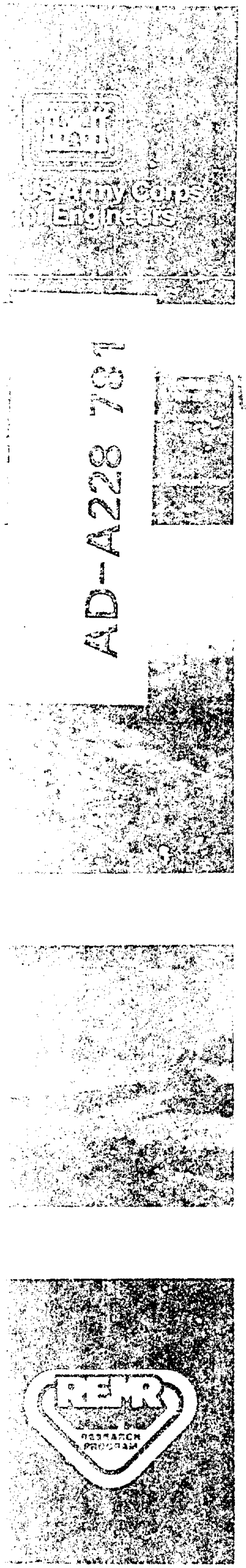

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REPAIR, EVALUATION, MAINTENANCE AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-GT-3

GEOTECHNICAL ASPECTS OF ROCK EROSION IN EMERGENCY SPILLWAY CHANNELS

Report 5
SUMMARY OF RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

by

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	Problem Area		Problem Area
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS

TOP — Accelerated erosion at a knickpoint produced by relatively low discharge and unventing beneath waterfall.

MIDDLE — Knickpoint in emergency spillway at Brownwood, Texas.

BOTTOM — Failure of DMAD spillway (Utah) due to knickpoint migration.

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This document is a final report of a series of REMR reports which summarizes 5 years of research on erosion in unlined emergency spillway channels. Experience has shown that severe erosion of rock and soils flooring unlined emergency spillway channels may cause undermining or failure of spillway structures and catastrophic release of reservoirs waters. Significant erosion-induced damage is well documented in spillway channels at projects built and managed by the US Army Corps of Engineers (USACE) and other Federal Agencies, and one large privately owned dam lost impoundment by spillway failure. An observational data base was developed to document cases of spillway erosion using data from site visits, Periodic Inspection Reports, videos of spillway flow, and the literature. The data base showed that severe erosion occurred at discharges which were less than 10 percent of Project Maximum Floods and at velocities which were greater than those recommended by current guidelines; spillway channel erosion was driven by processes

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A report of the Geotechnical problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. This report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

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similar to knickpoint migration (headcutting) in natural stream channels; and the occurrence of stratigraphic and structural discontinuities in the spillway foundation were important factors in controlling the occurrence and extent of erosion. Laboratory flume studies using simulated earth materials were conducted to investigate knickpoint migration at a waterfall. The waterfall consisted of an erosion resistant layer overlying a material of low erosion resistance. The geometric and hydraulic conditions at the waterfall were mathematically defined using a vented, erosion-dissipating drop structure as an analog. The flume studies showed that erosion and headcutting were maximized when the waterfall became unvented, the ratio of stage height-to-height of waterfall was 1:8 or less, the ratio of thickness of the erosion resistant layer to height of backroller was greater than 1:5, and there were structural discontinuities in the resistant layer. Furthermore, the model studies and computer simulations showed that erosion did not accompany peak discharge but rather it occurs on the lower portions of the rising and falling limbs of the hydrograph. These findings supports the observation that severe erosion may occur at discharges significantly lower than Project Maximum Flood or Spillway Design Flood. The evaluation of spillways channels having experienced erosion or suspected to be susceptible to erosion requires preparation of detailed engineering geologic maps and cross sections showing distribution of rock and rock mass properties, particularly lithostratigraphic and structural discontinuities; data from borings including geophysical logs, and information relative to the flood history of the facility (including hydrographs). Spillway erosion is a site-specific problem. The extent of erosion in a spillway may be described and compared with other sites by horizontal and volumetric erosion rankings which, respectively, show the relative amount of headcutting toward the spillway crest and the relative amount of material eroded from the spillway channel. Erosion susceptibility, similar to spillway evaluation, must emphasize rock-mass ratings or classification systems (e.g. rippability) which, when combined with lithostratigraphic discontinuity and hydraulic data, may provide indices indicative of conditions conducive to severe erosion. Remedial and preventive measures at sites having experienced erosion should be designed and emplaced to secure and protect rocks at the top and face of the knickpoint; gabions, rockbolts, and standard cement-based techniques are the most common used. The following recommendations are derivatives from these research activities: the CE should maintain close liaison and cooperation with the SCS in terms of site visits and the sharing of research information; sites which have experienced spillway flow should be documented, preferably by video, and described geotechnically, as well, and hydraulically; and future research should address erosion prediction, knickpoint pressure differentials and venting by flume and prototype testing, numeric modeling and computer simulation of knickpoint erosion, risk analyses (at conditions less than Project Maximum Flood or Spillway Design Flood), and the downstream sedimentation effects of severe erosion in spillway channels.

