\delta_b \sin\theta_b \\ \cos\delta_b \cos\theta_b \\ -\sin\delta_b \end{Bmatrix} \qquad (2)$$

In equation (2), the *z*-axis is assumed to be positive upward in equation (2), so a downward directed borehole will have a negative *z* component, the *x* component is positive towards east, and the *y* component is positive towards north. This is a different convention than used by some authors (e.g., Borradaile, 2003), so care must be used if equations from different sources are used to calculate structural orientations. For the pole to a discontinuity with dip δ_d and dip direction θ_d the direction cosines are, in comparison,

$$\mathbf{d} = \begin{Bmatrix} d_x \\ d_y \\ d_z \end{Bmatrix} = -\begin{Bmatrix} \sin\delta_d \sin\theta_d \\ \sin\delta_d \cos\theta_d \\ \cos\delta_d \end{Bmatrix} \qquad (3)$$

In practice, the values used in equations (2) and (3) will be the mean orientations of discontinuity sets, either estimated visually or calculated as a vector mean (e.g., Fisher et al., 1987; Cronin, 2008). The angular dispersion of the discontinuity sets around the borehole can be expressed as the normalized sum of the squared angular differences between the borehole and the poles to $i = 1 \ldots n$ discontinuity sets, which is

$$\sigma_\alpha^2 = \frac{1}{n}\sum_{i=1}^{n} \arccos^2(\mathbf{b}\cdot\mathbf{d}_i) \qquad (4)$$

in which $\mathbf{d}_i$ contains the direction cosines for the ith of *n* discontinuity sets and $\mathbf{b}\cdot\mathbf{d}_i$ signifies the vector dot product. Equation (4) is similar in form to the angular variance of vectors with respect to their mean (Borradaile, 2003) and has units of degrees or radians squared, depending on the input units. The square root of equation (4) is analogous to an angular standard deviation, which has units of ±degrees or ±radians and is therefore a physically sensible measure of dispersion likely to be conceptually familiar to most geotechnical practitioners. The standard deviation-like measure is known as the linear sampling angular deviation (LSAD). The optimum drilling direction is found by either plotting σ_α over the ranges $0° \leq \delta \leq 90°$ and $0° \leq \theta < 360°$ and visually identifying minima or, in simple cases, using a mathematical minimization algorithm (Haneberg, in review).

Even in situations where the *a priori* information necessary to use the LSAD to optimize drilling directions is unavailable, the LSAD can be used to evaluate general degrees of bias likely to be introduced by the common practice of limiting geotechnical characterization to vertical borings. For example, Figure 9 shows LSAD values for two vertical (N-S and E-W striking) and one horizontal discontinuity sets contoured on a lower hemisphere equal area projection. There are four LSAD minima, each plunging 35°, toward 045°, 135°, 225°, and 315°. The LSAD maximum of > ±70° at the center of Figure 9 further shows that vertical boreholes have the worst possible orientation for characterization of rocks with one horizontal (for example, sedimentary or volcanic layering) and two orthogonal sets of vertical discontinuities. In other cases, most notably where all of the discontinuities are horizontal to gently dipping and no steeply dipping discontinuities exist, vertical boreholes can be an effective means of characterization.

Before choosing vertical boreholes, however, the project geologist should be confident that they represent a good choice. It must also be recognized that optimal drilling directions almost always represent compromises, and that in some cases it may be worthwhile to choose several drilling directions designed to target specific discontinuity sets rather than relying on a single optimized direction.

