SD94-09-F

SD Department of Transportation
Office of Research

Highway Rock Slope Reclamation and Stabilization Black Hills Region South Dakota Part I, Report

Study SD94-09-F
Final Report

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January 1995

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. SD94-09-F	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Highway Rock Slope Reclamation and Stabilization Black Hills Region, South Dakota Part I, Report		5. Report Date January 5, 1995 6. Performing Organization Code
7. Author(s) Kenneth Buss, Rod Prellwitz, Mary Ann Reinhart		8. Performing Organization Report No.
9. Performing Organization Name and Address GeoEngineers, Inc. 8410 154th Avenue Northeast Redmond, Washington 98052		10. Work Unit No. 11. Contract or Grant No. 310301
12. Sponsoring Agency Name and Address South Dakota Department of Transportation Office of Research 700 East Broadway Avenue Pierre, SD 57501-2586		13. Type of Report and Period Covered Final; May 1994 to January 1995 14. Sponsoring Agency Code

15. Supplementary Notes

Part II, Guidelines is also part of this report.

16. Abstract

Numerous constructed rock slopes along highways traversing the Black Hills region require considerable maintenance every year. Many of these slopes are steeply inclined and are susceptible to the effects of erosion and possible instability. The objectives of the study are to (1) categorize existing constructed rock slope conditions in the Black Hills, (2) evaluate treatment methods presently used in the Black Hills, (3) evaluate other treatment methods with respect to Black Hills conditions, (4) develop site-specific rock slope treatment methods for several specific Black Hills rock slopes, (5) develop recommendations for improving rock slope stability and provide guidelines for cost-effective implementation of those recommendations.

The report provides recommendations for treatment methods for sites identified by the SDDOT and also provides "problem-specific" guidelines for selecting treatment methods that may be applied to other sites. Twenty-five study site were selected from highway sections identified by the SDDOT, which include sections of US85, US385, US16, US16A, and SR71. The sites were selected to give a representative cross section of cut slope performances.

Rock and soil units represented in the 25 site studies are grouped into six categories based on rock and soil engineering characteristics, slope failure mechanisms, optimum stable slope ranges, and applicable slope treatment methods.

The report consists of two parts, each bound separately. Part I provides a detailed discussion of the site conditions, research methods and results, and suggestions for continuing studies; the Appendix to Part I contains information and photographs compiled during field reconnaissance for the 25 study sites. Part II of the report provides a detailed discussion of the "problem-specific" guidelines, and references; the Appendix to Part II contains blank site reconnaissance forms and examples of completed forms.

17. Keyword		18. Distribution Statement No restrictions. This document is available to the public from the sponsoring agency.	
19. Security Classification (of this report) Unclassified	Security Classification (of this page) Unclassified	21. No. of Pages	22. Price

Highway Rock Slope Reclamation and Stabilization
Black Hills Region, South Dakota
Part I

January 5, 1995

For

South Dakota Department of Transportation

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GEOTECHNICAL EVALUATION
HIGHWAY ROCK SLOPE RECLAMATION AND STABILIZATION
BLACK HILLS REGION, SOUTH DAKOTA
FOR
SOUTH DAKOTA DEPARTMENT OF TRANSPORTATION

EXECUTIVE SUMMARY

Numerous constructed rock slopes along highways traversing the Black Hills region require considerable maintenance every year. Many of these slopes are inclined steeper than 2H:1V (horizontal to vertical) with no or only sparse vegetation after construction. Subsequently, many of these slopes are susceptible to the effects of weathering, erosion or instability.

Concerns associated with constructed slopes in this area range from aesthetics to public safety hazards, and a considerable maintenance effort is required annually for rockfall cleanup. The problems vary from sloughing and ravelling (relatively minor concerns), to rockfall and mass movement (relatively high maintenance or public safety concerns).

The objectives of the study are to (1) differentiate and categorize existing constructed rock slope conditions in the Black Hills, (2) evaluate the effectiveness of existing rock slope treatment methods in the Black Hills, (3) evaluate other rock slope treatment methods with respect to Black Hills conditions, (4) develop site-specific rock slope treatments that will enhance safety, reduce maintenance and improve aesthetics of constructed Black Hills rock slopes, and (5) develop recommendations for improving rock slope stability and provide guidelines for cost-effective implementation of those recommendations.

Our approach to this project is twofold: (1) provide recommendations for treatment methods for each of the sites identified by the SDDOT, based on evaluation of data gathered from each site, and (2) provide "problem-specific" guidelines for selecting treatment methods that may be applied to other sites.

We selected 25 study sites for analysis. The sites were selected from highway sections identified by the South Dakota Department of Transportation and include sections of US85, US385, US16, US16A and SR71. The sites were selected to give a representative cross section of cut slope performances; the cut slopes chosen vary from those experiencing severe maintenance problems to those performing well within initial design parameters.

We compiled existing rock slope conditions and maintenance histories on prepared "site reconnaissance data sheets." Included on the data sheets for each site is a discussion of the optimum slope range for that site and recommendations for appropriate treatment methods. Each of the study sites and our recommended methods of treatment are described in detail in the Appendix of the report.

Rock and soil units represented in the 25 studies were grouped into six broad categories. The categories are based on rock and soil engineering characteristics, typical slope failure mechanisms, optimum stable slope ranges, and applicable slope treatment methods. The

categories are (1) competent rocks with two or more parallel sets of intersecting discontinuities (open planes of separation), (2) competent rocks with two or more parallel sets of very closely spaced, intersecting discontinuities, (3) competent rock beds with discontinuities interbedded with or completely surrounded by incompetent rock, (4) incompetent rocks that decompose easily into soil, (5) cohesionless soils ranging from silt to gravel that have relatively high friction angles (greater than 30 degrees), and (6) cohesive soils that are relatively impermeable and have relatively low frictional strength (less than 20 degrees).

We developed "problem-specific" guidelines to aid in the examination and evaluation of rock cut slopes and treatment methods appropriate for stabilizing slopes. They are also intended to aid in the selection process for slopes in new construction, and are structured to lead the user to the final design stage at which point final considerations of costs, materials, construction techniques, and a myriad of other considerations must be included in the design process. An outline of the guidelines is presented in Part II, followed by a listing of major considerations for each step of the guidelines. References are listed at the end of appropriate guideline steps.

Our studies confirm that a variety of conditions contribute to stability problems with rock slopes in the Black Hills. The studies also demonstrate a systematic method for examining those slopes and developing solutions for treatment of those slopes.

It is evident that additional studies beyond the scope of this project will be valuable to the development of treatment methods for rock slopes on highways in South Dakota. Additional areas of study suggested include vegetation methods, effectiveness of current and past practices, steep slope seeding methods, and evaluation of successful benches in rock slopes.

GEOTECHNICAL EVALUATION
HIGHWAY ROCK SLOPE RECLAMATION AND STABILIZATION
BLACK HILLS REGION, SOUTH DAKOTA
FOR
SOUTH DAKOTA DEPARTMENT OF TRANSPORTATION

INTRODUCTION

We are pleased to present the results of our geotechnical evaluation for highway rock slope reclamation and stabilization in the Black Hills region of southwestern South Dakota. Our study was performed in accordance with the requirements specified by South Dakota research project SD94-09. The region extends approximately 160 miles in the north-south direction from Spearfish to Hot Springs, and about 60 miles in the east-west direction from Rapid City to Newcastle, Wyoming.

Information provided to GeoEngineers, Inc. by the South Dakota Department of Transportation (SDDOT) indicates that numerous constructed rock slopes along highways traversing the Black Hills region require considerable maintenance every year. Many constructed slopes along these roads are inclined steeper than 2H:1V (horizontal to vertical) and have little or no vegetation after construction. The slopes are underlain by a variety of geologic materials and conditions, including strongly deformed metasedimentary sequences, jointed granitic rocks, and relatively low-strength rocks such as siltstones and shales. As a result, many of the slopes are susceptible to the effects of weathering, erosion or instability. Therefore, the need exists for guidelines and recommendations for effective, site-specific treatment of these slopes.

PROJECT DESCRIPTION

The performance of constructed rock slopes in the Black Hills region is often problematic for a variety of reasons. The variability of such factors as rock strength, planar discontinuities, surface and ground water conditions, the presence of colluvium or deeply weathered zones, and vegetation contributes to a wide range of performance characteristics for constructed slopes. Furthermore, slopes of similar configuration and similar materials often perform differently as a result of climatic variability associated with differences in elevation and aspect.

Problems associated with constructed slopes in this area range from aesthetics to public safety hazards, and a considerable maintenance effort is required annually for rockfall cleanup. Those problems requiring treatment vary from sloughing and ravelling, which present a relatively minor maintenance concern although they may be aesthetically unacceptable, to rockfall and mass movement, which require extensive maintenance or reconstruction and can be a hazard to public safety. The erosion of rock or soil from unstabilized slopes may also result in unacceptable sedimentation in adjacent streams and waterways.

In the Black Hills a variety of solutions have been used for stabilization of rock slopes. These solutions include benching, vegetation, asphalt and fiberglass roving, structural restraints, and others. The success of these solutions has varied depending on geologic conditions, ground water, slope aspect, and other considerations.