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PREFACE

The work described in this report was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Geotechnical-Rock Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Work Unit 32317, "Geotechnical Aspects of Rock Erosion in Emergency Spillway Channels," for which Dr. James H. May was Principal Investigator. Mr. Lewis Gustafson (CECW-EG) was the REMR Technical Monitor for this work.

Mr. Jesse A. Pfeffer, Jr. (CERD-C) was the REMR Coordinator at the Directorate of Research and Development, HQUSACE; Mr. James E. Crews (CECW-OM) and Dr. Tony C. Liu (CECW-ED) served as the REMR Overview Committee; Mr. William F. McCleese (CEWES-SC-A), US Army Engineer Waterways Experiment Station (WES) was the REMR Program Manager. Mr. Jerry S. Huie was the Problem Area Leader.

The work was performed at the US Army Engineer Waterways Experiment Station (WES) and this report was prepared by Drs. Christopher P. Cameron and David M. Patrick, Department of Geology, University of Southern Mississippi, Hattiesburg; and Dr. James H. May, Messrs. John B. Palmerton, and Colin C. McAneny, EEGD; with technical assistance from Dr. Allen W. Hatheway and Mr. Craig O. Bartholomew, Department of Geological Engineering, University of Missouri, Rolla; and Dr. Christopher C. Mathewson and Mr. Kerry D. Cato, Department of Geology, Center for Engineering Geosciences, Texas A&M University. The study was under the direct supervision of Mr. Huie, Soils and Rock Mechanics Division (SRMD); and Dr. J. H. May, Earthquake Engineering and Geosciences Division (EEGD); Geotechnical Laboratory (GL). General supervision was provided by Dr. Lawson W. Smith, Chief, Engineering Geology Branch, EEGD; Dr. A. G. Franklin, Chief, EEGD; Dr. D. C. Banks, Chief, SRMD; and Dr. W. F. Marcuson III, Chief, GL. Mrs. Joyce H. Walker, Information Technology Laboratory, edited the report.

This research study benefited from the helpful suggestions, constructive criticism, and information provided by CE District and Division geotechnical and hydraulic engineers, and like technical personnel in other Federal and State Agencies, academic institutions, and the private sector. Appreciation is also extended to Messrs. Randy Oswalt and Bobby Flecther (WES

Hydraulics Laboratory) who provided early information and guidance with respect to spillway structure design and channel hydraulics, as well as to Dr. Robert H. Denson and Mr. John Boa (WES Structures Laboratory) who assisted in the design and fabrication of simulated materials used in laboratory flume experiments. The Delta, Utah, Chamber of Commerce, Mr. Chad R. Gourly (State of Utah Department of Natural Resources), and Mr. Robert L. Morgan (State Engineer, State of Utah Department of Natural Resources) provided a valuable videotape and technical information concerning the failure of the Delta, Melville, Abraham, and Deseret Irrigation Company (DMAD) spillway.

WES also gratefully acknowledges Mr. David C. Ralston, Mr. John A. Brevard, and Mr. Louis Kirkaldie (retired), National Headquarters, Soil Conservation Service (SCS); and Dr. Darrel M. Temple, Water Conservation Structures Laboratory, Agricultural Research Service (ARS), Stillwater, Oklahoma, US Department of Agriculture (USDA), whose on-going research, helpful cooperation, and collaboration made a substantial contribution to the WES spillway channel erosion study.

Commander and Director of WES during the preparation of this report was COL Larry B. Fulton, EN. Dr. Robert W. Whalin was the Technical Director

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
acre-feet	1,233.489	cubic metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
degrees (angle)	0.01745329	radians
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
square feet	0.09290304	square metres

GEOTECHNICAL ASPECTS OF ROCK EROSION IN EMERGENCY SPILLWAY CHANNELS

Report 5

SUMMARY OF RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

PART I: INTRODUCTION

Background

1. Several factors prompted the US Army Corps of Engineers (CE) to include the problem of rock erosion in unlined spillway channels as a work unit in the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program* conducted by the US Army Engineer Waterways Experiment Station (WES) during FY 85-89:

a. Experience spanning two decades demonstrates that severe erosion of rock and soils flooring unlined emergency spillway channels may cause undermining or failure of spillway structures and catastrophic release of reservoir waters; the latter resulting in severe downstream flooding and possible loss of life. Lesser significant effects of severe erosion in unlined spillway channels include damage to dam embankments, spillway channel bank failure, and sedimentation in the spillway exit and main channel.

b. Significant erosion-induced damage is well-documented in unlined emergency spillway channels at flood control and water-storage projects built and managed by the CE, other Federal Agencies, state, and local interests (Cameron et al. 1986, 1988a, 1988b).

c. The prediction of initiation, rate, and intensity of channel erosion during spillway overflow is far from being a precise science; and effective, cost-efficient, engineered solutions regarding erosion prevention and remediation are often difficult to perceive, justify, and enact.

d. The complex interrelationship between site-specific geological features and hydrodynamic factors leading to unlined spillway channel erosion was, (and to a certain extent still is), poorly understood.