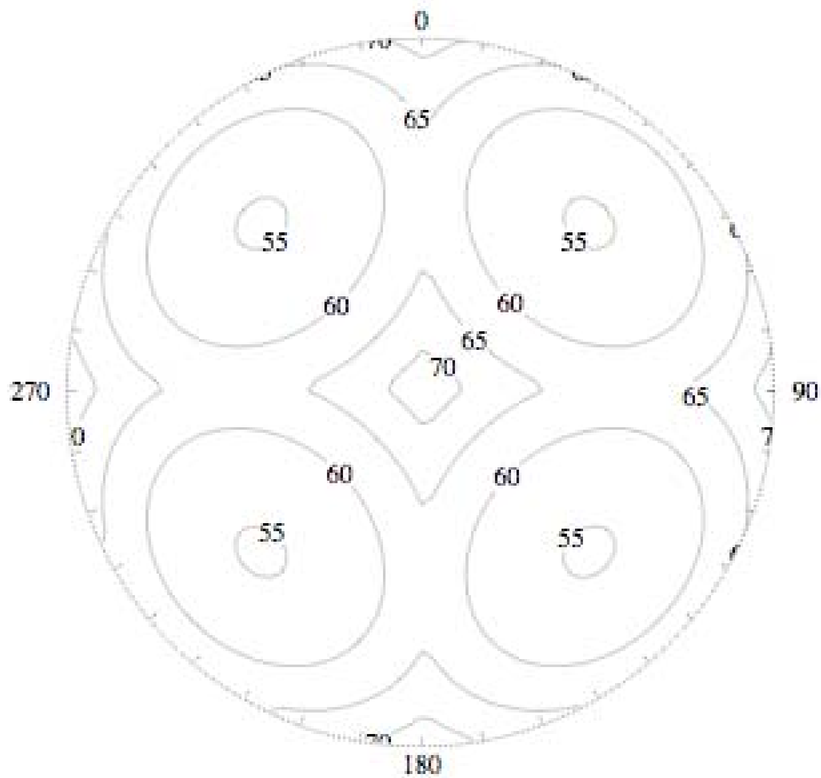

Figure 9. Lower hemisphere equal area projection with contoured LSAD values for three sets of mutually orthogonal discontinuities: one horizontal and two vertical (striking E-W and N-S). Optimal drilling directions are indicated by LSAD minima and the most unfavorable drilling directions are indicated by LSAD maxima. LSAD units are ±degrees.

Some stereo net software can perform weighting, commonly known as a Terzaghi correction (Terzaghi, 1965), in which the frequency of discontinuity occurrence is weighted by 1/cos α, where α is the angle between the borehole and a discontinuity, to account for orientation bias when sampling discontinuities that fall outside of blind zones. Although Terzaghi corrections can help reduce some of the bias associated with boring orientation, the corrections are of questionable value when applied to discontinuities in the blind zone. Martel (1999) proposed a method in which hypothetical discontinuity orientations are simulated, taking into account the effects of borehole orientation bias, and compared to observed distributions to predict a bias-free discontinuity distribution.

DELINEATION OF DISCONTINUITY SETS

The numbers and mean orientations of discontinuity sets present at a site, knowledge of which is essential in order to estimate block size, can be determined using several common methods. In some simple cases, the sets will be well enough defined and localized that they can be identified by inspection without any additional processing of filtering. Some commercially available stereo net software allows users to manually define the location and extent of discontinuity sets.

In cases where the numbers or mean orientations of discontinuity sets are not obvious to the unaided eye, techniques such as contouring, outlier removal, and statistical cluster analysis of dip vectors or poles to planes can help to delineate sets. Several techniques are described below

One commonly used method of contouring uses the percentage of dip vectors or poles falling into overlapping counting circles that each cover 1% of the equal area net (e.g., Marshak and Mitra, 1998). An alternative method proposed by Kamb (1959), uses counting circles that are sized according to the number of data being contoured and takes into account the statistical distribution of the measurements (also see Pollard and Fletcher, 2005). In Kamb contouring, the radius of the counting circles, r, is

$$r = \frac{3R}{\sqrt{N+9}} \qquad (5)$$

in which R is the radius of the equal area net and N is the number of orientations being contoured. Thus, the smaller the number of data available the larger the counting circles must become in order to generate statistically significant results.

Equation (5) can be evaluated to show that the common choice of counting circles that occupy 1% of an equal area net is justified only if $N = 891$, which will be unlikely in most geotechnical exploration data sets. For a more reasonable number, say $N = 100$, equation (5) yields a value of $r/R = 0.29$, which corresponds to a counting circle area of about 8% of the equal area net. Using counting circles that are small relative to the number of data being contoured can produce irregular contours with no statistical significance. Kamb contour plots typically use contour intervals proportional to the standard deviation of the binomial probability distribution assumed in the derivation of equation (5), which is

$$s = \sqrt{f\,N(1-f)} \qquad (6)$$

If the number of data to be contoured is small, however, then the Kamb (1959) method may require large counting circle sizes that make it difficult to identify clusters of data that represent discontinuity sets.

