SLOPE**STABILITY**
in Surface Mining

EDITED BY

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Published by the
Society for Mining, Metallurgy, and Exploration, Inc.

Contents

This book is dedicated to Chuck Brawner
for his pioneering efforts in slope stability and his leadership in
establishing symposia and publications to advance the
art and science of slope stability in surface mining.

Preface

The First International Conference on Stability in Open Pit Mining was held in 1970 in Vancouver, British Columbia. The purpose of the conference was to review, in practical terms, what was known about the rock mechanics relating to slope stability. The guiding force for this meeting was C.O. Brawner. Sponsorship came from the Center for Continuing Education, University of British Columbia; the Engineering Institute of Canada (B.C. Section); and the Canadian Institute of Mining and Metallurgy (B.C. Section). The contents of the proceedings published by the Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME) included:

Introduction, *C.O. Brawner*

The Role of Slope Stability in the Economics, Design and Operation of Open Pit Mines, *Richard M. Stewart and Bruce A. Kennedy*

Geologic Factors Controlling Slope Stability in Open Pit Mines, *F.D. Patton and D.U. Deere*

Influence of Rock Structure on the Stability of Rock Slopes, *Evert Hoek*

The Influence of Groundwater on Stability, *Norbert R. Morgenstern*

The Influence and Evaluation of Blasting on Stability, *Alan Bauer and Peter N. Calder*

Influence of Earthquakes on Stability, *Robert V. Whitman*

Methods of Analysis of Stability of Rock Slopes, *David L. Pentz*

Field Instrumentation for Rock Slopes, *K. Barron, D.G.F. Hedley, and D.F. Coates*

The Stabilization of Slopes in Open-Pit Mining, *H.Q. Golder*

Design and Construction of Tailings Dams, *Leo Casagrande and B.N. McIver*

Case Studies of Stability on Mining Projects, *C.O. Brawner*

Panel Discussion, *K. Barron, C.O. Brawner, L. Casagrande, H.Q. Golder, B.A. Kennedy, and D.L. Pentz*

Conference Summary, *Evert Hoek*

This conference generated so much interest that the Second International Conference on Stability in Open Pit Mining was held in 1971 in Vancouver. At this conference, the practical application of the factors influencing stability was stressed, with significant emphasis placed on case studies. Again the guiding force behind the meeting was C.O Brawner. The sponsors for this conference were the Center for Continuing Education, University of British Columbia; the Engineering Institute of Canada (B.C. Section); the Canadian Institute of Mining and Metallurgy (B.C. Section); and AIME. The proceedings covered the requirements for stability in mining; a review of recent stability research in the United States, England, and Canada; the influence of pit slopes on the economics of open pit mining; and the requirements for stability investigations and geological studies for slopes in soil, rock, and tailings dams.

The contents of the proceedings published by the Society of Mining Engineers of the AIME included:

Requirements for Stability in Open Pit Mining, *Richard M. Stewart and B.L. Seegmiller*

The Practical Side of Mining Research at Kennecott Copper Corporation, *C.D. Broadbent*

Recent Rock Slope Stability Research at the Royal School of Mines, London, *E. Hoek*

Recent Research on Rock Slope Stability by the Mining Research Center, *G. Herget*

Pit Slopes—Their Influence on the Design and Economics of Open Pit Mines, *R.B. Moffitt, T.W. Friese-Greene, and R.M. Lillico*

The Stability of Natural and Man-Made Slopes in Soil and Rock, *H.Q. Golder*

Stability of Slopes in Overburden Excavations, *T. Cameron Kenney*

Stability Investigations for Tailings Dams, *J.C. Osler*

Geological Investigations to Evaluate Stability, *Richard E. Goodman*

Redesign and Construction of a Tailings Dam to Resist Earthquakes, *C.O. Brawner*

Tailings Dams in British Columbia, *Earle J. Klohn*

The Control of Water in Tailings Ponds, *A.L. Galpin*

Blasting Effects and Their Control in Open Pit Mining, *L. Oriard*

A Slide in Cretaceous Bedrock at Devon, Alberta, *K.D. Eigenbrod and N.R. Morgenstern*

A Study of the Stability of a Disused Limestone Quarry Face in the Mendip Rills, England, *D. Roberts and E. Hoek*

Rock Mechanics and Slope Stability at Mount Isa, Australia, *K. Rosengren*

The Third International Conference on Stability in Open Pit Mining was held in 1981 in Vancouver. As with the first and second conferences, the guiding force behind the meeting was C.O. Brawner. This time the advisory organizations were the Society of Mining Engineers of the AIME, the B.C. and Yukon Chamber of Mines, the B.C. Mining Association, and the B.C. Department of Mines and Petroleum Resources.