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* REMR is a comprehensive investigation of the problems associated with the maintenance and preservation of Civil Works structures constructed and operated by the CE. Research work units supporting these efforts are operated by various Engineering Laboratories at the WES.

2. Those elements of the problem area which clearly related to geotechnical aspects of rock erosion in spillway channels were tasked to the WES Geotechnical Lab work unit; whereas, hydraulic considerations relating to the engineering design of spillways and associated structures were assigned to a research work unit of the WES Hydraulic Lab.

3. Cameron et al. (1986) emphasized that many CE flood control and water storage projects with unlined emergency spillway channels are the beneficiaries of conservative hydrologic and hydraulic design--and that no CE spillway structure or dam has failed. However, the same authors recognized that only very infrequent flow in many CE unlined spillway channels, (and some have never experienced spillway overflow), has kept the spillway channel erosion problem from reaching serious proportions in some Districts, particularly those in parts of the central and southern United States.

4. Other Federal Agencies responsible for the construction and administration of dam facilities have also targeted as an area of needed research the problem of rock erosion in emergency spillway channels. For example, the on-going research efforts of the Agricultural Research Service (ARS) of the US Department of Agriculture (USDA) are notable in this regard.

5. Combined research efforts have resulted in substantial improvement in knowledge and understanding of the dimensions and potential impacts of the spillway channel erosion problem, and the causes of the initiation, rate, and extent of rock erosion in spillway channels. This progress has resulted in better schemes for erosion prediction in spillway channel evaluation procedures as well as enhanced documentation and concepts with respect to erosion prevention and remediation.

6. It is also clear that work will be needed in the future to guarantee the safety and integrity of many unlined spillway channels. Use of revised hydrological criteria had tended to increase to probable Project Maximum Flood (PMF) and/or the maximum Spillway Design Flood (SDF) at some CE projects. Increased awareness of potential impacts of sudden reservoir release has occurred as a function of demographic shifts and socioeconomic changes in the nearby environs of many CE projects. Urban and suburban development and clearcutting in particular impact the regional hydrology of watersheds by increasing runoff rates (and possibly associated PMF). Recognition that substantial erosion damage and dangerous headcutting in unlined channels can

occur during flows which amount to only a small fraction of PMF or SDF* is prompting reevaluation of facility safety in some cases.

7. Evaluation of engineered solutions in spillway and channel design, as well as performance of emplaced remedial measures, are key areas of ongoing research needs. Effective sharing of research progress and improved techniques in erosion prediction, prevention, and remediation with District hydraulic and geotechnical engineering personnel should remain a high priority of the REMR Program.

Objectives

8. The overall objective of this work unit was to develop procedures for predicting, detecting, preventing, and repairing rock erosion in unlined emergency spillway channels; to document these procedures in a series of technical reports; and to transfer technology to interested parties in a timely manner. Specific objectives identified by the research work unit are documented in Reports 1-4 (Cameron et al. 1986, 1986a, 1986b; May 1989) of this series and include the following:

- a. To maintain and continually update an observational data base which documents important erosive spillway overflow events at CE projects.
- b. To identify and document the geotechnical and hydraulic factors influencing the rate and mechanism of erosion in unlined spillway channels.
- c. To conceive and conduct laboratory experiments to determine the significance of geologic and hydrodynamic controls on the mechanics of headcutting and knickpoint erosion.
- d. To identify and document channel response to emergency spillway flow and to assess the nature, magnitude, and severity of downstream impacts.
- e. To develop quantitative site-characterization procedures for the evaluation of the relative potential for rock and soil erosion in unlined emergency spillway channels.

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* PMF or SDF estimates of the magnitude of hydrologic flood events have no direct relationship with the phenomena of rock erosion in an unlined spillway channel. PMF and SDF are used in the hydraulic design of the spillway structure. Since these hydraulic parameters do not consider the geotechnical aspects of the unlined spillway channel, they have no bearing on its erodability.

f. To identify and document cost-effective remedial and preventive measures to minimize the problem of severe erosion in unlined emergency spillway channels.

g. To provide timely technology transfer in this problem area to CE personnel and other interested parties in Federal, state and local agencies.

9. Most of the research work unit objectives were successfully met in the period FY 85-89, discussed later in this report. However, significant future work must be performed in such areas as field verification of the results of laboratory flume experiments, implementation and verification of recommended spillway channel evaluation procedures, evaluation of performance of erosion prevention and remedial measures employed in unlined spillway channels, and amplification of the observational data base, as discussed later in this report.