PURPOSE AND SCOPE

The purpose of this study is to identify and characterize existing constructed rock slope conditions in the Black Hills of South Dakota, and to develop recommendations and guidelines for effective, economical, site-specific slope treatment. To those ends, the following objectives were developed:

1. Obtain sufficient information on existing constructed rock slope conditions in the Black Hills to differentiate and categorize existing conditions.
2. Obtain sufficient information on existing rock slope treatment methods in the Black Hills to evaluate the effectiveness of those methods.
3. Evaluate other rock slope treatment methods described in published papers and agency design handbooks to identify methods appropriate for the conditions in the Black Hills.
4. Develop alternative, site-specific rock slope treatments and implementation criteria that will enhance safety, reduce maintenance and improve aesthetics of constructed rock slopes in the Black Hills.
5. Develop recommendations for improving rock slope stability and provide guidelines for cost-effective implementation of those recommendations.

GeoEngineers identified the following tasks for this study in response to the research objectives outlined above.

1. Meet with the technical panel to review the project objectives, proposed scope and work plan. Conduct preliminary reconnaissance in the Black Hills region with SDDOT and other appropriate personnel to inspect representative areas of concern along Black Hills highways.
2. Conduct relatively detailed reconnaissance of representative slope areas in the Black Hills to obtain site-specific data for categorization of existing constructed rock slopes. Slope categorization is based on the following parameters, as appropriate:
   - Physical characteristics of the slope, including height and inclination.
   - Bedrock conditions such as rock type, weathering state, estimated unconfined compressive strength, condition and orientation of planar discontinuities.
   - Soil conditions, including extent and physical characteristics of slopewash, colluvium or mass wasting deposits. Significant soil deposits are classified using the Standard Practice for Description and Identification of Soils (Visual-Manual Procedure), ASTM D2488-90.
   - Surficial processes and mechanisms such as ravel, rill erosion, sloughing, block fall and toppling associated with direct precipitation, frost action or other factors.

- Surface and ground water conditions such as surface runoff, ground water seepage, and stormwater drainage features.
- Evidence of slope instability, including large-scale and local features.
- Type and extent of existing vegetation.
- Type and effectiveness of existing slope treatment methods.

3. Categorize existing Black Hills rock slope conditions by compiling the field data together with information from the following sources:

   U.S. Geological Survey topographic quadrangle maps, geologic maps, aerial photographs, climatological databases, and existing pertinent geotechnical and geological reports from local, state or federal agencies or private consulting firms.

4. Review the international literature on state-of-the-practice rock slope reclamation technologies. Our review focused on rock slope stabilization, slope protection, erosion control, and biotechnology applications. The review includes information obtained from state transportation departments and natural resource offices, federal agencies such as the U.S. Forest Service, Federal Highway Administration and National Park Service, mining operations, private consulting firms and universities.
5. Meet with the technical panel to review our preliminary categorization of the rock slope parameters and our findings from the literature review. We also presented our preliminary guidelines for treatment of slopes in the Black Hills and discussed the feasibility of those guidelines with respect to local conditions.
6. Develop treatment guidelines from site-specific information obtained and compiled in tasks 2 and 3. Provide recommendations for future field testing or research, where appropriate.
7. Prepare an executive summary and a final written report outlining the research methods, results, conclusions and recommendations, the slope treatment guidelines, and literature review.
8. Meet with the SDDOT Research Review Board to make an executive presentation at the conclusion of the project.

As indicated in the project tasks, the studies include the development of treatment guidelines for rock slopes in the Black Hills. The guidelines were developed based on information from specific, identified sites that represent the full spectrum of rock slope conditions in the Black Hills. They are therefore, by definition, both "site specific" and "problem specific" in their application.

Consequently, our approach to this project is twofold: (1) provide recommendations for treatment methods for each of the sites identified by the SDDOT, based on evaluation of data gathered from each of those sites, and (2) provide "problem-specific" guidelines for selecting treatment methods that may be applied to other sites. Recommended treatment methods for each of the site-specific studies are presented on the data sheets in the Appendix of Part I of this report. Development of a detailed design for each slope will require engineering analysis of specific slope, ROW considerations, costs and other factors beyond the scope of this study. Our problem-specific guidelines for evaluation of rock cut slopes and the selection of treatment methods for slope stabilization is presented in Part II of this report.

Our report is organized as follows:

Part I:
- Site Conditions - Regional Geology and Study Area
- Research Methods
- Research Results
- Appendix - Data sheets and photographs, and recommended treatment methods (grouped by rock and soil unit categories)

Part II:
- Rock Slope Stabilization Guidelines
- Appendix - Blank Site Reconnaissance Forms
  - Example Completed Site Reconnaissance Forms

The slopes examined in this study were evaluated using the techniques outlined in the guidelines. The field "Site Reconnaissance" forms were developed to aid in recording pertinent site data and applying the guidelines for the field portion of the studies.

The guidelines are intended to be used for examination of any rock slope, not just those included in this study. As such, photos illustrating various sections of the guidelines are from a variety of locations and include a wide range of geology, types of vegetation, climatic conditions, and treatment methods. This variety is intended to demonstrate that the guidelines are indeed applicable to a variety of rock slopes, not only those studied in the Black Hills.

SITE CONDITIONS

REGIONAL GEOLOGY

The Black Hills area shown in Figure 1 is both oval shaped and domed; the elevation reaches up to 7,242 feet in the center of the area and decreases steadily away from the center in all directions, to about 3,000 to 4,200 feet around the perimeter of the area. The dome structure is a result of block faulting and uplift, and crustal folding.

The general geology of the area is relatively simple. The region consists of older, deformed igneous and metamorphic rocks overlain by younger, undeformed sedimentary rocks. The older rocks are exposed at the surface within the central core of the area as a result of folding and uplift, followed by prolonged periods of erosion. These older rocks are PreCambian in age and consist mostly of phyllite, schist, rhyolite, granite and granitic pegmatite. The younger rocks are mostly Paleozoic-Mesozoic in age and are exposed around the perimeter of the central core as a result of erosion. These younger rocks consist of sandstone, siltstone, shale, limestone and gypsum.

We grouped the rock and soil units exposed in Black Hills hillslopes into six broad categories. The categories are based on typical rock and soil engineering characteristics, typical slope failure mechanisms, optimum stable slope ranges, and applicable slope treatment methods.

The six categories describing Black Hills rock and soil units are as follow: (1) competent rocks with two or more parallel sets of intersecting discontinuities (open planes of separation), (2) competent rocks with two or more parallel sets of very closely spaced, intersecting discontinuities, (3) competent rock beds with discontinuities interbedded with or completely surrounded by incompetent rock, (4) incompetent rocks that decompose easily into soil, (5) cohesionless soils ranging from silt to gravel that have relatively high friction angles (greater than 30 degrees), and (6) cohesive soils that are relatively impermeable and have relatively low frictional strength (less than 20 degrees).

STUDY AREA

The study area shown in Figure 1 covers several highways that traverse the Black Hills area, including US85, US385, US16, US16A and SR71. The following paragraphs describe the highway segments identified for the study by the South Dakota Department of Transportation.

1. **US85 - Deadwood North.** This highway section encounters massive limestone and sandstone beds (Paha Sapa, Minnelusa and Minnekahta formations). This is a recently completed section. Initial design concerns were focused on reducing the amount of waste on the project, subsequently, rock slopes were cut nearly vertically. Many of the slopes are more than 80 feet high. Overbreak during blasting and the unexpected presence of vugs and caverns left backslopes with a large amount of loose rock that continuously ravels out.
2. **US385 - Strawberry Hill.** The section traverses schist and rhyolite intrusions with high foliation angles. Rhyolite exposed in the northern Black Hills frequently weathers to cubic blocks of varying sizes, and is prone to rockfall. This section is proposed as a future grading project.
3. **US385 - Pluma to Custer.** This highway segment traverses the central core from north to south, and encounters schist and occasional pegmatites. The schist commonly exhibits high foliation angles. This section is subject to an ongoing project to widen US385 through the Black Hills region.
4. **SR71 - Cascade.** This highway section encounters primarily shale, gypsum and sandstone (Spearfish, Minnekahta and Inyan Kara Group) sedimentary sequences. This section is proposed as a future grading project. The project will leave relatively high backslopes in the Spearfish Formation (shale with gypsum).
5. **US16 - Reptile Gardens Hill.** This section encounters interbedded shale and sandstone (Opeche Formation) and limestone (Minnekahta Formation). The section was graded about 15 years ago and a portion of the rock slope was seeded using imported topsoil and fiberglass roving.

6. **US385 - Custer South.** This highway section traverses schist and pegmatites in the southern portion of the central core. A grading project was recently completed, and overbreak from controlled blasting lines left a large amount of fractured rock that is ravelling out. Some attempts were made to apply topsoil and hydroseed.
7. **US16 - Custer West to Wyoming Line.** The east side of this highway section encounters schist, the middle section encounters shale and limestone (Minnelusa and Paha Sapa formations), and the west encounters shale, sandstone and limestone (Minnelusa, Minnekahta and Spearfish formations). Two recent grading projects in the middle section left steep, benched slopes that failed within months of initial grading.
8. **US385 - Hot Springs to Maverick Junction.** This section encounters the Cretaceous Age sandstones that form the hogback around the Black Hills. No new work is scheduled for this section in the near future.
9. **US16A - Keystone to Mount Rushmore.** This highway section encounters schist with relatively high angles of foliation. The section was recently graded.

RESEARCH METHODS

FIELD METHODS

We performed site investigations on the nine highway sections between July 11 and July 15, 1994. Our investigation included selecting specific study sites from each highway section, measuring road cut profiles and any existing rock unit discontinuities, documenting road cut conditions and maintenance history, and interviewing South Dakota Department of Transportation personnel.