The program was developed in three parts:

1. State of the Art–Rock Slope Stability
2. Investigation, Research, and Design for Stability in Surface Mining
3. Case Examples of Stability in Surface Mining

State of the Art

The Role of Slope Stability in the Economics, Design and Operation of Open Pit Mines–An Update, *Michael R. Richings*

Influence of Rock Structure on Stability, *Carl D. Broadbent and Zavis M. Zavodni*

Influence and Control of Groundwater in Large Slopes, *Adrian Brown*

Influence of Blasting on Slope Stability; State of the Art, *L.L. Oriard*

Influence of Earthquakes on Rock Slope Stability, *Charles E. Glass*

Mechanics of Rock Slope Failure, *Douglas R. Pitea and Dennis C. Martin*

Shear Strength Investigations for Surface Mining, *Nick Barton*

Slope Stability Analysis Techniques Incorporating Uncertainty in Critical Parameters, *D.L. Pentz*

Monitoring Pit Slope Behavior, *Richard D.Call*

Artificial Support of Rock Slopes, *Ben L. Seegmiller*

Stabilization of Rock Slopes, *C.O. Brawner*

Research Requirements in Surface Mine Stability and Planning, *G. Herget and O. Garg*

Investigation, Research, and Design

Sedimentological Control of Mining Conditions in the Permian Measures of the Bowen Basin, Australia, *C.W. Mallett*

Geology and Rock Slope Stability–Application of the "Key Block" Concept for Rock Slopes, *Richard E. Goodman, and Gen-Hua Shi*

Analysis of Slope Stability in Very Heavily Jointed or Weathered Rock Masses, *Evert Hoek*

The Application of Stochastic Medium Theory to the Problem of Surface Movements Due to Open Pit Mining, *Liu Baoshen and Lin Dezhang*

Analytical Estimation of Parabolic Water Table Drawdown to a Slope Face, *Stanley M. Miller*

A Computer Program for Footwall Slope Stability Analysis in Steeply Dipping Bedded Deposits, *Brian Stimpson and Keith E. Robinson*

Analysis of Bolt Reinforcement in Rock Slopes, *Francois E. Heuze*

A Simple Core Orientation Technique, *R.D. Call, J.P. Savely, and R. Pakalnis*

Monitoring the Behavior of High Rock Slopes, *W.B. Tijmann*

Blasting to Achieve Slope Stability in Weak Rock, *G. Harries*

Blasting Practices for Improved Coal Strip Mine Highwall Safety and Cost, *Francis S. Kendorski and Michael F. Dunn*

Production Blasting and the Development of Open Pit Slopes, *John P. Ashby*

Case Examples

Practical Aspects of Wall Stability at Brenda Mines Ltd., Peachland, B.C., *G.H. Blackwell and Peter N. Calder*

Slope Instability at Inspiration's Mine, *James P. Savely and Victor L. Kastner*

Open Pit Slope Stability Investigation of the Hasancelebi Iron Ore Deposit, Turkey, *Caner Zanbak, Kemal A. Erguvanli, Erdogan Yuzer, and Mahir Vardar*

Redesign of the West Wall Kanmantoo Mine, South Australia, *Barry K. McMahon*

Design Examples of Open Pit Slopes Susceptible to Toppling, *Douglas R. Piteau, Alan F. Stewart, and Dennis C. Martin*

Successful Implementation of Steeper Slope Angles in Labrador, Canada, *Om P. Garg*

The Northeast Tripp Slide–11.7 Million Cubic Meter Wedge Failure at Kennecott's Nevada Mine Division, *Victor J. Miller*

Back Analysis of Slope Failure in the Cercado Uranium Mine (Brazil), *C. Dinis da Gama*

Case Examples of Blasting Damage and Its Influence on Slope Stability, *Roger Holmberg and Kenneth Maki*

Waste Dump Stability at Fording Coal Limited in B.C., *Robert S. Nichols*

Evaluation of Surface Coal Mine Spoil Pile Failure, *Peter M. Douglass and Michael J. Baile*

Slope Stability in Reclaimed Contour Stripping, *G. Faulkner, C. Haycocks, M. Karmis, and E. Topuz*

The Impact of the Federal Surface Mining Control and Reclamation Act, *R.W. Thompson and D.A. Ferguson*

It is now the occasion of the Fourth International Conference on Slope Stability in Open Pit Mining. Almost 30 years have passed since the first conference was held and nearly 20 years since the third conference. Some things have changed in the intervening years but many have not. To provide a basis for the reader to judge the changes, it is of interest to consider some of the remarks presented by C.O. Brawner in his introduction to the first international conference. The reader is strongly encouraged to read these comments in their entirety. For those who do not have access to the proceedings of the first conference, the following extracts are presented:

The advent of larger drilling, excavation, and milling equipment is resulting in a tremendous increase in the scale and annual tonnage of open pit mining.