Scope

10. The technical reports of the research work unit are intended to serve as a mechanism for communicating research results, ideas, and concepts to interested CE personnel and their counterparts in other Federal, state, and local agencies. CE District experience, case histories, and site visits, as well as considerable field and laboratory interaction with other concerned agencies (e.g., US Soil Conservation Service (SCS) and ARS of the USDA, Office of the State Engineer, Utah, etc.), have provided vital elements to the observational data base used in this investigation, and have helped to develop and refine research plans and objectives.

11. This report, the fifth and final in a series, provides a summary of the major results, conclusions, and recommendations of this REMR research work unit. As well, it documents the work conducted during FY 89. The combined results of the work unit serve as the basis for discussion of current and future research initiatives in the unlined spillway channel erosion problem area.

PART II: SUMMARY OF MAJOR RESULTS

Background

12. A preliminary review of the problem of rock erosion in unlined CE emergency spillways led to the development of an interactive observational data base which served as the hub for detailed investigations of the causes of rock erosion in unlined spillway channels, spillway evaluation procedures and erosion prediction, response model studies, and remedial and preventive techniques. Technical transfer and application of research results were also accomplished by the WES REMR work unit.

Data Base Information

13. An observational data base was developed from site visits, case histories, and information derived from the literature. An important source of these data was that provided by CE Districts and Divisions from Periodic Inspection Reports, and data provided by the SCS. During the first year, 25 projects were visited by REMR personnel. Videos were found to be important means of visualizing and studying the effects of spillway flow and these were obtained for Saylorville (Rock Island District) and Black Butte (Sacramento District) Reservoirs, and for the privately owned Delta, Melville, Abraham, and Deseret Irrigation Company (DMAD) Reservoir in Utah. During the early phases of this research, contacts were made with the CE Districts and Divisions, SCS, Bureau of Reclamation (BR), and state agencies. REMR personnel were invited to participate with the SCS on their Emergency Spillway Flow Study Task Group (ESFSTG) (established in 1983) for site-inspection visits to SCS dams which had experienced spillway flow and concomitant moderate to severe erosion. The main conclusions derived from the development and analysis of the data base were (Cameron et al. 1986):

a. Skewness of data base. Erosion in emergency spillway channels was not reported to be a problem area in all CE Districts; severe erosion appeared to be limited to selected regions of the country which had experienced significantly high reservoir stages. An absence of severe erosion in other areas may be due to the fact that at many reservoirs spillway channels have never flowed, and/or that many spillway channels are lined. Even so, there is concern that, in some Districts, potential spillway erosion problems exist, but have not been identified.

b. Percent PMF. When severe erosion did occur in CE spillway channels, spillway discharges were less than ten percent of PMF.

c. Maximum spillway discharge velocity. The maximum velocity experienced during spillway flows at CE and SCS dams was equal to or in excess of that recommended for poor rock in Engineer Manual 1110-2-1601 (8 fps).

d. Adequacy of geotechnical data. The amount and quality of subsurface geotechnical information in the spillway channels at many sites were inadequate to evaluate the response of the materials themselves to erosion.

e. Presence of knickpoints. Many emergency spillways exhibit a knickpoint (abrupt change in slope) where the downstream end of the excavated channel intersects the natural topography. The examination of longitudinal topographic cross-sections of severely eroded spillway channels showed that the once-smooth excavated section of the channel had become stair-stepped and irregular, and exhibited the characteristics of a natural stream channel with knickpoints.

f. Discontinuities. Field inspections and reference to geologic cross-sections showed that these knickpoints were capped with erosion-resistant material which overlaid highly erodible material which formed the knickpoint face. The spillway channels materials were, therefore, stratigraphically inhomogeneous.

g. Headcutting. The comparison of pre- and post-flow longitudinal cross-sections and the evaluation of videos suggested that the mechanism of erosion was related to the upstream migration of knickpoints or headcutting similar to that which may occur in natural stream channels and, thus, was controlled by stratigraphic and structural discontinuities (rock mass properties) in the spillway foundation materials.

h. Flow concentrations. Severely eroded channels exhibited natural or constructed features which tended to concentrate flow and enhance erosion; these features included pilot channels, roads, ruts made by off-the-road vehicles, and topographic irregularities.

i. Study and guidance. These early phases of the investigation demonstrated the need to study knickpoint erosion under the controlled conditions of the laboratory, to develop procedures for evaluating and predicting erosion, and to provide guidance for the remediation or eroded spillway channels.