A total of 25 study sites were selected from the nine highway segments. Each of the 25 sites is included in this report in order to develop the full spectrum of Black Hills rock slope conditions and their treatment methods, and to compile a sufficient amount of site-specific data such that a problem-specific approach to failure mechanisms can be effectively demonstrated.

Two or more sites per highway section were profiled, with the exception of Sections 4, 5 and 8, each of which has one. The sites were selected to give a representative cross section of cut slope performances; the slopes chosen vary from those experiencing severe maintenance problems to those performing well within initial design parameters. Each site was chosen on the basis of available maintenance history, information solicited from SDDOT personnel and motor reconnaissance of the entire highway section.

We measured cross-sectional profiles using a fiberglass tape and clinometer. Each profile was measured by extending the tape down the fall line of the slope and measuring the slope angle with a handheld clinometer. Features documented on the profiles include the cut slopes, graded benches, portions of the upper backslope, width of highway ditch and pavement width.

We compiled existing rock slope conditions and maintenance histories on prepared "site reconnaissance data sheets." The data sheets were used to ensure uniform treatment of each site. Information recorded includes slope angle, slope length and slope height, road azimuth, and rock unit discontinuities (bedding planes, joint sets and foliation angels). We also documented other slope conditions such as the presence of surface water runoff or ground water seepage, vegetation, condition and maintenance history of the ditch, and observed mechanisms of slope failure.

ANALYSIS CONSIDERATIONS

General

The "Guidelines" presented in Part II of this report recommends listing the concerns and constraints for each site in order to identify those items that affect the final slope design. Independent design criteria resulting from these concerns and constraints must then be evaluated when designing slopes. The criteria, which must be considered for every slope, include costs, safety, stability, sedimentation, maintenance, and aesthetics. Each of these criteria may be mutually exclusive of any or all of the others or may have an adverse effect on the others. These are discussed in greater detail in the Guidelines. For the specific sites in this study we considered the criteria of safety, stability, sedimentation, maintenance, and aesthetics as discussed in the following paragraphs.

Safety

For purposes of this study, which evaluates the stabilization of cut slopes in rock, safety relates primarily to rockfall and the potential effects on traffic. Generally, a "safe" slope in rock is defined as a slope from which rockfall does not enter the travelled way (driving lanes) of the highway and where traffic is not allowed to enter a designated rockfall area. For our studies we used the Oregon Rockfall Hazard Rating System (ref. 39, Part II), an effective and rational method for evaluating the rockfall hazard of existing slopes. By this method, a subjective numerical rating is determined for a rock slope which allows it to be compared to other slopes. Through this comparison, funding for hazard reduction can be directed at those slopes with the greatest hazard. This method not only includes geologic and geometric considerations but also such elements as sight distance, ADT, etc. to include the hazard exposure time in the rating. Sites 7 and 8 in the Appendix, pages 54-57, include example ratings by this method.

The FHWA has recently implemented a training program which includes a training manual and a two-day training session in which Larry Pierson, Oregon DOT Geologist, spends the first day instructing on the use of this rating system. On the second day, Chuck Browner, an authority on rockfall mitigation from British Columbia, discusses rockfall hazard mitigation measures. This course is intended for all preconstruction, construction, maintenance, and geotechnical personnel who deal in some manner with rockfall hazard. The cost of the program to any state agency is $2,000 for the instruction and training manuals and is intended for 40 students ($50/student). Arrangements for the course can be made through the nearest FHWA district office.

Rockfall can also be simulated by the Colorado Rockfall Simulator Computer Program, CRSP (ref. 37, Part II). This program allows the user to simulate the "rolling" of a number of rocks off of a slope profile and to evaluate such things as bounce height and distance travelled from the starting point. Through screen graphics, the user can visualize the rockfall on the slope profile. Design alternatives such as various cut slope inclinations, the use of strategically-placed benches, the use of revetment barriers, the consequences of not maintaining the benches and other effects can be evaluated and compared using this program. Site 17 in the Appendix, pages 27-37, includes the results of an example rockfall simulation by this program to determine the effectiveness of a bench as constructed, as compared to other design alternatives which might have been used.

Rockfall hazard reduction measures are primarily not intended to stop rockfall, but to contain it and prevent the entry of the rocks into the travelled way of the highway. There are several commonly used methods such as wide ditches, benches, screening, rock fences, revetment barriers, and retaining walls. Where appropriate, these methods have been recommended for specific sites on the Site Reconnaissance forms in the Appendix. The various treatment methods are also discussed in greater detail in the Guidelines, Part II including references for specific design procedures.

Stability

A "safe" slope is not necessarily a "stable" slope. There are differing definitions of "stable" as used in slope design. Some definitions include both the ability to resist surface erosion and mass failure along some plane. However, for this study, surface erosion is considered as sedimentation and only mass failure is considered when evaluating stability. Also, some definitions define stability in terms of a safety factor against mass failure. Others define stability in terms of a range of probability that mass failure will not occur within a given design life. For this study "stable" is defined as reduction of the potential for mass failure or rockfall to a level that can be accommodated by routine maintenance.

The slope ranges that can be constructed in a "stable" condition are determined in rock by the degree of weathering, the internal shear strength of the rock, the presence, inclination, and shear strength of rock discontinuities, and ground water. Failure along discontinuities are of the plane, wedge, and toppling varieties as outlined in the description of the Black Hills rock units. The potential for these failures depends on the discontinuity inclination angle and direction (dip and dip direction), and how a cut slope intersects these discontinuities as determined by the inclination and direction of the cut slope. The possibility of these failures occurring can be predicted using stereonet analysis of the geometry of the slope features. Limit equilibrium analysis of plane and wedge failures is also possible to evaluate the factor of safety against failure with or without mechanical stabilization (rock-bolting). Numerical methods are also available for moment analysis of a potential toppling failure. All of these methods are available in the ROCKPACK computer program (ref. 44, Part II) to aid the designer. Sites 13, 14, and 15, pages 5-26 in the Appendix, include examples of ROCKPACK analyses.

All of the factors that can cause a failure along rock discontinuities also interact within a soil mass, within incompetent rock, or at the contact between soil and rock. The potential for failure of this type is also analyzed using limit equilibrium but with soil mechanics methods and search routines for locating the potential failure surface with the least factor of safety against failure. The computer program XSTABL (ref. 47, Part II) is an excellent tool for this purpose. Sites 3 and 19, pages 91-99 and 103-118 in the Appendix, include examples of the use of this program to analyze the stability of two slopes in prefailure and postfailure conditions and to evaluate the effects of stabilization measures at these sites.

In addition to laying back the slope to a stable angle, there are several methods of slope stabilization discussed in the Guidelines section of this report including rock-bolting, buttressing, retaining structures, drainage structures, and shotcreting. This section also includes references to direct the user to specific design procedures for the treatment methods.

Sedimentation

The primary concern associated with sedimentation is the impact on streams and other resources related to the streams. For many of the rock slopes evaluated, sedimentation was not a major concern because the rock materials involved will contribute little or no sedimentation to streams. Where sedimentation concerns result from rock slope instability they can be mitigated in conjunction with the stabilization of the slope. Sites 3 and 5, pages 103-120 in the Appendix, are examples of sites where stabilizing the slopes using the recommended treatment methods will also mitigate the sedimentation concerns. The Guidelines discusses vegetative treatment methods and suggests references that provide design procedures for slope treatment methods that are very effective in mitigating erosion and sedimentation.

Maintenance

Generally, a slope designed to be stable with a minimum amount of sediment will also require minimum maintenance. For the sites evaluated in this study, future maintenance needs were considered in the development of recommendations for treatment methods and methods selected that will require low maintenance where appropriate. Occasionally sites are encountered where the cost of stabilizing the slope is so great that greater maintenance effort is more cost-effective.

Aesthetics

Aesthetics is a difficult design criterion to satisfy because of the personal judgment involved. Certainly a bare rock slope is viewed differently by a geologist and a landscape architect. Generally, however, a rock cut slope is not a natural occurrence and distracts from the natural beauty of the adjoining landscape. A primary design effort then is to "soften" the appearance of the cut slope and to attempt to make the slope appear more natural. This may add substantially to the construction costs, particularly in areas of high cut slopes and other restrictions. In our evaluation of sites in this study we have not provided suggestions for treatment methods specifically to enhance aesthetics. However, the Guidelines discusses a number of treatment techniques that provide for improved aesthetics. The treatment methods include the construction of benches, off-set shooting and other techniques to construct an irregular slope surface, and the inclusions of vegetation as appropriate to further soften the slopes. These treatment techniques should be considered when designing reconstruction of existing rock cut slopes or construction of new slopes.

RESEARCH RESULTS

GENERAL

As previously stated, rock and soil units for the Black Hills were classified and grouped in a "problem-specific" format based on readily recognizable characteristics. For simplicity, only four rock units and two soil units are used to describe typical Black Hills site conditions. There are many "shades of gray" between adjacent groups, and the user will have to select the most appropriate based on the engineering characteristics that appear to be most representative. The slope stability analysis, optimum stable slope ranges, and possible slope treatment methods for each group are necessarily broad in range with qualifiers in order to cover a wide range of possible site conditions. Examination of existing slopes will help to narrow these ranges, and geotechnical investigation and analysis will be required to evaluate to more specific standards.

The following format is used to describe each rock and soil unit:

1. Typical rock, soil, and site characteristics.
2. Typical slope failure mechanism and appropriate method(s) of slope stability analysis.
3. Optimum stable slope range(s).
4. Applicable slope treatment methods.
5. Photographs of typical Black Hills sites.