The effect of counting circle size on contouring results is illustrated in Figure 10, which shows the poles to 37 discontinuities measured in an outcrop along an interstate highway. Field observations and 3-D models created using terrestrial digital photogrammetry independently suggested the existence of three geologically reasonable discontinuity sets (Haneberg et al., 2006; Haneberg, 2008). Figure 10A shows the poles without contouring and, in the absence of any additional information, suggests the existence of two or three discontinuity sets. Figures 10B through 10F show how the distributions of contours change as the counting circle size is increased from 1% of the projection area, which is the standard size in many applications, to 20% of the projection area. The 20% circle corresponds to the counting circle area required by the Kamb (1959) method for $N = 37$. In this example, the selection of a counting circle size of 5% to 10% of the total area seems to be most useful for identifying three inferred discontinuity sets. Although it is statistically rigorous, a counting window of the size calculated using the Kamb (1959) method makes it difficult to distinguish between the two discontinuity sets with poles in the northern half of the projection. The traditional 1% counting window, on the other hand, is sensitive to the small number of data and suggests that five or six discontinuity sets may be present.

Filtering orientation data to remove outliers may also help to delineate discontinuity sets. One potentially useful method is based on the assumption that discontinuity sets will exhibit a greater degree of clustering than non-systematic or randomly oriented discontinuities (Mahtab and Yeulalp, 1982; Priest, 1993). The Poisson probability that more than t randomly oriented poles will plot within a defined by the angle ψ is (Priest, 1993)

$$P(> t,c) = 1 - \sum_{i=1}^{t} \frac{\exp(-Nc)(Nc)^i}{i!} \tag{7}$$

in which N is the number of data and c is the proportion of the randomly distributed poles falling within a cone defined by ψ, or (Priest, 1993)

$$c = 1 - \cos\psi \tag{8}$$

Thus, an infinitely small cone approaching $\psi = 0°$ will contain no poles and a cone encompassing the entire lower hemisphere with $\psi = 90°$ will contain all of the poles (c = 1). An orientation is considered to belong to a dense cluster, and presumably a discontinuity set, if the proportion of poles falling within a cone of size ψ is greater than c (or, equivalently, if the number of poles falling within the cone is greater than Nc).

Outlier removal using the Mahtab and Yeulalp (1982) procedure is implemented by first deciding upon a cone size in terms of the angle ψ and then calculating a critical value of, c_{crit} using equation (8). Equation (7) is then evaluated by increasing t until $P(> t,c) < c$ and the resulting value of t, termed t_{crit}, is retained as the critical number of orientations necessary to define a dense cluster. For each discontinuity orientation measurement, the number of data within an angle ψ are tabulated. If the result exceeds t_{crit} then the orientation is retained as a member of a cluster or set. For example, a sample size of 37 orientation measurements and a starting cone size of $\psi = 20°$ gives $c = 0.06$ from equation (8) and $t = 5$ from equation (7). Thus, any orientation measurement that lies within 20° of 5 or more other orientation measurements is considered to be part of a dense cluster. Figure 11 illustrates the result of outlier removal using gradually decreasing cone sizes of $\psi = 20°$, 10°, and 5° with a data set of 138 computer generated orientations known to consist of three sets (one horizontal and two vertical) along with random noise. The choice of cone size is to some degree subjective. Thus, if outlier detection and removal is used several different cone sizes should be selected and the results compared to select a geologically reasonable filtered data set.