Causes of Spillway Erosion as Determined by Flume Tests

14. The specific causes and relationships of spillway erosion were studied in the laboratory using a 16-ft-long, 1.5-ft-deep, and 1-ft-wide recirculating, tilting, variable discharge flume in which a waterfall

(knickpoint) was constructed of simulated, stratified, erodible and nonerodible, earth materials (gravel-gelatin mixtures). The geometric and hydraulic conditions at the waterfall were mathematically defined using a vented, erosion-dissipating drop structure as an analog. Having established that hydraulic similitude existed between the flume tests and field discharges, 37 individual discharge events were tested in the flume at varying stages (water elevations) and thicknesses of erosion-resistant capping material. All discharge events were documented on video tape. These investigations showed that the following factors control the occurrence and degree of erosion at a knickpoint (May 1989):

a. Height of tailwater. Erosion was maximized when the tailwater was minimized in relation to the stage.

b. Venting conditions. Erosion was maximized when the knickpoint became or was unvented. This condition resulted in a negative pressure between the nappe and waterfall face which pulled the nappe and backroller in against the face of the waterfall. The backroller is that portion of the total discharge in the nappe which flows backward in a circular path toward the face.

c. Ratio of stage height to height of waterfall. During vented conditions, maximum erosion occurred when this ratio was 1:8 or less. Ratios less than this value tended to cause the nappe emerging over the waterfall and accompanying backroller to strike the erodible material forming the waterfall face. At ratios greater than this value, the backroller was sufficiently beyond the face to minimize erosion. When unventilated, this factor was not critical.

d. Ratio of thickness of erodible layer to height of backroller. Erosion was maximized when this ratio was greater than 1:5. Values greater than 1:5 assured that full contact could be maintained between the backroller and the waterfall face. When these values were less than 1:5, the erosion-resistant layer came into contact with the backroller and interfered with this process.

e. Structural discontinuities in resistant layer. Maximum erosion and headcutting occurred when structural discontinuities, aligned normal to flow, were present in the resistant layer capping the waterfall. This resulted in the failure of the capping material by block failure. This process was exacerbated when the discontinuity spacing was such that the failed blocks were of minimum size such that they could be removed from the face by the tailwater discharge.

f. Stage on hydrograph. The interaction of the processes described above shows that maximum erosion does not necessarily accompany peak discharge but rather it occurs on the lower portions of the rising and falling limbs of the discharge hydrograph. Since the falling limb often exhibits a flatter slope than that of the rising limb, the most extensive erosion would be expected during ebbing discharges. Those conditions which are conducive to severe erosion are tabulated below:

		Position on Hydrograph		
Vented	Ratio of Stage of Waterfall Height	Rising Limb	Peak	Falling Limb
Yes	> 1/8	Erosion	None*	Erosion
Yes	< 1/8	None*	None*	None*
No	Not critical	Erosion	None*	Erosion

* Primarily tractive force scour.

Computer Simulation of Knickpoint Erosion

15. A computer program was developed to compute the trajectory of a free-falling plume subject to partial vacuum conditions. Specifically, the equations of motion were numerically solved for a given thickness of flowing water mass with an initial horizontal velocity, subject to the pressure differential caused by the partial vacuum condition. The orientation of the applied pressure differential was assumed perpendicular to the instantaneous trajectory of the falling plume. The computer program was used to develop the relationship between the flow discharge, the height of waterfall, and the nappe (vacuum) pressure which will result in the conditions conductive to the development of a scouring backroller. These relationships show that the potential for scour due to a backroller at the base of an overfall diminishes (at constant nappe vacuum pressure) as the flow increases because the increasing momentum of the stream will cause the overfalling nappe to move away from the waterfall face. The causes for the formation of the vacuum development beneath the nappe are not well known, nor is it known to what value the vacuum pressures can obtain.

16. The rates of headcutting via this scour roller process can be quite rapid because the hydraulic forces are concentrated within a small zone situated at the toe of the waterfall. Although alternate scouring processes (i.e., tractive force scour) may increase with flow discharge, the rate of this type of scour may not be nearly as rapid as backroller-caused scour. Generally, the rock and rock-mass properties of the waterfall materials will determine whether or not increasing discharges (stages) will result in increasing depths

of scour at the base of the waterfall and, therefore, increased height of waterfall both resulting in the movement of the nappe nearer to the face. The flume tests were conducted under situations in which the base of the waterfall was not erodible. Even so, the computational analyses strongly emphasize the need to include low and moderate flow discharges in the assessment of scour potential. These findings substantiate the observation that severe erosion can occur at discharges significantly lower than either PMF or SDF.

Spillway Channel Evaluation Procedures

17. Detailed evaluations of the potential for rock erosion in unlined spillway channels should be conducted at all CE flood control and water storage projects. These evaluations should provide the information required to:

- a. Predict spillway channel erosion on the basis of probability indices derived from measurable rock mass and lithostratigraphic continuity factors at site-specific and District levels.
- b. Identify significant factors for quantification of erosion damage in terms of flow or other variables, an important exercise in response (damage) modeling in spillway channels with a record of one or more flow events.
- c. Design safe, cost-effective, preventive, and remedial measures.
- d. Provide input for scale and/or numerical hydraulic modeling of spillways.

