Report No. RRTAC 88-12

A REVIEW OF THE INTERNATIONAL LITERATURE ON MINE SPOIL SUBSIDENCE

by

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of the

ALBERTA LAND CONSERVATION AND RECLAMATION COUNCIL
(Reclamation Research Technical Advisory Committee)

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This report is intended to provide government and industry staff with up-to-date technical information to assist in the preparation and review of Development and Reclamation Approvals, and development of guidelines and operating procedures. This report is also available to the public so that interested individuals similarly have access to the most current information on land reclamation topics.

ALBERTA'S RECLAMATION RESEARCH PROGRAM

Regulating surface disturbances in Alberta is the responsibility of the Land Conservation and Reclamation Council. The Council executive consists of a Chairman from Alberta Environment and two deputy chairmen from Alberta Forestry, Lands and Wildlife. The Council oversees a reclamation research program, established in 1978, to identify the most efficient methods for achieving acceptable reclamation in the province. Funding for the research program is provided by Alberta's Heritage Savings Trust Fund Land Reclamation Program.

To assist with development and administration of the research program, the Council appointed the interdepartmental Reclamation Research Technical Advisory Committee (RRTAC). The Committee consists of eight members representing the Alberta Departments of Agriculture, Forestry, Lands and Wildlife, and, Environment, and the Alberta Research Council. The Committee updates research priorities, reviews solicited and unsolicited research proposals, organizes workshops, and otherwise acts as the coordinating body for reclamation research in Alberta.

Additional information on the Reclamation Research Program may be obtained by contacting:

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RECLAMATION RESEARCH REPORTS

** 1. RRTAC 80-3: The Role of Organic Compounds in Salinization of Plains Coal Mining Sites. N.S.C. Cameron et al. 46 pp.

DESCRIPTION: This is a literature review of the chemistry of sodic mine spoil and the changes expected to occur in groundwater.

** 2. RRTAC 80-4: Proceedings: Workshop on Reconstruction of Forest Soils in Reclamation. P.F. Ziemkiewicz, S.K. Takyi, and H.F. Regier. 160 pp.

DESCRIPTION: Experts in the field of forestry and forest soils report on research relevant to forest soil reconstruction and discuss the most effective means of restoring forestry capability of mined lands.

N/A 3. RRTAC 80-5: Manual of Plant Species Suitability for Reclamation in Alberta. L.E. Watson, R.W. Parker, and D.F. Polster. 2 vols, 541 pp.

DESCRIPTION: Forty-three grass, fourteen forb, and thirty-four shrub and tree species are assessed in terms of their suitability for use in reclamation. Range maps, growth habit, propagation, tolerance, and availability information are provided.

N/A 4. RRTAC 81-2: 1980 Survey of Reclamation Activities in Alberta. D.G. Walker and R.L. Rothwell. 76 pp.

DESCRIPTION: This survey is an update of a report prepared in 1976 on reclamation activities in Alberta, and includes research and operational reclamation, locations, personnel, etc.

N/A 5. RRTAC 81-3: Proceedings: Workshop on Coal Ash and Reclamation. P.F. Ziemkiewicz, R. Stein, R. Leitch, and G. Lutwick. 253 pp.

DESCRIPTION: Presents nine technical papers on the chemical, physical, and engineering properties of Alberta fly and bottom ashes, revegetation of ash disposal sites, and use of ash as a soil amendment. Workshop discussions and summaries are also included.

N/A 6. RRTAC 82-1: Land Surface Reclamation: An International Bibliography. H.P. Sims and C.B. Powter. 2 vols, 292 pp.

DESCRIPTION: Literature to 1980 pertinent to reclamation in Alberta is listed in Vol. 1 and is also on the University of Alberta computing system (in a SPIRES database called RECLAIM). Vol. 2 comprises the keyword index and computer access manual.

N/A 7. RRTAC 82-2: A Bibliography of Baseline Studies in Alberta: Soils, Geology, Hydrology, and Groundwater. C.B. Powter and H.P. Sims. 97 pp.

DESCRIPTION: This bibliography provides baseline information for persons involved in reclamation research or in the preparation of environmental impact assessments. Materials, up to date as of December 1981, are available in the Alberta Environment Library.

N/A 8. RRTAC 83-1: Soil Reconstruction Design for Reclamation of Oil Sand Tailings. Monenco Consultants Ltd. 185 pp.

DESCRIPTION: Volumes of peat and clay required to amend oil sand tailings were estimated based on existing literature. Separate soil prescriptions were made for spruce, jack pine, and herbaceous cover types. The estimates form the basis of field trials.

N/A 9. RRTAC 83-3: Evaluation of Pipeline Reclamation Practices on Agricultural Lands in Alberta. Hardy Associates (1978) Ltd. 205 pp.

DESCRIPTION: Available information on pipeline reclamation practices was reviewed. A field survey was then conducted to determine the effects of pipe size, age, soil type, construction method, etc. on resulting crop production.

N/A 10. RRTAC 83-4: Proceedings: Effects of Coal Mining on Eastern Slopes Hydrology. P.F. Ziemkiewicz. 123 pp.

DESCRIPTION: Technical papers are presented dealing with the impacts of mining on mountain watersheds, their flow characteristics, and resulting water quality. Mitigative measures and priorities were also discussed.

N/A 11. RRTAC 83-5: Woody Plant Establishment and Management for Oil Sands Mine Reclamation. Techman Engineering Ltd. 124 pp.

DESCRIPTION: This is a review and analysis of information on planting stock quality, rearing techniques, site preparation, planting, and procedures necessary to ensure survival of trees and shrubs in oil sand reclamation.