Priest (1993) describes how the Mahtab and Yeulalp (1982) procedure can then be used to delineate discontinuity sets by serially grouping together dense orientations separated by angles of less than ψ from their nearest neighbor. However, the method is slow and existing set affinities can be overwritten because of the serial nature of the procedure. An alternative approach followed by a number of authors (Gauthier et al., 2000; Zhou and Maerz, 2002; Hofrichter and Winkler, 2003; Slob et al., 2005; Jimenez, 2008) is to use a statistical technique known as cluster analysis or, more simply, clustering, which groups together similar data according to some specified distance measure the reflects their degree of similarity. Two types of cluster analysis, known as hierarchical and partitional, are common. The latter is useful for discontinuity set delineation. Partitional clustering is an iterative process in which data points are assigned to clusters that minimize the distance from the point to the cluster mean. So-called *k*-means clustering assigns each data point to one and only one group. Fuzzy or *c*-means clustering assigns each data point a degree of membership in each group. While the simplest clustering algorithms require users to specify in advance the number of clusters, more advanced algorithms are capable of automated cluster detection without an *a priori* specification of the number of clusters.

Figure 12 illustrates the result of cluster analysis to delineate three discontinuity sets among the data introduced in Figure 11, both with and without filtering to remove outliers. Figure 13 compares the mean orientations of the three sets, showing that although outlier removal made the equal area plot more amenable to visual analysis it did not substantially change the mean orientations of the three sets. In this case, the clustering algorithm determined that three sets are present and this result was consistent with geologic inference. In other cases, automated determination of the number of clusters may not be consistent with geological interpretations; hence, the results of cluster analysis should always be critically evaluated before being used in any geotechnical calculations.

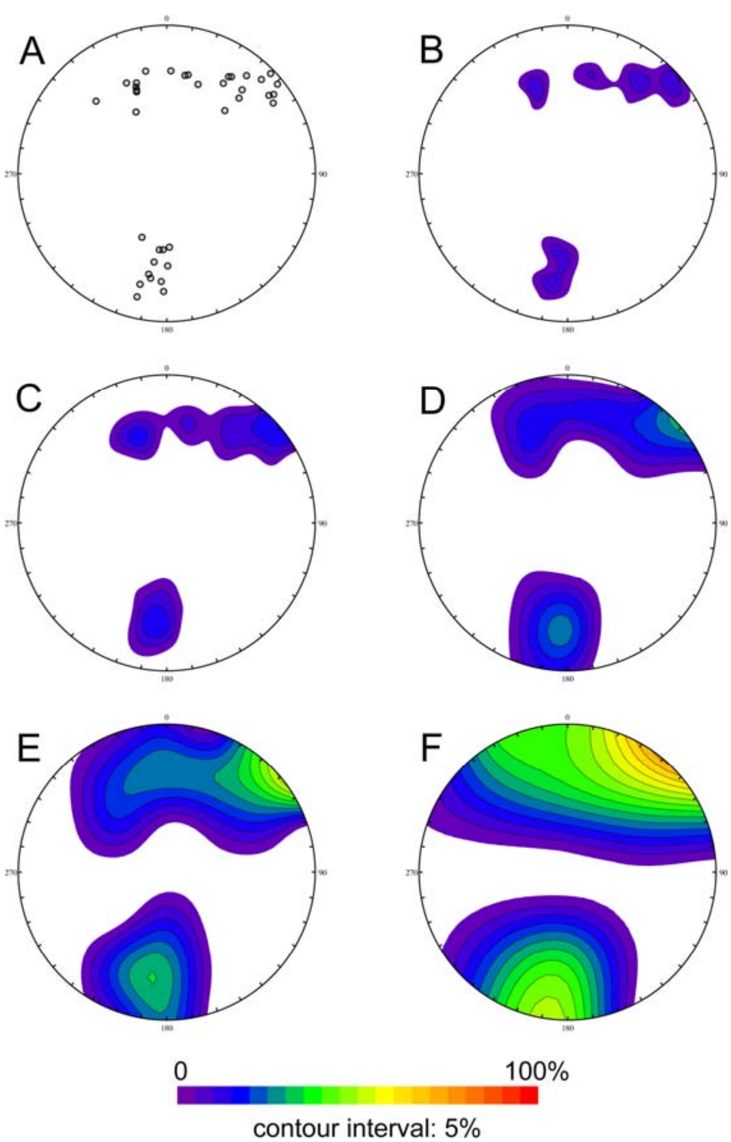

Figure 10. Equal area projections showing the effect of counting circle size on contouring results. Contours show the percentage of the poles falling within the counting circle as it is moved across the projection. A) Poles to 37 discontinuity planes without contours. B) Counting circle covering 1% of the projection area. C) Counting circle covering 2% of the projection area. D) Counting circle covering 5% of the projection area. E) Counting circle covering 10% of the projection area. F) Counting circle covering 20% of the projection area.