Stability at open pit mining developments must be assessed for tailings dams, waste dumps, open pit slopes in overburden soil, and open pit slopes in rock.

The science of soil mechanics developed by Dr. Karl Terzaghi provides the basis for analyzing:

- *bearing capacity of soil under dams and waste dumps*
- *amount of seepage under and through dams*
- *stability of slopes and determination of safe slope angles for tailings dams, waste dumps, and open pits*
- *influence of earthquakes on stability*
- *influence and cost of different excavation and construction techniques*

If soil mechanics principles had been applied, many major failures involving tailings, tailings dams, or waste dumps, such as those at Aberfan, Mufulira, Luanshya, and El Cobre would not have occurred.

Construction procedures used in the past have paid little attention to the compaction of the shell material or to the influence of earthquakes on stability. This neglect has led to failures. While failures in low dams may not be too serious, for high dams such failures could have catastrophic results.

Another major area of concern is the stability of rock slopes. From the standpoint of long-term safety and economics, rock mechanics problems are frequently more serious than soil mechanics problems in open pit mining. This is partly due to the increasing depths of proposed open pit mines.

General application of rock mechanics to open pit stability was delayed for several reasons:

- *There has been a reluctance to spend money on rock mechanics because of an apparent lack of certainty of economic reward.*
- *Rock strength parameters relating to rock masses are infinitely variable and difficult, if not impossible, to determine precisely.*
- *Generalized models and theories of rock behavior are complex, as are the mathematics involved.*
- *Field conditions are extremely difficult, and often impossible to duplicate in the laboratory.*
- *Field testing is usually complicated, time consuming, and almost always very expensive.*

An important factor to recognize is that while rock mechanics is a new science, we can make use of theory and experience from many other related fields. The following are examples:

- *The theory of elasticity may be used for studies of stress distribution in rock masses.*
- *The techniques of triaxial and uniaxial compression, direct shear and permeability tests, as applied to soils, can also be used to test rock.*
- *The principle of effective stress and the mechanics of the stability analysis, developed many years ago in soil mechanics, are applicable to rock slopes.*
- *The measurement of water pressures and the flow of water through porous media can take advantage of experience used in investigation for the construction of major dams. These studies date back to the 1930s.*
- *Geologic mapping techniques to classify rock and to define the orientation and frequency of discontinuities are essential in rock mechanics studies.*
- *The principles and techniques of stabilization of landslides in soil are usually equally effective for many types of slides in rock.*

The advent of the computer and the finite element technique have made it possible to incorporate the third dimension in stability studies. However, these new techniques are not a cure-all. When used with discretion, in the hands of experienced engineers, they are a powerful tool. In the hands of the inexperienced, they may only provide a quicker way of getting the wrong answer.

Many fallacies regarding stability have developed over the years. It is important to recognize that:

- *Water does not generally act as a lubricant in slides.*
- *Reduction in water pressure is a more important factor in stability than is the amount of water that is intercepted.*
- *The influence of blasting on stability is far more important than most mining engineers recognize.*
- *Placement of tailings by hydraulic means does not provide a high degree of density.*
- *The length of time that the seismic vibrations last during an earthquake can have a major influence on stability.*

If an open pit operation does not have some evidence of instability, money is being wasted. However, if potential instability exists and is unsuspected, lives may be lost. Controlled stability is good mine management. Accordingly, operating mine engineers should have a knowledge of the general techniques of stabilization. This should also include a knowledge of the instrumentation used to monitor slope movement.

The late Dr. R.A.L. Black, former Head of the Dept. of Mines, Royal School of Mines, London, and Dr. E. Hoek, Head of the Rock Mechanics Project, made some very pertinent comments at the 9th US Symposium on Rock Mechanics (1967) Conference held in Golden, Colorado. [Black, R.A.L., and E. Hoek. 1967. Status of rock mechanics as applied to mining. Status of Practical Rock Mechanics. Proceedings of the 9th U.S. Symposium on Rock Mechanics (edited by N.E. Grosvenor and P.W. Paulding, Jr.). AIME., pp 5–27].