*** 12. RRTAC 84-1: Land Surface Reclamation: A Review of the International Literature. H.P. Sims, C.B. Powter, and J.A. Campbell. 2 vols, 1549 pp.

DESCRIPTION: Nearly all topics of interest to reclamationists including mining methods, soil amendments, revegetation, propagation and toxic materials are reviewed in light of the international literature.

** 13. RRTAC 84-2: Propagation Study: Use of Trees and Shrubs for Oil Sand Reclamation. Techman Engineering Ltd. 58 pp.

DESCRIPTION: This report evaluates and summarizes all available published and unpublished information on large-scale propagation methods for shrubs and trees to be used in oil sand reclamation.

* 14. RRTAC 84-3: Reclamation Research Annual Report - 1983. P.F. Ziemkiewicz. 42 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

** 15. RRTAC 84-4: Soil Microbiology in Land Reclamation. D. Parkinson, R.M. Danielson, C. Griffiths, S. Visser, and J.C. Zak. 2 vols, 676 pp.

DESCRIPTION: This is a collection of five reports dealing with re-establishment of fungal decomposers and mycorrhizal symbionts in various amended spoil types.

** 16. RRTAC 85-1: Proceedings: Revegetation Methods for Alberta's Mountains and Foothills. P.F. Ziemkiewicz. 416 pp.

DESCRIPTION: Results of long-term experiments and field experience on species selection, fertilization, reforestation, topsoiling, shrub propagation and establishment are presented.

* 17. RRTAC 85-2: Reclamation Research Annual Report - 1984. P.F. Ziemkiewicz. 29 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

** 18. RRTAC 86-1: A Critical Analysis of Settling Pond Design and Alternative Technologies. A. Somani. 372 pp.

DESCRIPTION: The report examines the critical issue of settling pond design, and sizing and alternative technologies. The study was co-funded with The Coal Association of Canada.

** 19. RRTAC 86-2: Characterization and Variability of Soil Reconstructed after Surface Mining in Central Alberta. T.M. Macyk. 146 pp.

DESCRIPTION: Reconstructed soils representing different materials handling and replacement techniques were characterized, and variability in chemical and physical properties was assessed. The data obtained indicate that reconstructed soil properties are determined largely by parent material characteristics and further tempered by materials handling procedures. Mining tends to create a relatively homogeneous soil landscape in contrast to the mixture of diverse soils found before mining.

* 20. RRTAC 86-3: Generalized Procedures for Assessing Post-Mining Groundwater Supply Potential in the Plains of Alberta - Plains Hydrology and Reclamation Project. M.R. Trudell and S.R. Moran. 30 pp.

DESCRIPTION: In the Plains region of Alberta, the surface mining of coal generally occurs in rural, agricultural areas in which domestic water supply requirements are met almost entirely by groundwater. Consequently, an important aspect of the capability of reclaimed lands to satisfy the needs of a residential component is the post-mining availability of groundwater. This report proposes a sequence of steps or procedures to identify and characterize potential post-mining aquifers.

** 21. RRTAC 86-4: Geology of the Battle River Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze, R. Li, M. Fenton and S.R. Moran. 86 pp.

DESCRIPTION: This report summarizes the geological setting of the Battle River study site. It is designed to provide a general understanding of geological conditions adequate to establish a framework for hydrogeological and general reclamation studies. The report is not intended to be a detailed synthesis such as would be required for mine planning purposes.

** 22. RRTAC 86-5: Chemical and Mineralogical Properties of Overburden: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 71 pp.

DESCRIPTION: This report describes the physical and mineralogical properties of overburden materials in an effort to identify individual beds within the bedrock overburden that might be significantly different in terms of reclamation potential.

* 23. RRTAC 86-6: Post-Mining Groundwater Supply at the Battle River Site: Plains Hydrology and Reclamation Project. M.R. Trudell, G.J. Sterenberg and S.R. Moran. 49 pp.

DESCRIPTION: The report deals with the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is in the Battle River Mining area in east-central Alberta

* 24. RRTAC 86-7: Post-Mining Groundwater Supply at the Highvale Site: Plains Hydrology and Reclamation Project. M.R. Trudell. 25 pp.

DESCRIPTION: This report evaluates the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations. The study area is the Highvale mining area in west-central Alberta.

* 25. RRTAC 86-8: Reclamation Research Annual Report - 1985. P.F. Ziemkiewicz. 54 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

** 26. RRTAC 86-9: Wildlife Habitat Requirements and Reclamation Techniques for the Mountains and Foothills of Alberta. J.E. Green, R.E. Salter and D.G. Walker. 285 pp.

DESCRIPTION: This report presents a review of relevant North American literature on wildlife habitats in mountain and foothills biomes, reclamation techniques, potential problems in wildlife habitat reclamation, and potential habitat assessment methodologies. Four biomes (Alpine, Subalpine, Montane, and Boreal Uplands) and 10 key wildlife species (snowshoe hare, beaver, muskrat, elk, moose, caribou, mountain goat, bighorn sheep, spruce grouse, and white-tailed ptarmigan) are discussed. The study was co-funded with The Coal Association of Canada.

** 27. RRTAC 87-1: Disposal of Drilling Wastes. L.A. Leskiw, E. Reinl-Dwyer, T.L. Dabrowski, B.J. Rutherford and H. Hamilton. 210 pp.

DESCRIPTION: Current drilling waste disposal practices are reviewed and criteria in Alberta guidelines are assessed. The report also identifies research needs and indicates mitigation measures. A manual provides a decision-making flowchart to assist in selecting methods of environmentally safe waste disposal.