All of the sites investigated in this project have been classified by this method and the site investigation data are included in the Appendix, complete with photographs and highway locations. The data sheets for each site also include recommended treatment methods for that particular slope. The potential user of the guidelines and recommended site reconnaissance data form will benefit by reviewing these classifications and visiting the sites if necessary.

ROCK UNIT A (RUA)

1. **RUA, Typical Rock and Site Characteristics.** Rocks in this group are competent (URC [Unified Rock Classification] weathering classes A and B and estimated strength classes A and B) and have two or more parallel sets of intersecting open planes of separation (discontinuities - URC class E). The spacing between parallel discontinuities is far enough apart that ripping would probably be difficult, but controlled blasting effective in cut slope construction. Rock-bolting can be considered to be an effective method if mechanical slope stabilization is required. Rockfall from RUA can be quite hazardous because of the size of the failure blocks and quantity of failure material that might end up in the driving lanes.
2. **RUA, Typical Slope Failure Mechanism and Stability Analysis.** Failure of rocks in this category is primarily along relatively parallel discontinuity sets. Measurement of the dip and dip direction (slope angle and slope direction) of the discontinuities that form the boundaries of existing small failures at a site can be used to predict larger failures that might result from the intersection of one or more of these discontinuity sets by a highway cut slope. Photo I-1 illustrates a site where the dip is favorable and will not be intersected by the cut slope.
    a. **Plane Failures.** Photo I-2 shows a plane failure that has only one failure surface (surface of sliding) along one discontinuity set intersected by the cut slope. Plane failure occurs when the dip direction of the failure surface discontinuity is oriented nearly at right angles to the direction of the cut slope. The possibility of this intersection occurring can be analyzed rapidly by stereonet projection. Stability analysis by limit equilibrium is required to determine the relative degree of stability (factor of safety against failure) and to estimate the stabilizing effects of rock-bolting. The data for Site 14, pages 11-20 in the Appendix, include an example of plane failure analyses.
    b. **Wedge Failures.** Photo I-3 shows a wedge failure that requires the intersection of two sets of discontinuities somewhere on the cut slope face. Stereonet and limit equilibrium analyses are also used to determine the potential for and relative stability of wedge failures. The analyses are more complicated than for plane failure since there are two failure surfaces (surfaces of sliding) that must be accounted for. The data for Sites 13 and 15, pages 5-10 and 21-26 in the Appendix, include examples of wedge failure analyses.
    c. **Toppling Failures.** A toppling failure is possible when two sets of discontinuities intersect to form a relatively tall and slender, steep-sided column with the sides nearly at right angles to a sloping base formed by a third discontinuity. As the name implies, when the column is constructed relatively high in relation to slope of the base, it can become off balance and simply tip or topple toward the cut face. Although this type of failure is possible in RUA, there was little evidence of this failure at Black Hills sites.

3. **RUA, Optimum Stable Slope Range(s).** Since the potential failures are controlled by the orientation of discontinuities, the slope ranges that will be stable depend on how the discontinuities that can become failure surfaces are intersected by a cut slope. If the orientation is favorable (potential failure surfaces dipping into the slope, see Photo I-1) the cut slopes can be constructed very steep (1/2H:1V or steeper). If the orientation is unfavorable, plane or wedge failures are possible and the optimum slope without mechanical (rock-bolting) stabilization can be as low as the friction angle of the rock (about 40 degrees for Black Hills rocks without any soil infilling of the discontinuities), which is about 1.2H:1V. This occurs if the potential failure plane for plane failures or the intersection of the two potential failure planes for a wedge failure is steeper than 40 degrees. Cut slopes from 1.2H:1V to 1/4H:1V may be stable if the unfavorable potential failure surface(s) that intersect the cut slope are inclined at an angle less than 40 degrees out of the slope. Although unlikely, the potential for toppling failure should be considered for cut slopes steeper than 1/2H:1V (the steeper the column side slopes, the higher the probable failure column). Observations of the existing slopes, evidence of past stability or instability, and the construction and maintenance history of the slope should be helpful in determining the optimum slope range. Geotechnical stability analysis should be used in the final evaluation of questionable proposed cut slopes.
4. **RUA, Applicable Slope Treatment Methods.** Because of the relative competency of this rock unit, if a stable cut slope cannot be designed without mechanical stabilization, rock-bolting is a favorable method of providing the required mechanical support (see Site 14, pages 11-20, for a sample analysis to stabilize a potential plane failure). Other stabilization methods that might be considered are buttressing or retaining walls. If these methods are not feasible and steep cut slopes with potential rockfall hazard must be constructed, the use of wire netting, benching, rock fences, and other rockfall barriers should be considered. Refer to the "Guidelines" section of this report (Part II) for a summary and suggested references for each of these techniques.

5. **RUA, Photographs of Typical Black Hills Sites.** See also Sites 9, 13, 14, 15, 17, 18, 21, 22, and 23 for typical photographs.

Photo I-1. RUA with favorable dip.

Photo I-2. Plane failure in RUA.

5. RUA, Photographs of Typical Black Hills Sites. (Continued)

Photo I-3. Wedge failure in RUA.

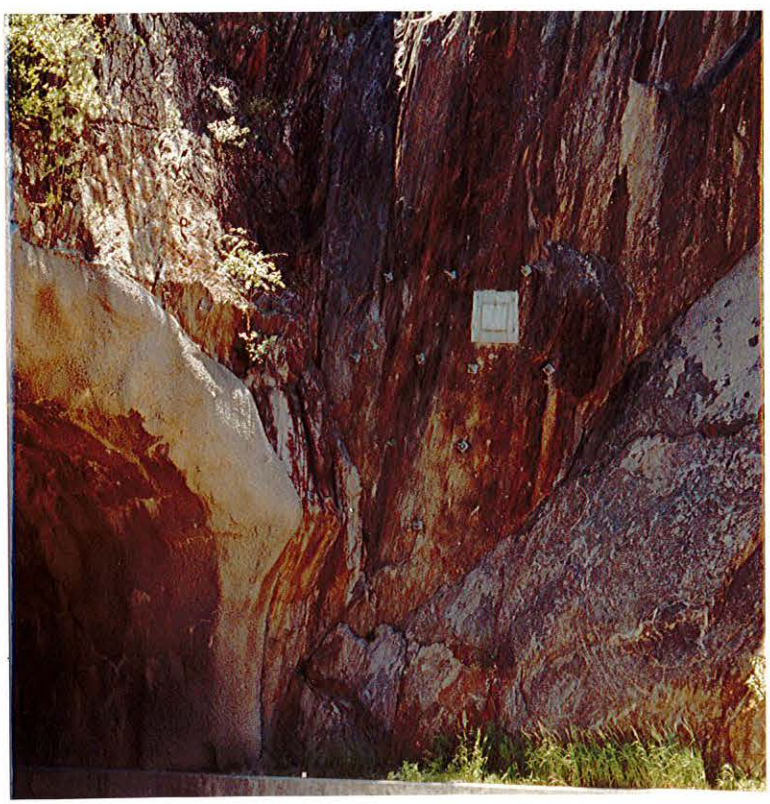


Photo I-4. Mechanical stabilization (rock-bolting) in RUA.

ROCK UNIT B (RUB)

1. **RUB, Typical Rock and Site Characteristics.** Rocks in this group are as competent as RUA (URC weathering classes A and B and estimated strength classes A and B) and have two or more parallel sets of intersecting open planes of separations (discontinuities - URC class E). But in this group, the discontinuities are so close together that they are easily separated. Ripping would probably be an effective method, and controlled blasting, although possible, probably would not be a satisfactory method of cut slope construction. Rock-bolting would not be an effective method of mechanical stabilization. RUB rockfall is less hazardous than RUA since the small platy blocks are more likely to form a talus slope. Typical slopes in RUB material are shown in Photos I-5, I-6, I-7 and I-8.
2. **RUB, Typical Slope Failure Mechanism and Stability Analysis.** As with RUA, failures may still be controlled by the orientation of the discontinuities so that plane and wedge failures are still possible. However, because of the close discontinuity spacing, a potential failure surface can readily form across discontinuity planes. Plane and wedge failure analyses are appropriate, but for cut slopes steeper than 40 degrees (the anticipated friction angle for these rocks in the Black Hills), the proposed cut slope should also be analyzed by a limit equilibrium method much like a residual soil slope. This analysis requires a search routine for the potential failure surface with the least factor of safety against failure. Toppling failures are very unlikely because of the unlikely occurrence of a tall, slender failure column.
3. **RUB, Optimum Stable Slope Range(s).** Conservatively, the slope should be flattened to 1H:1V or flatter. This is because of the potential for failure much like a residual soil slope. Slopes flatter than the friction angle (about 40 degrees, which is about 1.2H:1V) would be preferable for revegetation by trees and/or grass.
4. **RUB, Applicable Slope Treatment Methods.** Rock-bolting is not an option. Flattening the slope and revegetating would probably be preferable. Stabilization by buttressing and retaining walls would also be applicable. Rockfall would be a problem if a slope steeper than 1H:1V has to be constructed. All of the rockfall hazard reduction techniques mentioned for RUA, such as wire netting, benching, and barriers, are also applicable for RUB.

5. **RUB, Photographs of Typical Black Hills Sites.** See also Sites 7, 8, 10, 11, and 12 for typical photographs.