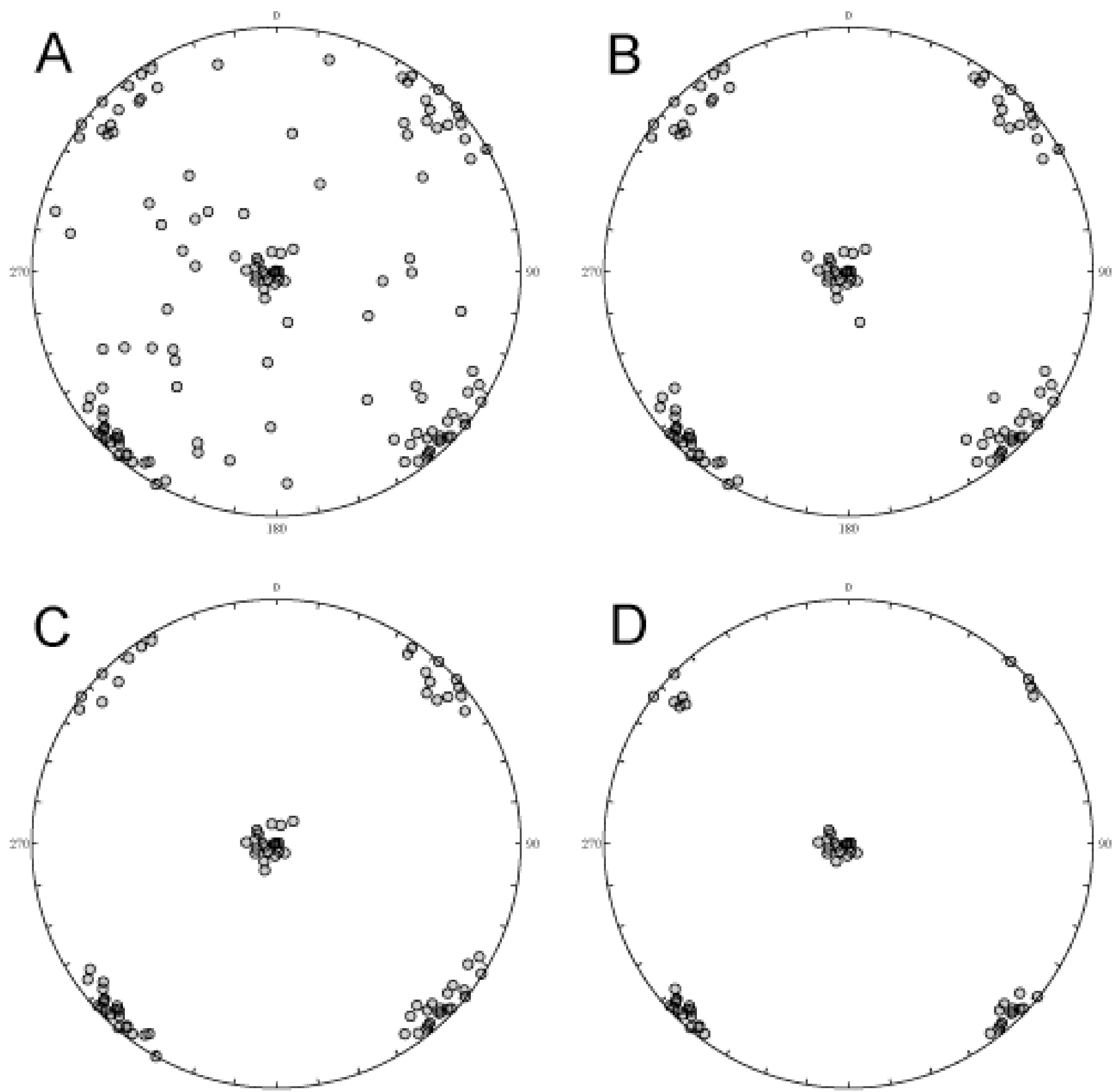

Figure 11. Examples of outlier detection and removal to help elucidate discontinuity sets using computer generated data consisting of three sets and random noise. A) Unfiltered data consisting of 138 poles to planes. B) Poles remaining (N = 101) after outlier removal using a cone size of $\psi = 20°$. C) Poles remaining (N = 85) after outlier removal using a cone size of $\psi = 10°$. D) Poles remaining (N = 57) after outlier removal using a cone size of $\psi = 5°$.