** 28. RRTAC 87-2: Minesoil and Landscape Reclamation of the Coal Mines in Alberta's Mountains and Foothills. A.W. Fedkenheuer, L.J. Knapik and D.G. Walker. 174 pp.

DESCRIPTION: This report reviews current reclamation practices with regard to site and soil reconstruction and re-establishment of biological productivity. It also identifies research needs in the Mountain-Foothills area. The study was co-funded with The Coal Association of Canada.

** 29. RRTAC 87-3: Gel and Saline Drilling Wastes in Alberta: Workshop Proceedings. D.A. Lloyd (compiler). 218 pp.

DESCRIPTION: Technical papers were presented which describe: mud systems used and their purpose; industrial constraints; government regulations, procedures and concerns; environmental considerations in waste disposal; and toxic constituents of drilling wastes. Answers to a questionnaire distributed to participants are included in an appendix.

* 30. RRTAC 87-4: Reclamation Research Annual Report - 1986. 50 pp.

DESCRIPTION: This report details the Reclamation Research Program indicating priorities, descriptions of each research project, researchers, results, and expenditures.

* 31. RRTAC 87-5: Review of the Scientific Basis of Water Quality Criteria for the East Slope Foothills of Alberta. Beak Associates Consulting Ltd. 46 pp.

DESCRIPTION: The report reviews existing Alberta guidelines to assess the quality of water drained from coal mine sites in the East Slope Foothills of Alberta. World literature was reviewed within the context of the East Slopes environment and current mining operations. The ability of coal mine operators to meet the various guidelines is discussed. The study was co-funded with The Coal Association of Canada.

** 32. RRTAC 87-6: Assessing Design Flows and Sediment Discharge on the Eastern Slopes. Hydrocon Engineering (Continental) Ltd. and Monenco Consultants Ltd. 97 pp.

DESCRIPTION: The report provides an evaluation of current methodologies used to determine sediment yields due to rainfall events in well-defined areas. Models are available in Alberta to evaluate water and sediment discharge in a post-mining situation. SEDIMOT II (Sedimentology Disturbed Modelling Techniques) is a single storm model that was developed specifically for the design of sediment control structures in watersheds disturbed by surface mining and is well suited to Alberta conditions. The study was co-funded with The Coal Association of Canada.

* 33. RRTAC 87-7: The Use of Bottom Ash as an Amendment to Sodic Spoil. S. Fullerton. 83 pp.

DESCRIPTION: The report details the use of bottom ash as an amendment to sodic coal mine spoil. Several rates and methods of application of bottom ash to sodic spoil were tested to determine which was the best at reducing the effects of excess sodium and promoting crop growth. Field trials were set up near the Vesta mine in East Central Alberta using ash readily available from a nearby coal-fired thermal generating station. The research indicated that bottom ash incorporated to a depth of 30 cm using a subsoiler provided the best results.

* 34. RRTAC 87-8: Waste Dump Design for Erosion Control. R.G. Chopiuk and S.E. Thornton. 45 pp.

DESCRIPTION: This report describes a study to evaluate the potential influence of erosion from reclaimed waste dumps on downslope environments such as streams and rivers. Sites were selected from coal mines in Alberta's mountains and foothills, and included resloped dumps of different configurations and ages, and having different vegetation covers. The study concluded that the average annual amount of surface erosion is minimal. As expected, erosion was greatest on slopes which were newly regraded. Slopes with dense grass cover showed no signs of erosion. Generally, the amount of erosion decreased with time, as a result of initial loss of fine particles, the formation of a weathered surface, and increased vegetative cover.

** 35. RRTAC 87-9: Hydrogeology and Groundwater Chemistry of the Battle River Mining Areas. M.R. Trudell, R.L. Faught and S.R. Moran. 97 pp.

DESCRIPTION: This report describes the premining geologic conditions in the Battle River coal mining area including the geology as well as the groundwater flow patterns, and the groundwater quality of a sequence of several water-bearing formations extending from the surface to a depth of about 100 metres.

** 36. RRTAC 87-10: Soil Survey of the Plains Hydrology and Reclamation Project - Battle River Project Area. T.M. Macyk and A.H. MacLean. 62 pp. plus 8 maps.

DESCRIPTION: The report evaluates the capability of post-mining landscapes and assesses the changes in capability as a result of mining, in the Battle River mining area. Detailed soils information is provided in the report for lands adjacent to areas already mined as well as for lands that are destined to be mined. Characterization of the reconstructed soils in the reclaimed areas is also provided. Data were collected from 1979 to 1985. Eight maps supplement the report.

** 37. RRTAC 87-11: Geology of the Highvale Study Site: Plains Hydrology and Reclamation Project. A. Maslowski-Schutze. 78 pp.

DESCRIPTION: The report is one of a series that describes the geology, soils and groundwater conditions at the Highvale Coal Mine study site. The purpose of the study was to establish a summary of site geology to a level of detail necessary to provide a framework for studies of hydrogeology and reclamation.

** 38. RRTAC 87-12: Premining Groundwater Conditions at the Highvale Site. M.R. Trudell and R. Faught. 83 pp.

DESCRIPTION: This report presents a detailed discussion of the premining flow patterns, hydraulic properties, and isotopic and hydrochemical characteristics of five layers within the Paskapoo Geological Formation, the underlying sandstone beds of the Upper Horseshoe Canyon Formation, and the surficial glacial drift.

* 39. RRTAC 87-13: An Agricultural Capability Rating System for Reconstructed Soils. T.M. Macyk. 27 pp.