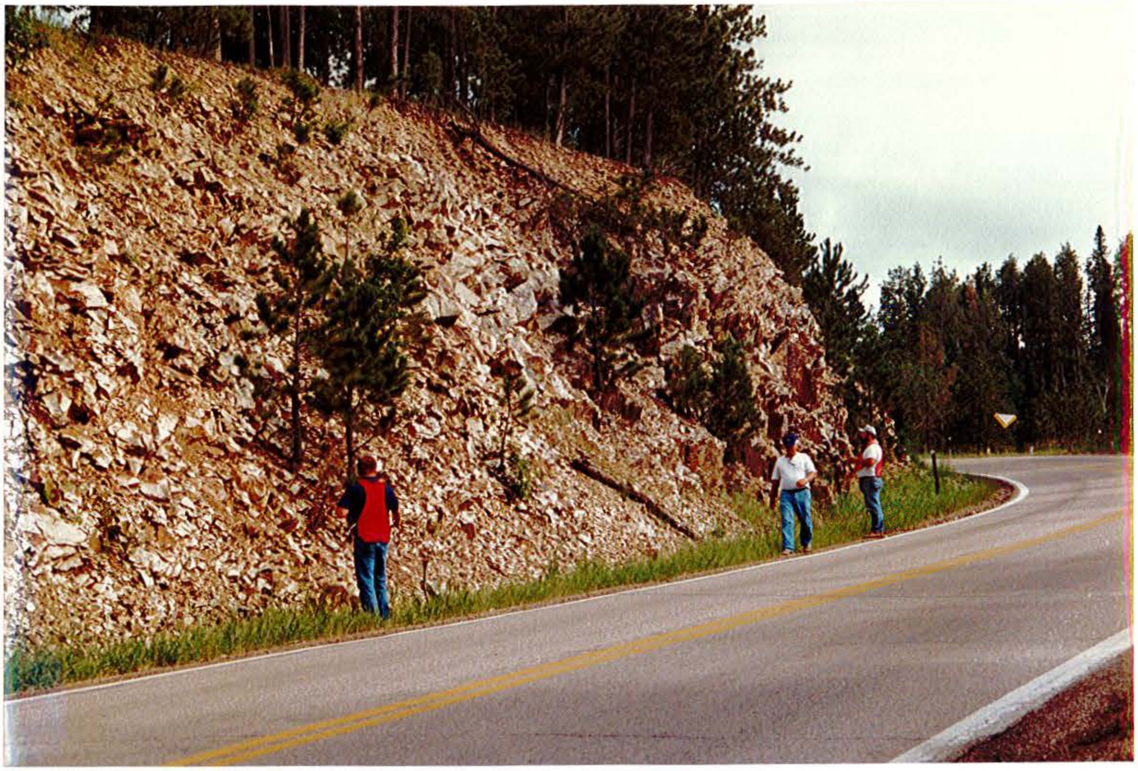


Photo I-5. Typical RUB slope.

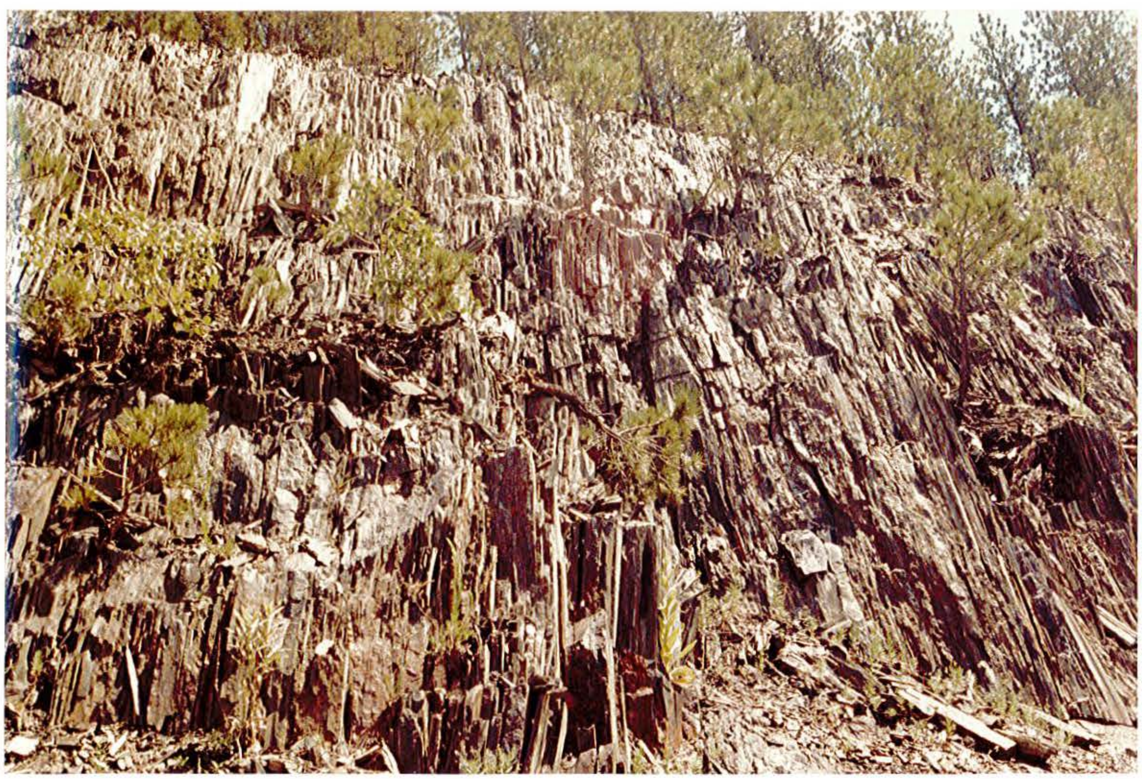
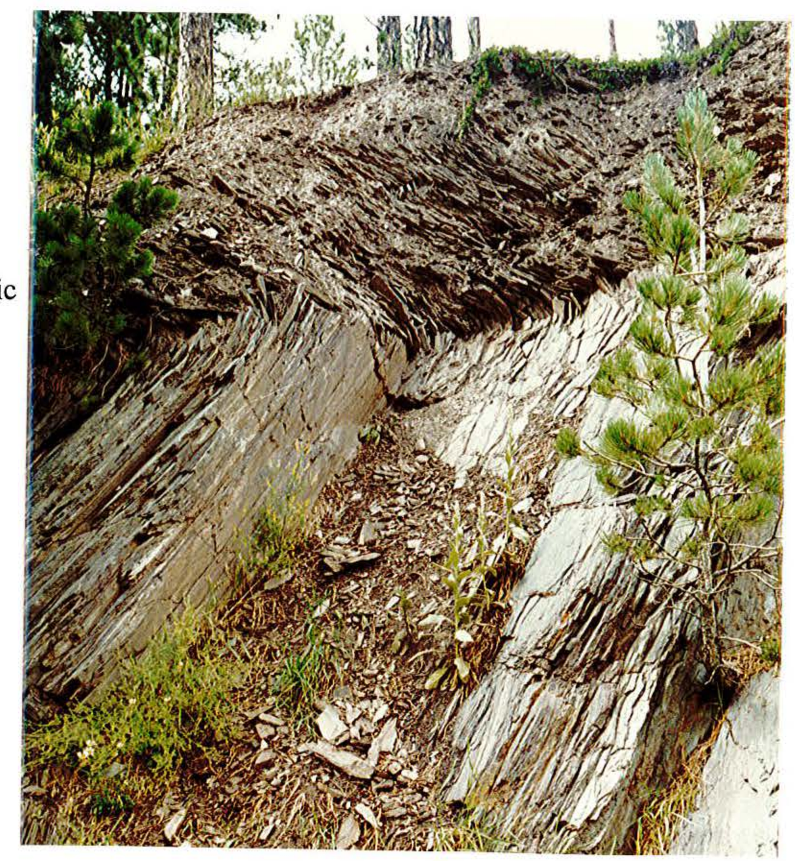


Photo I-6. Typical RUB slope.

5. **RUB, Photographs of Typical Black Hills Sites. (Continued)**

Photo I-7. Typical RUB slope with natural tree revegetation.

Photo I-8. Unique geologic formation in RUB (overturned folding).



ROCK UNIT C (RUC)

1. **RUC, Typical Rock and Site Characteristics.** Rocks in this group have relatively competent beds or zones (URC weathering classes A to C and estimated strength classes A to C) either interbedded or completely surrounded by incompetent beds or zones (URC weathering classes D and E and estimated strength classes D and E). The competent beds have discontinuities that form relatively large blocks with low angle base slopes which, because of differential weathering of underlying incompetent beds, are subject to failure. Construction of a cut slope by ripping is possible in the incompetent beds, but may be difficult in the competent beds. Conversely, controlled blasting might be effective in the competent beds, but ineffective to control a cut slope angle in the incompetent beds. This can result in construction difficulty if the competent rocks are merely a zone completely surrounded by incompetent rocks (see Photo I-9). Rock-bolting is probably not a likely method of stabilization as there may be nothing to bolt a possible failure block to. Rockfall from RUC can be extremely hazardous because of the size and shape of the blocks that can roll onto the driving lanes.