- *"Rock mechanics is no longer only an esoteric study for academic initiates: It is the essential basis of practical mine design."*
- *"A body of really useful knowledge in rock slope stability cannot be developed unless the more academic studies are developed and validated in practice in the field. There are no short cuts, no cheap solutions and no substitutes for a proper and complete appreciation of the basic problems involved. The nature of the forces which are at work when ancient equilibrium is disturbed by the creation of mining excavations must be understood before real progress in the application of rock mechanics to mine design can be made."*
- *"The penalty for the practical engineer for attempting to defy the known laws of strata behavior is relentlessly exacted in hard economic terms and sometimes in blood."*

We must apply the knowledge that we already have. We must build the knowledge up from carefully validated experience. The work must be coordinated between research establishments, such as universities, and the mining companies concerned.

We have developed analysis and design techniques that are far beyond our capability to determine the necessary strength and boundary parameters. We are desperately in need of case studies and analysis of field failures to test theoretical concepts. Only then will real practical progress be made.

Apart from the economic advantages of applying rock mechanics principles correctly, there is the certain benefit of better and safer working conditions.

To make or to save money we must be prepared to spend it in commensurate amounts. There are no ready made solutions in the field of mining rock mechanics, but given time and reasonable financial aid and other support from industry, solutions can be found.

The content of this fourth conference, like that of the preceding conferences, is heavily focused toward rock slope stability. This reflects, in some sense, the need for more published information in this area. A number of other publications and conference proceedings are available on the topics of waste rock and tailings embankments. Particularly noteworthy is the Engineering and Design Manual–Coal Refuse Disposal Facilities/ (I69.8:EN3) prepared for the U.S. Department of the Interior, Mining Enforcement and Safety Administration by E. D'Appolonia Consulting Engineers, Inc. This publication appeared in 1975 and provided the first definitive resource for practitioners in the United States subsequent to the Buffalo Creek disaster in 1972. In recognition of the need to expand available resources to include waste rock embankments other than those associated with coal, a workshop was held in conjunction with a meeting of the Society of Mining Engineers, AIME. A proceedings of this workshop, Non-Impounding Mine Waste Dumps, appeared in 1985 published by SME and edited by M.K. McCarter and an organizing committee composed of Bruce C. Vandre, John D. Welsh and Zavis M. Zavodni. This publication contained the following papers:

Classification and Surface Water Controls, *M.J. Taylor and R.J. Greenwood*

Planning Models: Operating and Environmental Implications, *Thomas R. Couzens*

Optimum Dump Planning in Rugged Terrain, *Ernest L. Bohnet*

Geotechnical Site Investigation, *John D. Welsh*

Evaluation of Material Properties, *Richard D. Call*

Simplified Stability Analysis, *Jack A. Caldwell and Allan S.E. Moss*

Limit Equilibrium Slope Analysis, *Steven G. Wright*

Scoping Regulatory Requirements, *Bruce Vandre*

Surface and Groundwater Pollution Potential, *Duane L. Whiting*

Water Movement, *John D. Nelson and David B. McWhorter*

Design of Drainage Systems for Embankments and Other Civil Engineering Works, *Harry R. Cedergren*

Influence of Earthquakes, *Charles E. Glass*

Failure Mode, *Geoff Blight*

Construction and Performance in Mountainous Terrain, *David B. Campbell*

Foundation Investigation and Treatment, *Z.M. Zavodni, B.D. Trexler and J. Pilz*

Stability Monitoring, *M.K. McCarter*

Reclamation in the Intermountain Rocky Mountain Region, *Bland Z. Richardson*

At the same time, efforts were underway by Bruce C. Vandre to produce an engineering guide for the U.S. Department of Agriculture, Forest Service Intermountain Region. This guide is titled Stability of Non Water Impounding Mine Waste Embankments. More recently, a series of manuals was produced for the Province of British Columbia Ministry of Energy, Mines, and Petroleum Resources by the British Columbia Mine Waste Rock Pile Research Committee. These manuals deal with mined rock and overburden piles and include titles such as *Investigation and Design Manual,* 1991; *Operating and Monitoring Manual,* 1991; *Methods of Monitoring,* 1992; *Failure Runout Characteristics,* 1992; and *Review and Evaluation of Failures,* 1992. These manuals provide a wealth of information pertaining to conditions in the mountainous terrain of British Columbia and similar environs.