DESCRIPTION: This report provides the rationale and a system for assessing the agricultural capability of reconstructed soils. Data on the properties of the soils used in this report are provided in RRTAC 86-2.

** 40. RRTAC 88-1: A Proposed Evaluation System for Wildlife Habitat Reclamation in the Mountains and Foothills Biomes of Alberta: Proposed Methodology and Assessment Handbook. T.R. Eccles, R.E. Salter and J.E. Green. 101 pp. plus appendix.

DESCRIPTION: The report focuses on the development of guidelines and procedures for the assessment of reclaimed wildlife habitat in the Mountains and Foothills regions of Alberta. The technical section provides background documentation including a discussion of reclamation planning, a listing of reclamation habitats and associated key wildlife species, conditions required for development, recommended revegetation species, suitable reclamation techniques, a description of the recommended assessment techniques and a glossary of basic terminology. The assessment handbook section contains basic information necessary for evaluating wildlife habitat reclamation, including assessment scoresheets for 15 different reclamation habitats, standard methodologies for measuring habitat variables used as assessment criteria, and minimum requirements for certification. This handbook is intended as a field manual that could potentially be used by site operators and reclamation officers. The study was co-funded with The Coal Association of Canada.

** 41. RRTAC 88-2: Plains Hydrology and Reclamation Project: Spoil Groundwater Chemistry and its Impacts on Surface Water. M.R. Trudell (compiler). 135 pp.

DESCRIPTION: Two reports comprise this volume. The first "Chemistry of Groundwater in Mine Spoil, Central Alberta," describes the chemical make-up of spoil groundwater at four mines in the Plains of Alberta. It explains the nature and magnitude of changes in groundwater chemistry following mining and reclamation. The second report, "Impacts of Surface Mining on Chemical Quality of Streams in the Battle River Mining Area," describes the chemical quality of water in streams in the Battle River mining area, and the potential impact of groundwater discharge from surface mines on these streams.

** 42. RRTAC 88-3: Revegetation of Oil Sands Tailings: Growth Improvement of Silver-berry and Buffalo-berry by Inoculation with Mycorrhizal Fungi and N_2-Fixing Bacteria. S. Visser and R.M. Danielson. 98 pp.

DESCRIPTION: The report provides results of a study: (1) To determine the mycorrhizal affinities of various actinorrhizal shrubs in the Fort McMurray, Alberta region; (2) To establish a basis for justifying symbiont inoculation of buffalo-berry and silver-berry; (3) To develop a growing regime for the greenhouse production of mycorrhizal, nodulated silver-berry and buffalo-berry; and, (4) To conduct a field trial on reconstructed soil on the Syncrude Canada Limited oil sands site to critically evaluate the growth performance of inoculated silver-berry and buffalo-berry as compared with their uninoculated counterparts.

** 43. RRTAC 88-4: Plains Hydrology and Reclamation Project: Investigation of the Settlement Behaviour of Mine Backfill. D.R. Pauls (compiler). 135 pp.

DESCRIPTION: This three part volume covers the laboratory assessment of the potential for subsidence in reclaimed landscapes. The first report in this volume, "Simulation of Mine Spoil Subsidence by Consolidation Tests," covers laboratory simulations of the subsidence process particularly as it is influenced by resaturation of mine spoil. The second report, "Water Sensitivity of Smectitic Overburden: Plains Region of Alberta," describes a series of laboratory tests to determine the behaviour of overburden materials when brought into contact with water. The report entitled "Classification System for Transitional Materials: Plains Region of Alberta," describes a lithological classification system developed to address the characteristics of the smectite rich, clayey transition materials that make up the overburden in the Plains of Alberta.

** 44. RRTAC 88-5: Ectomycorrhizae of Jack Pine and Green Alder: Assessment of the Need for Inoculation, Development of Inoculation Techniques and Outplanting Trials on Oil Sand Tailings. R.H. Danielson and S. Visser. 177 pp.

DESCRIPTION: The overall objective of this research was to characterize the mycorrhizal status of Jack Pine and Green Alder which are prime candidates as reclamation species for oil sand tailings and to determine the potential benefits of mycorrhizae on plant performance. This entailed determining the symbiont status of container-grown nursery stock and the quantity and quality of inoculum in reconstructed soils, developing inoculation techniques and finally, performance testing in an actual reclamation setting.

* 45. RRTAC 88-6: Reclamation Research Annual Report - 1987. Reclamation Research Technical Advisory Committee. 67 pp.

DESCRIPTION: This annual report describes the expenditure of $500,000.00 of Alberta Heritage Savings Trust Fund monies on research under the Land Reclamation Program. The report outlines the objectives and research strategies of the four program areas, and describes the projects funded under each program.

* 46. RRTAC 88-7: Baseline Growth Performance Levels and Assessment Procedure for Commercial Tree Species in Alberta's Mountains and Foothills. W.R. Dempster and Associates Ltd. 66 pp.

DESCRIPTION: Data on juvenile height development of lodgepole pine and white spruce from cut-over or burned sites in the Eastern Slopes of Alberta were used to define reasonable expectations of early growth performance as a basis for evaluating the success of reforestation following coal mining. Equations were developed predicting total seedling height and current annual height increment as a function of age and elevation. Procedures are described for applying the equations, with further adjustments for drainage class and aspect, to develop local growth performance against these expectations. The study was co-funded with The Coal Association of Canada.

** 47. RRTAC 88-8: Alberta Forest Service Watershed Management Field and Laboratory Methods. A.M.K. Nip and R.A. Hursey, Alberta Forest Service. 4 Sections, various pagings.