2. **RUC, Typical Failure Mechanism and Stability Analysis.** Failure of rocks in this category is primarily a result of the differential weathering of the incompetent rocks, which causes a ravelling and sedimentation problem and undermines overlying competent rocks. The overlying rocks, although they have relatively low angle base slopes (usually bedding planes), have intersecting discontinuities that form potential failure blocks.

   a. **Plane and Wedge Failures.** Since the base slopes are relatively low angle, plane and wedge type failures are not as common as they are in RUA and RUB. However, where ground water is present, underlying incompetent rocks such as shale can weather to a clay of low shear strength. As a result, low angle plane or wedge failures can develop in the more competent overlying rocks from the hydrostatic water pressure above the clay and with the failure surface within the low shear strength clay layer (see Photo I-10).

   b. **Toppling and Collapse Failures.** Frequently, the potential failure blocks are relatively tall and slender columns. Failure of these blocks can either be by toppling (as a result of the slope and compressibility of the underlying basal material [Photo I-11]) or if completely undermined, simply by collapse (Photo I-12). Toppling failures can be analyzed by moment analysis of the column dimensions and base slope. Refer to Site 6, pages 76-81, for a sample toppling analysis for RUC. However, it can be difficult to tell a toppling failure from a collapse failure. The open joints at the back of a potential failure block (see Photo I-11) can be an indicator that the column is rotating about the base and "toppling." Whether toppling or collapse, the potential failures are best corrected by the control of differential weathering or otherwise stabilizing the incompetent rock beds or zones.

3. **RUC, Optimum Stable Slope Range(s).** Because of the low base angle of the competent beds, cut slopes can be constructed at steep angles (1/2H:1V or steeper) as long as differential weathering of the underlying incompetent beds can be controlled. The potential for toppling failures must still be considered a possibility. The shear strength of the incompetent beds can be variable. If they weather to clay, which is common for shale beds, a stable slope may be flatter than 3H:1V, especially if ground water is present. Usually, slopes in the range of 1H:1V to 1.5H:1V will be stable in the incompetent beds. If the competent beds are a caprock, a compound slope of something like 1/4H:1V through the competent caprock and 1H:1V in the incompetent rocks underneath may be possible.
4. **RUC, Applicable Slope Treatment Methods.** Mechanical stabilization such as rock-bolting is unlikely to be successful because there may be little to bolt a potential failure block of competent rock to. Control of the differential weathering or otherwise stabilizing the incompetent beds should be the most successful. Flattening the slope in the incompetent rocks and revegetating will probably be the most satisfactory method. If this cannot be accomplished, methods such as shotcreting, buttressing, and retaining structures can be considered. The rockfall hazard reduction techniques, wire netting, benching, and barriers, listed for RUA are also applicable for RUC.

5. RUC, Photographs of Typical Black Hills Sites. See also Sites 1, 2, 4, 6, 20, and 24 for typical photographs.

Photo I-9. Competent zone in RUC surrounded by incompetent rock.

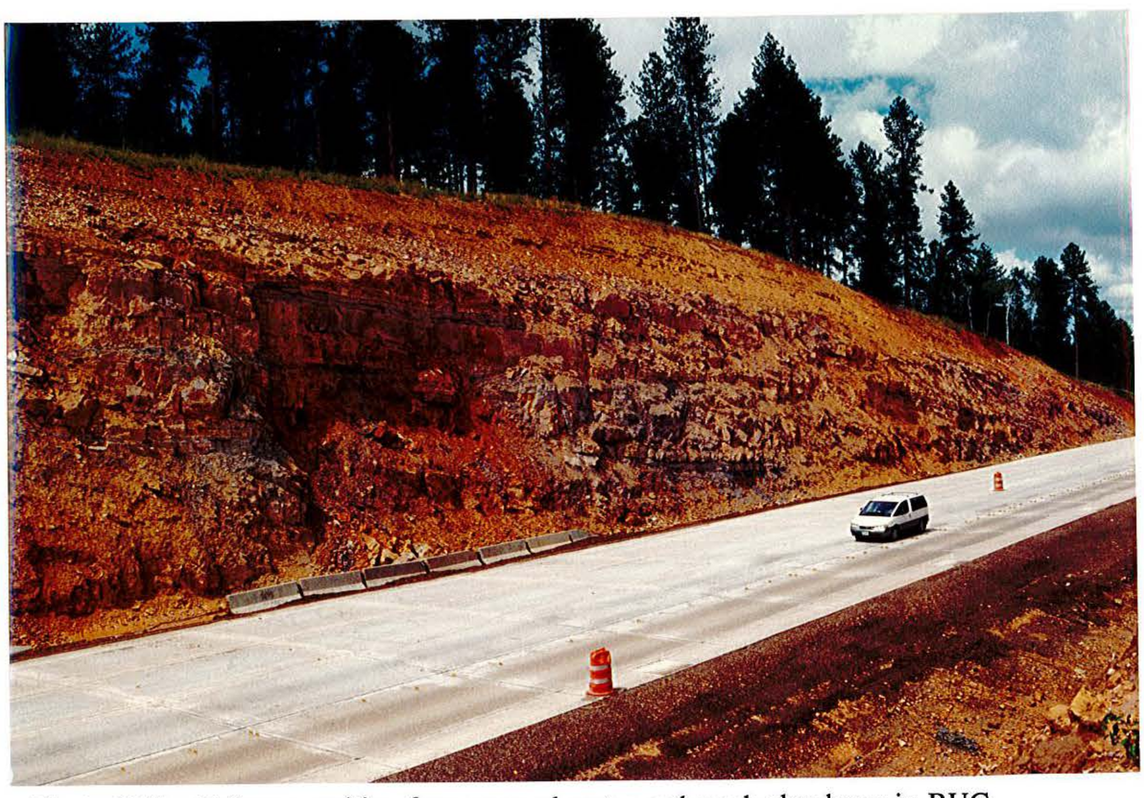
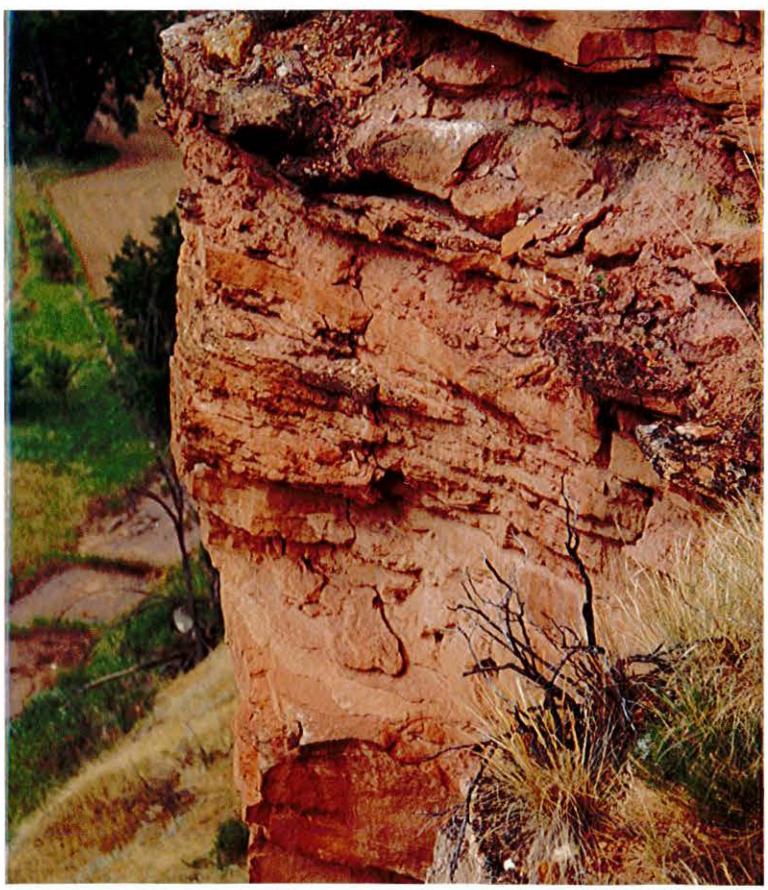


Photo I-10. Failure resulting from ground water and weak clay layer in RUC.

5. RUC, Photographs of Typical Black Hills Sites. (Continued)

Photo I-11. Potential toppling failure in RUC.

Photo I-12. Typical RUC slope with potential collapse failure.



ROCK UNIT D (RUD)

1. **RUD, Typical Rock and Site Characteristics.** Rocks in this class are incompetent and decompose easily into soil (URC weathering classes D and E and estimated strength class E). Even though there may be some isolated competent zones, they are surrounded by incompetent material and cannot be relied on to support the slope (see Photo I-14). Discontinuities may be present and provide some control of the failure surface (see Photo I-13), but generally the failure surface can cross discontinuity surfaces and is controlled by the internal strength of the incompetent rock. Moderate rockfall hazard can be expected from the more competent blocks that might ravel out of a steep cut slope.
2. **RUD, Typical Slope Failure Mechanism and Stability Analysis.** Failure can be along any potential failure surface within the incompetent rock mass. The shear strength of the decomposed rock controls the type of failure. If the rock decomposes into a sandy or gravelly soil (Photo I-15) the failure surface will be relatively steep and can be circular arc or translational (planar) in shape. If the rock decomposes and weathers into a clayey soil, the failure is likely to have a low angle translational surface and often will involve ground water because of the relatively impermeable nature of the clay (Photo I-16). In this case, often the clay is only a thin zone at the top of a shale bed and the failure is along the dip slope of the shale. This is why the shape is often translational. The analysis for each of these potential failures should be by limit equilibrium with a search routine for the failure surface with the minimum factor of safety against failure. Site 19 data, pages 91-99 in the Appendix, include a sample analysis of an RUD failure.
3. **RUD, Optimum Stable Slope Range(s).** For the sandy and gravelly decomposed material, slopes from 3/4H:1V to 1.5H:1V should be stable if ground water does not appear to be a factor. For the clayey residual soil, the stable slope may be flatter than 3H:1V and will probably be impractical to design without additional stabilization.
4. **RUD, Applicable Slope Treatment Methods.** Flattening the slope and revegetating should be successful for the sandy and gravelly decomposed material. Buttressing and retaining structures are the most likely methods of artificial stabilization. Because of the low failure angles in a clay material with ground water, drainage of the overlying material and removal of the weak clay zone at the toe should be successful. See Site 3 in the SUS/SUC section, pages 103-117 of the Appendix, for an applicable analysis for a similar treatment of a colluvial soil over a clay failure surface. All of the rockfall hazard reduction techniques, including wire netting, benching, and barriers, listed for RUA are also applicable for RUD slopes.