18. The interrelations ships between engineering design features, hydraulic factors, and geological parameters controlling rock erosion are often complex and difficult to understand. Cameron et al. (1986 and 1988) and the WES Hydraulics Laboratory recommended that spillway channel evaluations be conducted by multidisciplinary teams staffed by experienced civil, hydraulic, geotechnical engineers, and engineering geologists.

19. Prerequisites to meaningful geotechnical evaluation of erosion potential (particularly headcutting) at site-specific levels are:

- a. Detailed engineering geological maps and cross sections which provide maximum understanding of the nature and distribution of rock and rock-mass parameters, particularly structural and lithostratigraphic discontinuities in the rocks underlying the channel both in and downstream of the spillway.

b. Where drilling was a part of site characterization, all borehole records; borehole lithologic logs of cuttings and/or core, borehole geophysical logs, etc.

c. The flood history of the dam facility including all spillway flood hydrographs, and velocity and water depth data for specific precipitation events.

d. Records of damage or failure of the rocks underlying the spillway channel or its banks.

e. Records of the performance of previously emplaced preventive or remedial measures.

Erosion prediction

20. Previous reports of this series have highlighted the importance of developing methods of predicting the onset, rate, and extent of rock erosion in unlined spillway channels. The case history of the loss of the DMAD Reservoir during the West Millard County (Utah) floods of 1983 (Cameron et al. 1986) provides stark illustration of how lack of attention to adverse conditions in the spillway channel can result in excessive erosion leading to structural failure of a spillway and catastrophic release of stored waters. Also, in an era of limited funding, it is essential that human and financial resources be allocated to those built unlined spillway channels which are most in need of preventive and remedial measures. The latter task requires technically sound, cost-efficient methods of evaluation, prioritization, and forced-ranking damaged or endangered channels.

21. Cameron et al. (1988a) recommends site-specific "proof of concept" testing of an Erosion Probability Index (EPI) based on rock-mass rippability rating and lithostratigraphic countinuity factors for geotechnical evaluation of unlined spillway channels. This approach is based on the assumption that rock-mass response to hydraulic forces (of the scale of those acting on unlined channels during overflow of most CE spillways) is governed to a substantial degree by the same rock and rock-mass parameters that provide key input parameters to Weaver's (1975) Rippability Rating (RR) scheme (or Bieniawski's (1974) Rock Mass Rating (RMR) System) when combined with quantified horizontal and vertical lithostratigraphic continuity factors (see Cameron et al. 1988a, pp 11-14).

22. Rock-mass classification or rating schemes devised to aid or enhance engineering judgment with the respect to assessment of rock-mass behavior under the influence of applied stress are based on fundamental rock and rock-mass parameters. These include rock type, hardness, weathering,

structure (strike and dip orientation, joint spacing, continuity, fracture, cleavage, and condition of discontinuity), fabric, and seismic P-wave velocity.

23. Use of accepted rock-mass rating schemes (combined with factors quantifying horizontal and vertical lithostratigraphic continuity) in spillway channel erosion evaluations has certain obvious advantages:

- a. The rock mass can be divided into segments or sectors of similar behavior along the spillway channel. Contoured values of EPI, RR, and/or RMR in plan and section along the spillway channel might well highlight those areas where erosion will initiate and/or be most severe, as well as those areas most in need of preventive of remedial measures.
- b. RMR schemes use simple, quantifiable, parametric terms and terminology which are easily remembered and widely accepted by the geotechnical engineering community.
- c. RMR schemes are based on parameters which can (usually) be determined by relatively low-cost detailed geological mapping of the spillway channel, albeit that comprehensive core drilling and analyses are necessary in some cases to accurately assess subsurface geology and lithostratigraphic continuity.

24. RMR, as per the Geomechanics Classification proposed by Bieniawski (1974, 1979), was initially developed for tunnel engineering applications. However, it has been successfully applied to rock slopes and foundations, mining problems, and assessment of ground rippability. RMR is more comprehensive than RR in terms of rock mass parameters used in its derivation, in that Rock Quality Designation (RQD), condition of discontinuity, and groundwater condition, are considered.

25. It is thus suggested that RMR will provide a better estimate of rock mass behavior (than RR) in those evaluations where core drilling and analysis play an important role in site characterization.

Response model studies

26. A response model study using data from SCS and CE spillway channels to analyze geometric and hydraulic parameters with respect to the severity of erosion produced during one or more flow events is described in Cameron et al. (1988a). An analysis of 14 SCS and 2 CE spillway channels which had previously experienced spillway revealed that the extent of spillway channel erosion could be categorized in terms of volumetric and horizontal erosion rankings.