DESCRIPTION: Disturbances such as coal mines in the Eastern Slopes of Alberta have the potential for affecting watershed quality during and following mining. The collection of hydrometric, water quality and hydrometeorologic information is a complex task. A variety of instruments and measurement methods are required to produce a record of hydrologic inputs and outputs for a watershed basin. There is a growing awareness and recognition that standardization of data acquisition methods is required to ensure data comparability, and to allow comparison of data analyses. The purpose of this manual is to assist those involved in the field of data acquisition by outlining methods, practices and instruments which are reliable and recognized by the International Organization for Standardization.

** 48. RRTAC 88-9: Computer Analysis of the Factors Influencing Groundwater Flow and Mass Transport in a System Disturbed by Strip Mining. F.W. Schwartz and A.S. Crowe, SIMCO Groundwater Research Ltd. 78 pp.

DESCRIPTION: Work presented in this report demonstrates how a groundwater flow model can be used to study a variety of mining-related problems such as declining water levels in areas around the mine as a result of dewatering, and the development of high water tables in spoil once resaturation is complete. This report investigates the role of various hydrogeological parameters that influence the magnitude, timing, and extent of water level changes during and following mining at the regional scale. The modelling approach described here represents a major advance on existing work.

*	49. RRTAC 88-10:	D.R. Pauls, S.R. Moran and T. Macyk, Alberta Research Council. Review of Literature Related to Clay Liners for Sump Disposal of Drilling Wastes. 61 pp.
	DESCRIPTION:	The report reviews and analyses the effectiveness of geological containment of drilling waste in sumps. Of particular importance was the determination of changes in properties of clay materials as a result of contact with highly saline brines containing various organic chemicals.
**	50. RRTAC 88-11:	D.N. Graveland, T.A. Oddie, A.E. Osborne and L.A. Panek, Monenco Consultants Limited. Highvale Soil Reconstruction Project: Five Year Summary. 102 pp.
	DESCRIPTION:	This report provides details of a five year study to determine a suitable thickness of subsoil to replace over minespoil in the Highvale plains coal mine area to ensure return of agricultural capability. The study also examined the effect of slope and aspect on agricultural capability. This study was funded and managed with industry assistance.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

This is one of a series of reports that presents the findings of the Plains Hydrology and Reclamation Project (PHRP), an interdisciplinary study that focuses primarily on hydrologic aspects of reclamation of surface coal mines in the plains of Alberta. This research has been conducted by the Alberta Research Council, as part of the Alberta Government's Reclamation Research Program. The program is managed by the Land Conservation and Reclamation Council and is supported by the Heritage Trust Fund.

The focus of the PHRP is to develop a predictive framework that will permit projection of success for reclamation and impact of mining on water resources on a long-term basis. The predictive framework is based on an understanding of processes acting within the landscape so that in the future, mine sites that are not totally analogous to those that have been studied, can be evaluated as well.

The project involves a holistic approach to reclamation by integration of studies of geology, hydrogeology, and soils, not only in the proposed mining area, but also in the adjoining unmined areas. This approach permits the assessment of impacts and of long-term performance, not only in reclaimed areas, but also in the surrounding area.

The research of the PHRP has been directed toward the following two major objectives and eight sub-objectives.

Objective A

To evaluate the potential for reclamation of lands to be surface-mined. The focus is on features of the landscape that make it productive in a broad sense not restricted to revegetation. This objective was organized into five sub-objectives.

1. To assess and evaluate the potential for long-term degradation of reclaimed soils through salt build-up.
2. To assess and evaluate the effectiveness of topographic modification and selective placement of

materials to mitigate deleterious impacts on chemical quality of groundwater.

3. To assess the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations.
4. To evaluate the productivity potential (capability) of post-mining landscapes and the significance of changes in capability as a result of mining.
5. To assess and evaluate limitations to post-mining land use posed by physical instability of cast overburden.

Objective B

To evaluate the long-term impact of mining and reclamation on water quantity and quality. This objective was organized into three sub-objectives.

1. To assess and evaluate the long-term alteration of quality of groundwater in cast overburden and surface water fed from mine spoil as a result of the generation of weathering products.
2. To assess and evaluate infiltration, groundwater recharge, and groundwater-surface water interactions within cast overburden.
3. To characterize the groundwater chemistry generated within cast overburden.

Studies directed at these objectives began in 1979 at the Battle River site in east-central Alberta. Work began in 1982 at a second study area at Highvale Mine south of Lake Wabamun. Significant progress had been made on all project objectives by the end of the first phase of study in March 1984. This present series of reports summarizes the state of our knowledge at the end of this first phase of study. Work is now continuing on the Phase II objectives to gain an even greater understanding of the complex physical and chemical processes in reclaimed landscapes.

This report focuses on Sub-objective A5, which is concerned with subsidence behaviour in reclaimed mine spoil. Differential subsidence of reclaimed surfaces has been demonstrated to create water-holding depressions that disrupt farming operations and to cause pavement distress in roads crossing reclaimed areas. Subsidence depressions have the potential to delay granting of reclamation certification in the Plains region of Alberta. As part of our study of this phenomenon, we have reviewed the available engineering literature relative to subsidence of reclaimed mine spoil.

For those interested readers, copies of the abstracts and summaries of the papers referenced in the body of this report are available from the Terrain Sciences Department of the Alberta Research Council.

ABSTRACT

This literature review was compiled as background for our investigations of the settlement behaviour of uncompacted mine spoil. All the major relevant engineering, geotechnical, and reclamation bibliographic data bases and indices were searched for the period 1970 to 1984.