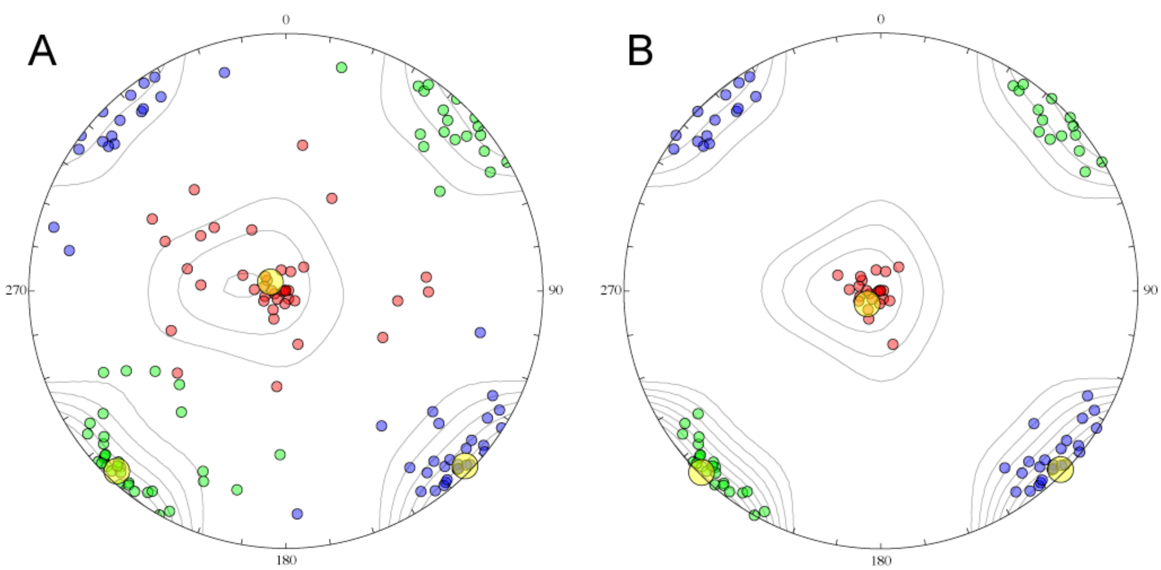

Figure 12. Contoured equal area projections showing clustering of unfiltered and filtered data introduced in Figure 11. Yellow dots are the mean orientations of the three clusters. The contours generated using a counting circle area of 10% and the contour interval of 5%. A) Unfiltered data with no outlier removal. B) Filtered data with outliers removed using a cone size of $\psi = 20°$.