27. The erosion ranking parameters thus provide a measure of the seriousness of the erosion threat at a particular site and allow for some prioritization of remediation. The volumetric and horizontal erosion rankings were statistically compared with hydraulic and geometric parameters with the following results:

a. Overall, only minor statistical significance exists among the attempted correlations. The absence of overall significant statistical correlation is ascribed to variable geological conditions between the sites studied, particularly with respect to discontinuities.

b. Regression analyses indicate that hydraulic parameters pertaining to flow in most unlined spillway channels (water depth, velocity, etc.) are not important primary measures for predicting the nature and extent of rock erosion which may occur. However, these parameters should be important in predicting erosion in nonlithified soils and sediments.

c. R-squared values for correlations involving geometric parameters were higher than those involving hydraulic parameters, supporting the idea that knickpoints in the channel are important in terms of initiation and extent of channel erosion.

Remedial and Preventive Techniques

28. Remediation of spillway channel erosion damage is a relatively new, but significant, concern to CE Districts and to other dam owners and operators. Because some CE unlined emergency spillways flow only infrequently, only a few projects have thus far implemented or planned preventive or remedial works. Measures are termed preventive or remedial depending on their time of application; i.e., whether the measure is applied before or after a given spillway channel overflow event.

29. Cameron et al. (1983) documented and assessed preventive and remedial measures implemented or contemplated to avoid or impede erosion in unlined spillway channels and provided the following observations:

a. Erosion prevention and remediation design is highly site-specific. Hydraulic design variables, geotechnical conditions, public safety, downstream impacts, and legislated purpose(s) of the reservoir can complicate the selection of appropriate preventive and remedial measures.

b. Preventive and remedial techniques in unlined spillway channels should be recommended on the basis of site-specific geotechnical characterization of the rocks forming the unlined channel.

c. Geotechnical site characterization of unlined spillway channels should describe and quantify rock and rock-mass parameters including rock composition(s) and strength, structural and stratigraphic discontinuities, and precursor erosion elements, all of which control rock erosion and its rate.

d. Erosion prevention and remediation design must be cost-effective, while at the same time address public safety. When possible, prevention and remediation works should provide for continued reservoir operation.

e. Depending on the anticipated or experienced severity of erosion, preventive or remedial engineered works need not be permanent; the "impermanent fix" may be a viable option, especially in those unlined channels which only rarely experience flow.

f. Proper utilization of physical and/or numeric modeling techniques may result in substantial savings when remediation design involves high-cost measures as well as provide valuable data base information for more effective employment of engineering techniques.

g. Site-specific physical and/or numeric modeling studies of erosion in an unlined spillway channel cannot be undertaken without accurate input and model design parameters provided by thorough hydraulic and geotechnical characterization of the project site.

30. Potentially useful erosion preventive measures identified in Cameron et al. 1989 include the construction of stilling basins and energy dissipators (tailwater conditions permitting), cutoff walls, and the removal of vegetation and other obstacles to flow. Measures to overcome or relieve uplift pressures in jointed rock masses may prevent wholesale "plucking" of large blocks during spillway channel inundation. The placement of natural and/or geotechnical grasses (especially in poorly lithified rocks and soils) may also offer useful and attractive alternatives.

31. Reservoir reregulation is viewed as a temporary means of reducing the potential for erosion damage in an unlined spillway channel, and is probably best justified as a stopgap measure employed during emplacement of other remedial or preventive works. This alternative obviously cannot be employed at projects built without mechanical regulatory structures.

32. Potentially useful remedial engineering techniques discussed by Cameron et al. (1988b) include cement-based methods such as grouting, shotcrete, soil/cement/rollcrete, and high strength, unreinforced and reinforced concrete as well as rock bolts, wire mesh, anchored gabions, and riprap.

33. Cameron et al. (1988b) also identified the following needs with respect to cost-effective erosion prevention and remediation in unlined spillway channels:

- *a*. Documentation and assessment of the performance of preventive and remedial engineered works for unlined spillway channels which have experienced erosion or where such damage is anticipated.
- *b*. Further documentation and monitoring on a nation-wide (or world-wide) basis of remediated unlined spillway channels.
- *c*. Further evaluation of risk and uncertainty as related to factor of safety in achieving prevention and/or remediation goals.
- *d*. Testing of methods to predict rock erosion in unlined spillway channels by the use of erosional rankings and indices.

Technology Transfer and Research Applications

34. The technology transfer phases of this investigation involved technical assistance to CE Districts on specific projects in which spillway erosion was of concern, the presentation of the REMR research findings and their applications at a workshop, and continued participation with the SCS on site visits.

Technical assistance

35. The technical assistance involved a review of the proposed plans by the Omaha District to construct a municipal youth athletic field and parking lot in the unlined emergency spillway of a small dam in Nebraska. The review recommended caution and reevaluation of these plans since such facilities could concentrate flow and enhance erosion susceptibility at this site.

36. The Rock Island District requested review of the proposed plan for remediation at the Saylorville Reservoir near Des Moines, Iowa, in which the District proposed to construct a concrete cut-off wall and use rock bolts to stabilize and strengthen the cap rock forming the base of the spillway channel. The review recommended the preferred location for the cut-off wall, the probable effect of the rock bolting, and the importance of protecting the face of the knickpoint closest to the spillway crest. Informal assistance was also provided to the St. Louis and Los Angeles Districts.