Settlement is reported to occur through various mechanisms, some well understood and predictable, and others much more complex. Properties of spoil that must be known to assist settlement prediction include lithology, initial dry density, initial moisture content, stress history, water sensitivity, and compaction characteristics. Difficulty in comparing settlement data from various mine sites arises from a lack of standardization of research and reporting methods. Great variation in drilling, monitoring, and laboratory programs, along with nonstandardized reporting of soil classification, settlement data, and laboratory results complicated comparison or application of predictive settlement trends between reclamation sites. Treating spoil to ameliorate excessive settlement has been attempted by several researchers. Post-reclamation ground treatments take the forms of preloading the spoil by earth moving operations, saturating the spoil by flooding, and compacting the spoil by dynamic or vibration compaction techniques. Each method is effective to some degree, but each method is costly. It is more cost-effective to control settlement during the reclamation process. Settlement of unsaturated spoil is difficult to understand and involves many controlling variables. A theory that may be applicable to one type of spoil in one setting is not necessarily relevant to other types of spoil. Therefore, few generalizations or conclusive recommendations were made by the numerous authors whose work was included in the review.

1. INTRODUCTION

An investigation of the settlement behaviour of mine backfill has been conducted as part of the research studies of the PHRP, Alberta Research Council. The Faculty of Engineering of the University of Alberta began the mine backfill settlement studies in 1980. The investigation has obtained observations and measurements of settlement through field monitoring programs and through laboratory testing programs. The field work has concentrated on mine spoil from the Diplomat and Vesta Mine sites in the Battle River area near Forestburg, Alberta. Settlement of the spoil resulting in large depressions, sinkholes, and corrugated land surfaces has been observed on the reclaimed land. Installation of settlement monitoring instrumentation and laboratory testing of spoil material was initiated to measure the magnitude and duration of settlement and to assist in understanding the mechanisms causing and variables influencing settlement.

This literature review was compiled as background for our own investigation of the settlement behaviour of mine spoil and to direct the readers to the full body of literature discussing subsidence of mine spoil from an engineering point of view. The report consolidates a great variety of literature into a concise, readable directory suitable for easy reference but does not attempt to interpret all of the literature in the context of Alberta mining procedures and materials. The reader is left to assess the applicability of the many authors' findings to his own situation. We will further use the literature to assess our own research in subsequent topical reports.

1.1 SCOPE OF REPORT

The following paragraphs introduce the discussion topics of interest to various researchers and engineers studying mine backfill settlement. Selected comments from the literature make up the discussion sections (Sections 2 to 5), which describe various research methods, analyse mechanisms of settlement, investigate remedial measures for settlement, and list recommendations resulting from research observations.

Difficulty in comparing settlement data from various mine sites arises from a lack of standardization of research and reporting methods. Great variation in drilling, monitoring, and laboratory programs, along with unstandardized reporting of soil classification, settlement data, and laboratory results complicates comparison or application of predictive settlement trends between reclamation sites. The variety of research and reporting methods and the types of spoil materials are described in Section 2.

Understanding relationships between settlement and the initial mine spoil conditions will allow development of procedures for controlling settlement where necessary. Settlement takes place through various mechanisms, some well understood and predictable, and others much more complex. Properties of spoil that must be known to assist settlement prediction include lithology, initial dry density, initial moisture content, stress history, water sensitivity, and compaction characteristics. The effect of these conditions on the various mechanisms of settlement, along with a description of the mechanisms, is discussed, from the points of view of various authors, in Section 3.

Treating spoil to ameliorate excessive settlement has been attempted by several researchers and is discussed in Section 4. Post-reclamation ground treatments take the forms of preloading the spoil by earth moving operations, saturating the spoil by flooding, and compacting the spoil by dynamic or vibration compaction techniques. Each method is effective to some degree, but each method is costly. It is more effective and less costly to control settlement during the reclamation process. An understanding of techniques of recontouring that produce a spoil that only settles a manageable amount will lead to more effective, economic reclamation and will ease development of reclamation regulations specific for each type of spoil material.

Researchers are aware that settlement of unsaturated spoils is difficult to understand and involves many controlling variables. A theory may be true for one spoil and not for another. Therefore, few conclusive recommendations are made by the many authors. Recommendations in Section 5 typically suggest caution when building on mine spoil, or suggest approaches for regulation or future studies.

1.2 REFERENCE SOURCES

Many indices and information sources were searched to compile this literature review. The Engineering Index and Geotechnical Abstracts were searched, including articles from 1970 to the summer of 1984. "Coal Abstracts" was searched, not revealing any related material. Catalogues and reports from the Canada Centre for Mineral and Energy Technology again revealed no related articles between 1976 and October 1983. A computer search on the following files was accomplished.

File 165:Ei	Engineering Meetings	1970-1984/July
File 8: Compendex	Engineering Index	1970-1984/August
File 6:NTIS	US Government Reports	1964-1984/Issue 19

Lists of references from papers related to the PHRP project were checked. The computer and microfiche subject and title listings and the RECLAIM file of the University of Alberta libraries were scanned and the library shelves containing related material were browsed. Finally, reports of related studies accomplished in the Geotechnical Department and articles gathered during visitations to conferences such as the International Conference on Ground Movements and Structures, at Wales in 1984, are included to complete the list of related work discussed in this report.

An author index and an appendix listing abstracts and/or summaries of research papers related to the settlement of mine spoil are included as separate sections of this report. Abstracts are copied directly from those presented with a paper. Where no abstract was included, or where the abstract was deficient in describing the useful contents of the report, a summary was composed. The order of the presentation of abstracts and summaries follows the order of the bibliography found in the main body of the report.