5. **RUD, Photographs of Typical Black Hills Sites.** See also Sites 16, 19, and 25 for typical photographs.

Photo I-13. Typical RUD slope.

Photo I-14. RUD slope with ineffective isolated competent rock.

5. RUD, Photographs of Typical Black Hills Sites. (Continued)

Photo I-15. RUD failure with sandy and gravelly decomposed material.

Photo I-16. RUD failure with weathered clayey material.

SOIL UNIT SAND (SUS)

1. **SUS, Typical Soil and Site Characteristics.** These can be any number of cohesionless soils ranging from silt to gravel, which have relatively high friction angles (greater than 30 degrees) and behave as a sand rather than a clay. Typically these are colluvial deposits that overlie most rock slopes in the Black Hills. They may have seasonal "perched" ground water concentrations since the underlying rock formations are usually less permeable. This is really a problem if the underlying rock is a shale and a thin layer of SUC (soil unit clay) soil exists at the contact between the two (see Sites 3 and 5, pages 103-120). Photos I-17 and I-18 show typical slopes in SUS materials.
2. **SUS, Typical Slope Failure Mechanism and Stability Analysis.** Predominantly, failures are controlled by the internal strength of the soil and pore pressure from ground water (if present). Slope stability analysis should be by limit equilibrium with a search routine to determine the potential failure surface with the least factor of safety against failure (see Site 3, pages 103-117). Ravelling of slopes constructed at 1H:1V or steeper appears to be the most prevalent problem with these slopes in the Black Hills (see Photo I-19). The exception to that is the translational failure problem associated with the SUS over SUC and "perched" ground water in the SUS previously described (see Photo I-20). In that case, the shear strength of the underlying SUC controls the slope since it provides the surface on which the ground water is concentrated and the failure occurs.
3. **SUS, Optimum Stable Slope Range(s).** If ground water and an underlying SUC are not a problem, slopes constructed to 1H:1V or flatter should be stable. If ground water is a problem, drainage structures will be needed to stabilize these slopes.
4. **SUS, Applicable Slope Treatment Methods.** Flattening the slope and revegetating will be the most effective method for treating these shallow surficial deposits. If ground water is a problem, drainage may be required to stabilize. Buttressing and retaining structures may also be effective. Wire netting, benching, and barrier rockfall hazard reduction techniques listed for RUA are applicable to steep SUS slopes (1H:1V or steeper).

5. **SUS, Photographs of Typical Black Hills Sites.** See also Sites 3, 4, 5, 6, 20, and 25 for typical photographs.

Photo I-17. Relatively thick SUS colluvium deposit.

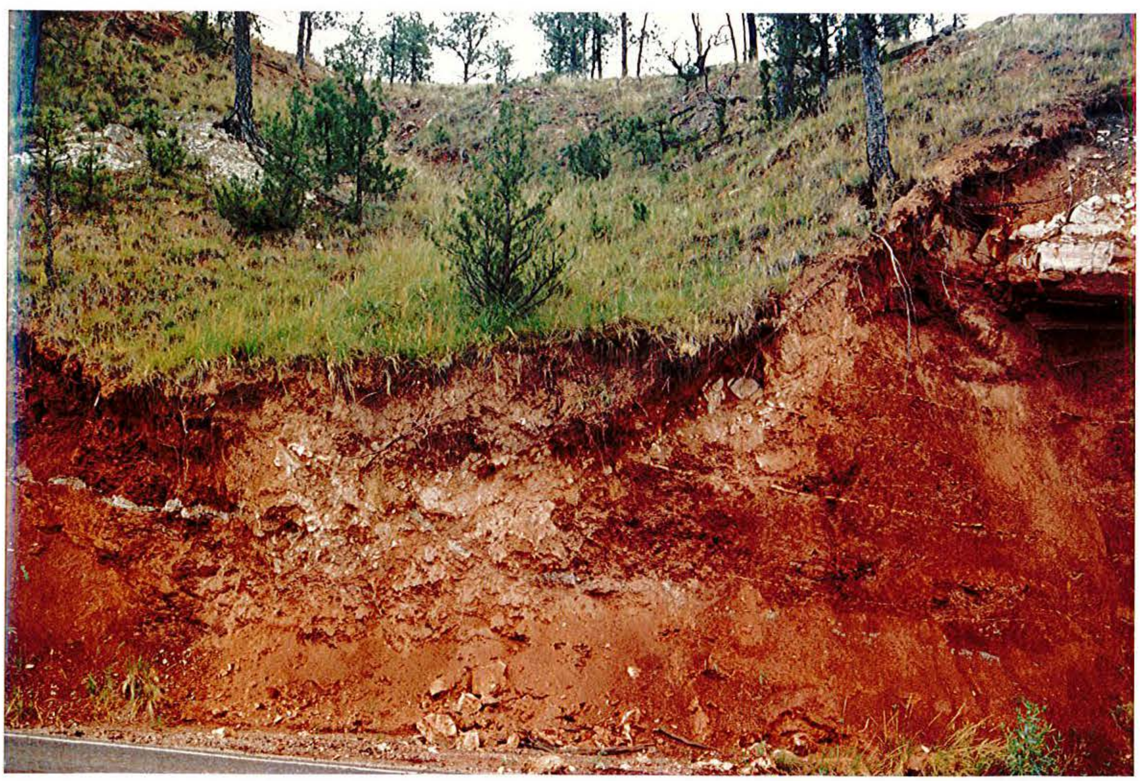


Photo I-18. Relatively thin SUS colluvium deposit.

5. SUS, Photographs of Typical Black Hills Sites. (Continued)

Photo I-19. Ravelling failure in SUS.

Photo I-20. Ground water-related failure of SUS over SUC.

SOIL UNIT CLAY (SUC)

1. **SUC, Typical Soil and Site Characteristics.** This group of soils includes any number of cohesive soils that are relatively impermeable and have relatively low frictional strength (less than 20 degrees). They usually occur as a thin layer at the surface of a shale rock unit. Since they are relatively thin, they may be difficult to recognize since the bulk of the failure mass is not SUC material but the overlying material (usually SUS, see Photo I-21). Photos 2 and 3 of Site 3, pages 103-117 in the Appendix, illustrate the outline of a clay layer at the top of a shale bed.
2. **SUC, Typical Slope Failure Mechanism and Stability Analysis.** Failures usually involve ground water concentrated above the relatively impermeable clay and are translational (planar) in shape following the weak clay layer. Since the frictional strength of the clay is low, failure can occur at low angles (15 degrees or less).
3. **SUC, Optimum Slope Range(s).** Since failures can occur at such low angles, it is difficult to stabilize a slope by flattening it. The material that is failing is usually an overlying material such as a SUS soil that by itself would be stable at slopes in the range of 1H:1V. Stabilization measures other than grading are usually required in the construction of a stable slope.
4. **SUC, Applicable Slope Treatment Methods.** Since the clay layer is usually quite thin and shallow, removal of the clay combined with drainage and buttressing is an effective method (see Site 3, pages 103-117 in the Appendix). Once the slope face is stabilized, revegetation is possible. Until stabilization is achieved, revegetation efforts will not be successful. Refer to Photo I-22 for an example of a failure in the clay caused by ground water. The failure completely destroyed the roving shown in the center of the photo while that in the upper left is still intact.

5. **SUC, Photographs of Typical Black Hills Sites.** See also Sites 3 and 5 for typical photographs.

Photo I-21. Ground water-related failure of SUS colluvium with basal SUC on red shale.

Photo I-22. Failed slope of SUS over SUC with roving damage.

CONTINUING STUDIES

GENERAL

During the course of our studies, it became evident that additional evaluations or development beyond the scope of this project will be valuable to the development of treatment methods for rock slopes on highways in South Dakota. For some methods, this continuing effort may involve the adaptation and trial use of a specific type of equipment for seeding of slopes using equipment developed earlier by another agency. Another area of further study is the evaluation of the adaptability and effectiveness of different types of vegetation used for stabilization and aesthetic improvement of slopes. This will involve developing a list of different types of vegetation appropriate for use in the Black Hills and conducting studies of test plots and selected sites to ascertain their effectiveness. These and other areas recommended for further study are described in greater detail in the following paragraphs.

VEGETATION

A primary factor in the effectiveness of vegetation treatment methods is the suitability of the type of vegetation for the particular location and application. To this end, it is important to have data relative to plant types, both indigenous and off-site species, and application or planting methods. Developing that information will require literature search, setting up test plots and completing observations, activities beyond the scope of this current study.