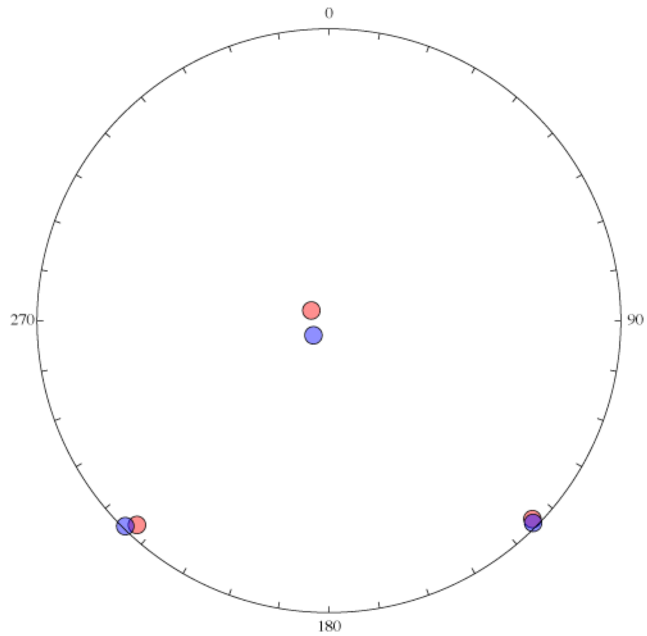

Figure 13. Mean orientations for the clusters shown in Figure 12. Red dots represent the clusters determined from the unfiltered data (Figure 12A) and blue dots represent the clusters determined from the filtered data (Figure 12B).

MEAN ORIENTATIONS

Once discontinuity sets have been identified, representative or mean orientations such as those illustrated in Figures 12 and 13 can be determined. Mean orientations can serve as useful representations of discontinuity sets, for example when evaluating favorable or unfavorable orientations relative to a stream bed.

For simple problems in which sets are clearly defined either by tightly clustered points or tightly closed contours on an equal area projection, it may be possible to visually estimate representative orientations with an accuracy of a few degrees. This may be adequate for many applications.

In cases where it is not easy to visually identify the center or mean of discontinuity sets, or at the discretion of the geologist, quantitative methods may be useful. The direction cosines describing the *x*, *y*, and *z* components of a dip vector with dip direction θ and dip angle δ are, by analogy with equation (2)

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = \begin{Bmatrix} \cos\delta \sin\theta \\ \cos\delta \cos\theta \\ -\sin\delta \end{Bmatrix} \tag{9}$$

For a discontinuity set represented by *N* measurements, the mean dip vector is calculated using the resultant of the direction cosines of each measurement (e.g., Borradaile, 2003; Fisher et al, 1987). The resultant is

$$R = \sqrt{\left(\sum x_i\right)^2 + \left(\sum y_i\right)^2 + \left(\sum z_i\right)^2} \quad i = 1,2,3\ldots N \tag{10}$$

and the direction cosines of the mean vector are

$$\begin{aligned} \bar{x} &= \frac{1}{R}\sum x_i \\ \bar{y} &= \frac{1}{R}\sum y_i \\ \bar{z} &= \frac{1}{R}\sum z_i \end{aligned} \tag{11 a,b,c}$$

The azimuth or dip direction of the mean dip vector is

$$\bar{\theta} = \arctan\left(\bar{y}/\bar{x}\right) \tag{12}$$

and the dip angle is (as above, defining the *z* axis to be positive upwards)

$$\delta = -\arcsin(\bar{z}) \tag{13}$$

Evaluation of equation (12) requires a four-quadrant arctangent function that preserves the signs of both the numerator and denominator. This is, for example, calculated in some popular spreadsheet software using the function ATAN2(*x*, *y*) rather than the single quadrant function ATAN(x/y). If the result of equation (12) is negative, add 360° to calculate the dip direction as a positive angle.

BLOCK SIZE ESTIMATION

Block size estimation, particularly *in situ* block size estimation in which each block cannot be moved for individual examination or measurement, as it might be in a mining application, is a complicated undertaking that requires simplifying assumptions in order to be tractable. Some highly specialized commercial software is able to estimate block sizes using statistical simulations based on discontinuity orientations and locations measured in boreholes or outcrops (*e.g.*, Rogers et al, 2007). In other cases, resource limitations dictate and/or design considerations allow that more simplified procedures to be used (*e.g.*, NRCS, 2001).