2. RESEARCH METHODS

2.1 SITE INVESTIGATIONS

2.1.1 Sampling

The settlement characteristics of a mine backfill depend greatly on the spoil material type. Undisturbed spoil samples are retrieved in order to classify the material as well as to measure the in-situ density and water content of the spoil. Laboratory tests performed on these samples commonly reveal grain-size distribution, shear strength, plastic and liquid limits, clay mineralogy, permeability, standard compaction density, and optimum water content. These laboratory tests assist the researcher to understand which spoil material properties govern the settlement behaviour of a specific spoil.

Undisturbed soil samples are retrieved as core samples (Armstrong 1986) or as shelby tube samples (Groenewold and Rehm 1980; Hankins 1984), they are typically 100 mm in diameter, as commonly used in Great Britain, or 73 mm, as used in the PHRP project. How closely these small samples represent the in-situ spoil, and how altered the samples become from pushing and extruding, are issues researchers are questioning (Groenewold and Rehm 1980). A shelby tube may contain a sample from a large undisturbed block of overburden that was not broken up during dragline operation, or it may contain a finely crushed, loose sample. In one site investigation, Groenewold and Bailey (1978) reported that during extrusion of the samples from the shelby tubes, 34 percent of the samples expanded (as much as 5 cm), 25 percent were compressed, and 41 percent showed no volume change. Larger diameter sampling equipment is needed to adequately represent the in-situ spoil (Groenewold and Rehm 1980).

2.1.2 Engineering Properties of Mine Spoil

Since spoil type greatly influences settlement characteristics, a general knowledge of the types of soils found at various locations of study is helpful. The following is a summary of the type of spoil found at four locations of study, namely at mine sites in Great Britain, at mine sites in the midwestern states of the United States, at mines sites in the Gulf Coast region in Texas, and at mine sites in Alberta.

British coal mine backfills commonly are clayey materials with 20 to 54 percent finer than 0.075 mm (Charles et al. 1978; Charles 1984, 1979). Dry densities range from 1.52 to 2.0 g/cm^3 (Charles et al. 1978; Knipe 1979), plasticity is moderate at 54 percent, water contents vary greatly, and standard compaction densities range from 1.92 g/cm^3 at optimum water content of 14 percent (Charles et al. 1978) to 1.76 to 1.84 g/cm^3 at water content of 10 to 18 percent (Knipe 1979). In-situ densities are usually lower than standard compaction density (Charles et al. 1978).

Castback overburden material from the surface coal mines of the mid-western states of the United States have bulk densities ranging from 1.3 to 2.0 g/cm^3 (Phelps et al. 1983). Spoil samples from the Indian Head Mine in North Dakota had liquid limits ranging from 22 to 94 percent with an average of 58 percent. Plastic limits ranged from 13 to 32 percent with an average of 20 percent. The natural water content ranged from 13 to 29 percent and averaged 22 percent. The samples averaged a dry density of 1.62 g/cm^3. Groenewold and Rehm (1980) also record results of triaxial shear tests. No information on compaction density is available from this location.

Overburden material in the Gulf Coast region of Texas is over-consolidated by 2.5 to 3.0 MPa. Bulk density of the reclaimed land averaged 1.54 g/cm^3 and water contents ranged between 18 and 24 percent. Liquid limits ranged from 37 to 70 percent and averaged 52 percent. Materials are typically quite sandy, existing as predominantly clayey sand, sandy clay, and sandstones. Clay and clay-shales also exist in this region. Sand content of the mined spoil ranges from 0 to 40 percent.

Open pit coal mining backfill from two sites in Alberta is generally a medium to highly plastic clay material. Dry densities typically range from 1.6 to 1.8 g/cm^3, although values lower than 1.4 g/cm^3 have been measured. Spoil at Highvale Mine contains 35 percent clay, 35 percent silt, and 30 percent fine-grain sand. Forestburg spoil is a similar mix with somewhat less silt and more sand. The standard compaction dry density of the spoil at Diplomat Mine was 1.84 g/cm^3 at an optimum water content of 15 percent. The spoil at Highvale Mine had a much lower standard compaction dry density of 1.53 g/cm^3 at a water content of 22 percent.

Other testing performed by various researchers determined the coefficient of consolidation, consolidation ratio (Groenewold and Rehm 1980), Youngs' modulus (Groenewold and Bailey 1978), and the constrained modulus (Charles and Burland 1982) of the spoil material. However, these parameters are properties of microstructure of material but do not describe the bulk property of spoil.

Table 1 summarizes the material characteristics from the various locations discussed. The missing information indicates the lack of standardization of research methods and spoil classification. Standardization of material testing and a system of classifying and reporting test results would allow researchers to attribute location specific settlement trends to the controlling variables of the site. Such a classification system has been devised for Gulf Coast lignite mine spoil. This classification system of mined strata allows prediction of spoil characteristics (Borbely 1986). Lump size distributions along with lithologic proportions of spoil are major parameters of the classification system.

2.1.3 Standard Penetration Test

A mine spoil will not only behave according to its lithological type and structure or microstructure, which can be investigated in the laboratory, but also according to its large-scale

Table 1. Classification of spoil material.