Spillway erosion workshop

37. During the period 3-5 May 1988, a spillway erosion workshop sponsored by the Rock Island District and WES was held in Des Moines, Iowa. The

purposes of the workshop were (a) to present the research findings and their applications to CE personnel and representatives from other government agencies, (b) to exchange views and experiences on spillway erosion, and (c) to consider remediation methods for the Saylorville Reservoir. The workshop was attended by 39 geologists and engineers representing the CE, SCS, ARS, BR, Iowa Geological Survey, the University of Southern Mississippi, the University of Missouri (Rolla), and Texas A&M University. Formal presentations were made on the first day of the meeting by the several researchers on this project followed by a field trip to the Saylorville site. On the second day, there was group participation in discussions of remedial measures which might be suitable for this particular emergency spillway channel. Generally, the workshop was the vehicle for the recommendations on remediation which were ultimately submitted to the Rock Island District.

SCS interaction

38. The on-going interaction with the SCS and ARS has been an important aspect of this investigation in terms of research and technology transfer. Throughout the duration of this project, REMR personnel have participated on ESFSTG and also in the Interagency Conference on Erosion in Earth Spillways, sponsored by the SCS and ARS in FY 88, in which the conclusions of this research were presented. During FY 89, six SCS dams located in Kentucky were visited by REMR personnel, and the SCS distributed copies of the REMR reports to subordinate offices and laboratories.

PART III: CONCLUSIONS AND RECOMMENDATIONS

39. This investigation identified and documented major causes of excessive erosion in unlined emergency spillways. This study has also identified specific research needs for which the present state of knowledge is insufficient. In particular, "proof-of-concept" field testing is necessary for concepts developed during laboratory experimentation related to knickpoint formation and migration, and erosion prediction indices. Documentation of performance of remediation in unlined spillways was also identified as future research initiative.

Conclusions

a. Causes of erosion. Excessive and severe erosion has occurred in unlined CE spillway channels as a function of: the presence of knickpoints on the longitudinal profiles of spillway channels, the thickness and spacing of stratigraphic and structural discontinuities in the spillway foundation rock, and geometric relations between these discontinuities and the spillway discharge.

b. Process of erosion. The headward migration of a knickpoint up a spillway channel toward the spillway crest is similar to those in the process occurring in natural streams undergoing channel degradation.

c. Evaluation and prediction. That an unlined emergency spillway channel has not flowed, or has not experienced high flow, should not be construed that, during the lifetime of the reservoir, flow and severe erosion will never occur. Evaluations of unlined spillway channels must be based on detailed geologic and geotechnical data; particularly that pertaining to discontinuities. Rock-mass rating or classification systems (e.g. rippability) when combined with lithostratigraphic discontinuity and hydraulic data may provide indices indicative of conditions conducive to severe erosion.

d. Remediation. Having established at a given site that severe erosion as a function of headward knickpoint erosion can occur, remedial or preventive measures should be designed and emplaced to secure and protect the rocks at the top and face of the knickpoint. Gabions, rockbolts, and standard cement-based techniques are the most common methods used.

Recommendations

a. Continue liaison with SCS. The CE should maintain close and continued liaison with the SCS for the purposes of inspection of SCS and CE dams which have experienced spillway flow, and to share research findings. The establishment of a multiagency task force to study and monitor spillway erosion should be considered.

b. Document spillway flows. CE Districts and Divisions should ensure that detailed geotechnical and geologic data are collected at those sites which have experienced spillway discharges, and at sites at which spillway discharge may be expected. Videotape recording and annotation of spillway flows and their effect(s) on unlined portions of the channel should also be done immediately prior to, during, and after spillway flood events.

c. Predict erosion. Detailed site-specific studies in selected Districts to test the validity of erosion prediction indices derived from combining rock-mass rating classification schemes with lithostratigraphic continuity factors and hydraulic factors should be conducted. The CE should consider identifying dams having unlined emergency spillways in which severe erosion may occur.

d. Test flume. Additional flume testing should be conducted in order to better understand the pressure differentials at a knickpoint in relation to the rate of headcutting in various geologic materials, and to further describe venting effects.

e. Test prototype. Investigations should be conducted at prototype sites, either in unlined emergency spillways which flow regularly or natural stream channels, which are instrumented to measure pressure differentials associated with knickpoint nappes and to further document venting conditions in the field.

f. Develop numeric modeling. Using data from flume and/or prototype testing, computer simulations should be developed to describe phenomena occurring at a knickpoint.

g. Incorporate downstream effects into risk analysis. The effects of severe erosion and possibly catastrophic release of water due to the failure of an unlined spillway should be incorporated into reservoir risk analyses for discharges less than those of SDF and/or PMF, and for studies of the downstream effects of released water and sediment.

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