The block size number used in the Natural Resources Conservation Service (NRCS) headcut erodibility index is the quotient of the standard rock quality designation (*RQD*) and a joint set number, J_n:

$$K_b = 100\,\frac{RQD}{J_n} \tag{14}$$

Estimation of the *RQD* is described in many engineering geology and rock engineering references, including ASTM D 6032 (Standard Test Method for Determining RQD of Rock Core). For each core run, the *RQD* is the sum the lengths of pieces greater than 0.1 m (4 inches) in length divided by the total length of the core run. *RQD* values less than 50% are considered poor to very poor, whereas values greater than 90% are considered excellent. *RQD* is more sensitive to borehole orientation that measures of discontinuity spacing or frequency and *RQD* estimates are therefore susceptible to considerable sampling bias if unfavorable drilling directions are chosen. Palmstrom (2005) gives a hypothetical example in which the *RQD* value calculated for a rock mass can vary between 0 and 100 depending solely on borehole orientation. Despite widespread acknowledgement of the shortcomings and potential for directional bias when using *RQD* values in design, guidance on the selection of appropriate *RQD* values to minimize bias is generally absent. Depending on the degree of conservatism required, one might select either the smallest of several directional *RQD* values, use an average of several directional values, or use a single value obtained from an optimally oriented borehole.

The role of the joint set number, values for which are shown in Table 2, is to modify the *RQD* to account for the existence of both systematic and random discontinuity sets when assessing headcut erodibility. The greater the number of discontinuity sets, the greater the reduction in J_n. In cases where sedimentary, volcanic, or metamorphic layering creates a mechanical discontinuities, they should be considered to be joints for the purpose of selecting a joint set number. Palmstrom (2005) includes an expanded set if J_n values in addition to an assessment of uncertainties arising from the use of equation (9) to estimate block size, showing that block volume typically ranges over a factor of 10 for a given K_b value.

Table 2. Joint Set Number (NRCS, 2001)

Discontinuities	**Joint Set Number (J_n)**
None or few	1.00
One set	1.22
One set + random	1.50

Two sets	1.83
Two sets + random	2.24
Three sets	2.73
Three sets + random	3.34
Four sets	4.09
More than four sets	5.00

RQD can also be estimated as a function of other variables such as the volumetric joint count, mean block diameter, or spacing of joints intersected by three mutually perpendicular transects or boreholes (*e.g.*, NRCS, 2001; Palmstrom, 2005).

It is also possible to estimate block volume without reference to *RQD* if suitable data are available. If three discontinuity sets exist, the average block volume, V_b, is (Palmstrom, 2005)

$$V_b = \frac{\Delta_a \Delta_b \Delta_c}{\sin\alpha \sin\beta \sin\gamma} \tag{15}$$

in which the Δ terms represent the average spacing for discontinuity sets *a*, *b*, and *c* and α, β, and γ are the angles between each pair of discontinuity sets. The spacing values can be measured from cores, televiewer logs, or outcrop transects (scanlines) and corrected if the borehole is not normal (or very nearly so) to the discontinuities.

The angles in the denominator of equation (15) can be measured using standard stereographic or equal area projection techniques (*e.g.*, Marshak and Mitra, 1998) or by calculating the direction cosines for the mean orientation of each set using equation (3) and then taking the vector dot product for each pair of direction cosines. Note that although the angle between two planes is identical to the angle between the normals to the planes, the relationship does not work for lower hemisphere poles to planes commonly used by geologists. Thus, it is best to use dip vectors for the calculation. For example, if plane *a* dips 30° towards 045° and plane *b* dips 60° towards 225°, the two sets of direction cosines are:

$$\mathbf{a} = \{0.6124 \quad 0.6124 \quad -0.5000\}$$
$$\mathbf{b} = \{-0.3535 \quad -0.3535 \quad -0.8660\} \qquad (16\text{ a,b})$$

and the angle between the two dip vectors is given by

$$\arccos \mathbf{a} \cdot \mathbf{b} = 90^{\circ} \qquad (17)$$

This result can be verified by simple geometry or a lower hemisphere projection. If the three sets are mutually perpendicular (orthogonal), the denominator in equation (10) becomes unity and the volume is simply the product of the three spacing values. Latham *et al* (2006) offer a more sophisticated version of this approach in which the statistical distribution of discontinuity spacing values for three sets is used to estimate block size distributions using coefficients derived from statistical modeling rather than simply an average block size.

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