We recommend that further study be completed that would develop data relative to vegetation in the following areas:

- Vegetation types suitable for use in the Black Hills. This should include mosses, grasses, legumes, flowers, shrubs, and trees. Consideration should be given to plants that are indigenous to the area as well as plants that have proven successful elsewhere.
- Planting methods appropriate to the vegetation type and the terrain. Evaluation should include hand planting or seeding; hydroseeding methods, especially the mixing of seeds such as grass, shrubs and trees; seeds included in protective blankets; and mechanical seeders.
- Effect of climate and slope aspect on germination and growth.
- Evaluation of success of past practices.

The results of such a study will provide information for selecting vegetation types and planting methods most suitable for site conditions in the Black Hills. This will aid in the completion of design and construction of effective vegetative treatment of slopes.

GEOLOGIC INTEREST SITES

South Dakota has a unique attribute in that it has a great variety of geologic conditions occurring within relatively short driving distances and readily accessible from the highway system. It is our opinion that this provides a great opportunity to create geologic interest sites that will inform the visitor and resident about those unique conditions and, perhaps, to convert a liability into an asset. There may be special opportunities where a troublesome rock cut also provides an unobstructed view of the local area geology. Providing a viewing area and an explanation of the conditions exposed in the slope may be more beneficial and cost effective than regrading the slope or obscuring it with a structure.

The results of establishing such geologic interest sites and the companion explanations should be a greater appreciation for such features. This may also attract more visitors who are interested in geology, especially those features evident in South Dakota and the Black Hills.

EFFECTIVENESS OF CURRENT AND PAST PRACTICES

It is evident from examination of existing slopes in the Black Hills that some vegetative treatment of slopes have been quite successful. We recommend that additional study be completed of treated slopes to assess the effectiveness of those treatments. In particular, those treatments that included innovative techniques should be examined and documented so that these treatment methods can be applied in other areas as appropriate. This study will involve primarily the examination of the slopes, the documentation of the techniques used and evaluation of the effectiveness of those techniques. The results will be very helpful in the future for selecting appropriate vegetative treatment methods.

STEEP SLOPE SEEDER

In the 1970s, the US Forest Service developed a seeder for drilling seeds into slopes too steep for normal seeding equipment. As developed, the machine was essentially a seed drill modified so as to be mounted on the arm of a Gradall hydraulic excavator. The machine was capable of planting seeds on steep slopes to a height equal to the reach of the excavator. Plants in trial plots seeded with the seeder germinated and grew much better than in plots seeded by conventional methods such as hydroseeding and by hand. Of special interest, the seeds of pine trees were included with the grass seed mix on a test plot in Idaho. That test plot showed markedly better germination and growth for the seeds planted with the seeder.

We recommend that this steep slope seeder be evaluated for use for steep slopes in the Black Hills. It appears this seeder would provide an alternative for the slopes too steep to be seeded with conventional seeding equipment. All of the information is readily available from the US Forest Service Research Station, so it should not be necessary to repeat any of the research work completed by them.

The benefit of the success of the seeder would be the revegetation of steep slopes. This may be a special benefit in those areas where appearance of the slope is of great importance and conventional methods of seeding have not been completely successful.

BENCHES IN ROCK SLOPES

The reluctance to use benching as a method to improve the stability of rock slopes has been expressed in the literature and by some agencies. However, during the conduct of our study we encountered a number of slopes treated quite successfully with benches cut into the slope. There is a need to evaluate the past use of benches on rock slopes in the Black Hills, and perhaps elsewhere with similar conditions, to identify those factors that led to the successful use of benches. In addition to identifying the specific geologic conditions at each site, the study should also determine all of the physical characteristics such as slope angles, width and height of bench, inslope or outslope, drainage, infilling, vegetation, inclination of bench, and others. This data could then be correlated with information at other sites to assist in the design and construction of benches on other slopes. The primary benefit of the study will be improved effectiveness of benches for treatment of rock slopes at other sites.

We will be pleased to discuss these recommended studies with you in greater detail and to answer any questions that you might have concerning completion of the studies.

CONCLUSIONS

The results of our studies confirm that a variety of conditions contribute to stability problems with rock slopes in the Black Hills. The studies also demonstrate a systematic method for examining those slopes and developing solutions for treatment of those slopes. For most of the slopes, two or more treatment methods may be appropriate. The choice of a preferred treatment method (or methods) will likely involve evaluation of all the concerns pertinent to a site before selection of the final treatment.

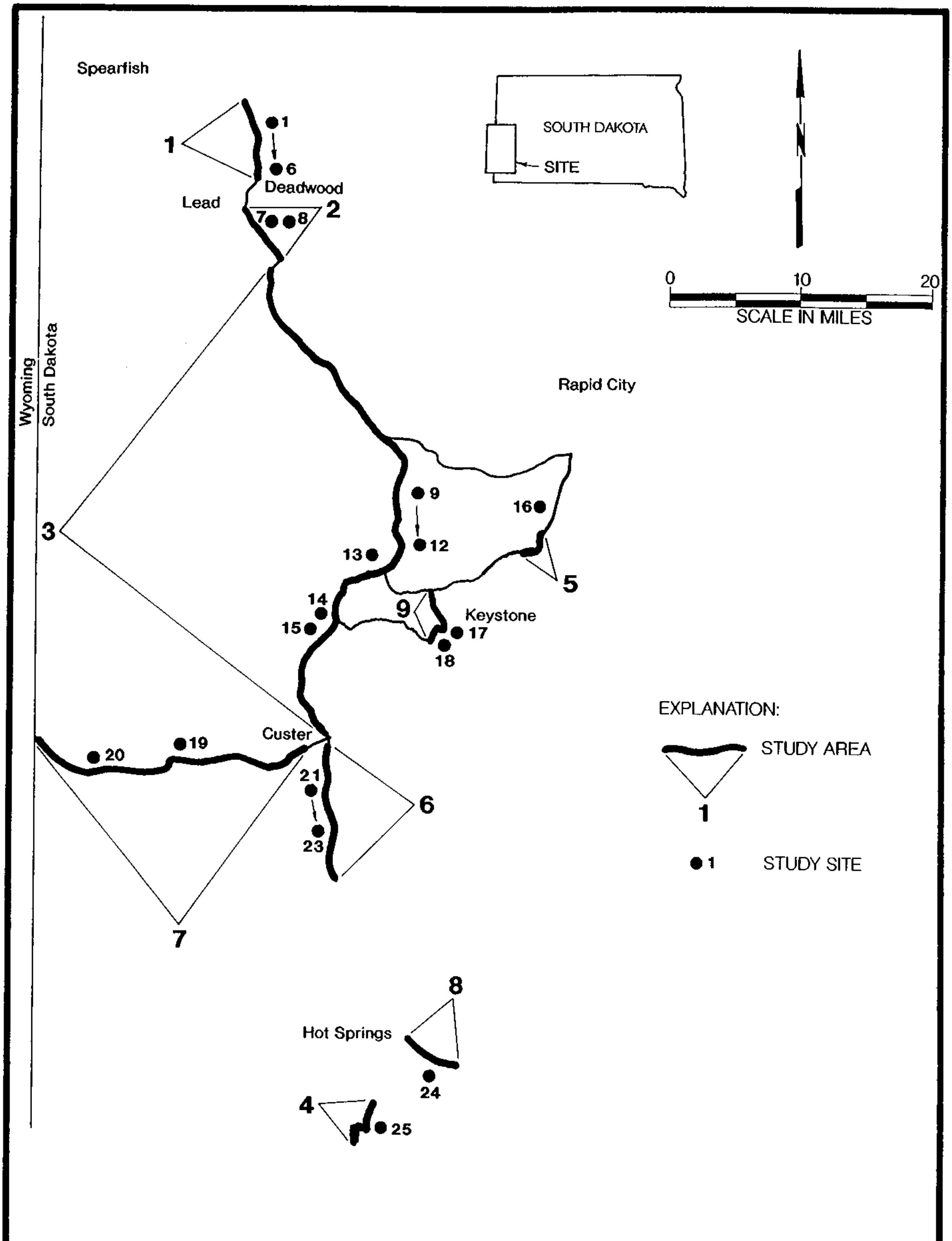
It is also our conclusion that many treatment methods are available that include the use of vegetation, either as a primary means of stabilization or in combination with some other method. Many of the sites we examined supported a growth of native trees and shrubs. It is our conclusion that methods are available to encourage the growth of such plants and such practices will enhance the stability and aesthetics of many of the rock slopes.

Each of the study sites is described in detail in the Appendix. Included on the data sheets for each site is a discussion of the optimum slope range for that site and recommendations for appropriate treatment methods.

RECOMMENDATIONS

In addition to site-specific and problem-specific recommendations presented in the Appendix and Part II of this report, the study team recommends the South Dakota Department of Transportation accomplish the following:

- Acquire the three analysis programs utilized in this study; Colorado Rockfall Simulation Program, Oregon Rockfall Hazard Rating System, and XSTABL, Reference Manual Version 5.0 for use by the geology and geotechnical group and others trained in the use and interpretation of the results.
- Implement the use of the Guidelines presented in Part II.
- Review the option of establishing geologic interest sites along South Dakota highways.
- Explore the use of various vegetation types and seeding methods for rock cut slopes. In particular, examine the successful growth of trees and evaluate methods for encouraging that seeding and growth.
- Treat slopes at trial sites using biotechnical slope treatment methods appropriate to those sites to develop familiarity with the methods and the vegetation most suited to those site conditions.
- Document the successful use of vegetative slope treatment methods in the past for application to other sites in the future.



GeoEngineers

SITE MAP

FIGURE 1

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APPENDIX

ROCK UNIT A (RUA)