Major contributions to the technical aspects of waste rock and tailings have been documented in a series of annual conferences held at Colorado State University and published under the title of *Tailings and Mine Waste.* Additional information applicable to tailings disposal structures is also contained in a series of publications by the U.S. Committee on Large Dams and the International Committee on Large Dams (many of these contributions may be found in the paper by Davies et al., which is included in this volume).

Large-scale field applications of heap leaching for the extraction of gold, silver, and copper developed during the last 20 years. Extensive use is made of synthetic materials (including geomembranes and geotextiles) in the construction of these facilities. This has added a new dimension to the stability evaluation of surface mine facilities. In 1987, a two-session symposium dealing with heap leaching was held at the annual meeting of SME. The resulting SME publication, *Geotechnical Aspects of Heap Leach Design,* edited by Dirk van Zyl, includes the following papers:

Optimizing Technology for Leach Pad Liner Selection, *D.R. East, J.R. Haile and R.V. Beck*

Design of Chemically Amended Soil Liners, *M.E. Smith and G.J. Gierzerski*

Compression Testing of Geomembrane Soil Interfaces, *L.A. Hanson and J.D. Deatherage*

Practical Design Considerations for the Installation of Leach Pad Liners, *J.D. Welsh*

Heap Leach Construction Over Tailings, *W.J. Attwooll and C. Gerity*

Slope Stability in Heap Leach Design, *R.T. Tape*

Construction of Leach Pads on Steeply Sloping Ground, *N.C. Shaver and A. Tapp*

Shear Testing of Geomembrane Interfaces, *L.A. Hanse*

Potential for Heap Leach Mass Instability, *R.T. Tape and T.G. Harper*

Engineering Properties of Agglomerated Ore in a Heap Leach Pile, *D.T. Kennard and A.A. Schweizer*

Feasibility Assessment for Increasing Heap Thickness at the Alligator Ridge Mine, *C. Stachan and D. Van Zyl*

Heap Leach Recovery Rates vs. Heap Height–A Case Study at Alligator Ridge Mine, Nevada, *A. Kuzycki and R.A. Womack*

In reviewing the titles contained in the preceding conferences and other volumes mentioned, it is noted that many of the papers are now regarded as classics and the information contained is highly relevant even today. By including these titles in this preface, it is hoped that the reader will become reacquainted with this valuable knowledge and the pioneers in this field. The editors expect that a number of the papers in this volume will enter into the "classic" category as well.

Because of the long time lapse between the third and fourth conferences and the significant changes in the knowledge base affecting all aspects of stability in surface mining, the editors made the decision to invite the papers included in this volume rather than to employ a Call-for-Papers. By doing this, it was hoped to ensure a more complete coverage by *Slope Stability in Surface Mining.* The volume has been divided into the following 4 sections:

1. Rock Slope Design Considerations
2. Case Studies in Rock Slope Stability
3. Stability of Waste Rock Embankments
4. Tailings and Heap Leaching

Immediately following the release of this volume, a symposium was held in conjunction with the 2001 SME Annual Meeting in Denver, Colorado. Participants were encouraged to expand the present volume by bringing their own contributions in electronic format to facilitate distribution.

In this way, we as editors and organizers of the symposium encourage on-going dialog via electronic means for professionals in this developing field. Never has there been such an opportunity as now exists through CD, email, and Web-based means to exchange ideas and advance the art and science of slope stability. We look forward with great optimism to potential benefits of improved safety, resource recovery, environmental stewardship, and economic reward that can result from such a dialog.

As we enter the twenty-first century, mines reaching depths of more than 1,100 m are being planned, waste rock embankments have surpassed 600 m in height, tailings dams have reached heights of 200 m, and heap leach facilities have reached heights of 150 m. There are great challenges to the rock- and geomechanics communities to ensure that these facilities are safe and economic today and in the future. It is only through information collection and exchange that improvements can be made in design concepts, construction methods, monitoring strategies, and reclamation practices. We hope, and expect, that the next state-of-the-art summary as contained in this volume will not require a gestation period of 20 years. This series of volumes and symposia initiated some 30 years ago by C.O. Brawner should be continued on a regular basis.

ACKNOWLEDGMENTS

To the authors of the chapters in this volume and their employers, we express sincere gratitude for the time and effort each of you has expended, along with your willingness to share your expertise. We also gratefully acknowledge the significant support provided by the Itasca Consulting Group in the initial stages of this project and the commitment of the departments of Mining Engineering at the University of Utah and the Mackay School of Mines.

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