Location of Mine Site	In-Situ Bulk Density g/cm^3	Plastic Limit ω_p %	Liquid Limit ω_l %	Plasticity Index I_p %	Natural Content ω %	Grain Size Distribution D_n*	Standard Compaction Test $\rho_{d(max)}$ g/cm^3	Standard Compaction Test $\omega_{(opt)}$ %	Preconsolidation Pressure	Lump Size Distribution
Alberta										
(Diplomat)	1.7 to 2.0	14	29	Med	14	?	1.84	15	0 (till)	?
(Highvale)	1.7 to 2.0	22	60	High	18	35/35/30	1.53	22	10 to 12 MPa (Bedrock)	?
USA										
(North Dakota)	1.62	20	58	Med	22	?	?	?	?	?
(Penn and Ohio)	1.3 to 2.0	?	?	?	?	?	?	?	?	?
Britain										
(Horsley)	1.5 to 2.0	?	?	Med	?	20 to 54% < 0.075 mm	1.80	10 to 18	?	?
Gulf Coast	1.54	26	52	Med	22	30/30/40	?	?	2.5 to 3.0 MPa	

* Particle size distributions are reported as a percentage of clay/silt/sand sizes as displayed by the Diplomat and Highvale data or as a percentage of material smaller or larger than a certain sized particle. However, particle size distribution curves are the best way of reporting this information.

lump size distribution and structure, which is referred to as its macrostructure. Spoil can contain zones of loose disaggregated material, homogeneous, densely packed material and zones of hard lumps interacting as building blocks with large voids between the blocks. If the lump size distribution in spoil is such that larger lumps are floating in a matrix of fine material, the fine material will govern the settlement characteristics of the spoil. However, if the distribution of lumps forms a structure where load paths result, the settlement will occur only as the structure breaks down. The percentage of recovered, undisturbed core samples, standard penetration tests (SPT), dynamic cone tests (DCT), and geophysical logs all give some indication of the macrostructure of a spoil.

Several attempts to relate SPT blow-counts to soil density have been carried out. The SPT has been used successfully in granular soil to indicate the relative density, but it is difficult to use this test for the same purpose in cohesive soils. However, El-Moursi et al. (1978) performed an extensive work to relate SPT blow-counts to the compressibility of a cohesive soil. They point out that using SPT along with a few laboratory consolidation tests to determine soil compressibility is less expensive than the usual extensive laboratory work and is more accurate on a heterogeneous or erratic spoil material. A large number of SPT values are needed to accomplish the suggested statistical analysis required for the compressibility determination.

Charles (1984) used SPT to describe the relative density of a mine backfill. The SPT value of 30 indicates a medium dense spoil, whereas a value of 10 indicates a loose spoil. Table 2 shows a comparison of SPT blow-counts with various spoil placement methods. SPT were performed on reclaimed mine spoil at both the Battle River and Wabamun mining areas, however, no correlation between density and blow-counts was found. Trends of increasing blow-counts with depth were noted but were attributed to increasing confining pressure not increasing density. Blow-counts from the Diplomat Mine near Forestburg average approximately 8 to 10 blow-counts per 30 cm at

Table 2. Standard penetration test blowcounts from spoils placed by various methods.

Location	Method of Placement	Mean Water Content %	Mean Dry Density g/cm^3	SPT Range	SPT Mean
North hole Leicestershire	Brought by scrapers in thin lifts	15	1.68	12 to 56	30
South and middle holes Leicestershire	Brought by trucks in lifts 1.5-2.0 m high	16	1.56	2 to 26	10
No. 3 dock Methil	Dozed into standing water	12		4 to 17	9
Diplomat Mine Alberta	Small dragline	14	1.67	7 to 28	13
Vesta Mine Alberta	Large dragline	16	1.66	9 to 36	21
Highvale Mine Alberta	Large dragline	18	1.63	5 to 38	22

(From Charles 1984).

shallow depths and increased to an average of 15 to 20 counts at an eight-metre depth. Spoil at Highvale Mine near Wabamun produced average counts of 10 to 12 at shallow depths and 22 to 25 at 15-meter depths.

2.1.4 Dynamic Cone Test

The dynamic cone penetration test consists of driving a cone through a complete depth of soil. No borehole is needed and is, therefore, a less expensive test than the SPT. Similar information on the density condition of the spoil is investigated with the DCT. Alberta studies have used it frequently and Charles (1979) mentions using this test on a domestic refuse fill in the east end of London, England. Results are similar to the SPT and also show an increase in blow-count with increasing depth.

Armstrong (1986) used the DCT to investigate the distribution and size of spoil clasts. He observed an increase in penetration resistance with depth of spoil and attributed it to dynamic compaction of deeper spoil by spoil dumping. The DCT data indicated geotechnical conditions exist for significant settlement where overburden spoil is predominantly clay-shale.

2.1.5 Geophysical Logging

Geophysical logs can give water content, bulk density, and soil lithology of the in-situ backfill. Boreholes drilled for core sampling and SPT testing can be used to access simple logging tools to the complete depth of spoil. Wells (1981) used geophysical logs extensively to collect bulk density values, water content measurements, and lithology profiles for his thesis data base. Geophysical logs have been performed on boreholes in Alberta mine spoil. A similar range of densities was measured by both the geophysical logging and shelby tube sampling. To rely heavily on geophysical logging, more interpretation of the logs would be necessary. Little is mentioned of geophysical logging in the British papers listed in the bibliography.

2.2 FIELD MONITORING PROGRAMS

Field monitoring programs typically involve measuring ground-surface settlement or compression of a particular layer of spoil. The settlement is related to the duration of time since reclamation or to a change of backfill conditions. Multipoint extensometers, surface monuments and piezometers are frequently used to obtain these data. The following section describes these instruments and their uses. Other miscellaneous field investigations are also mentioned.

2.2.1 Multipoint Extensometers

Multipoint extensometers are the most widely used instruments for collecting settlement data from in-situ backfill. They allow measurement of the total surface settlement as well as the compression of various layers of spoil. This allows careful examination of the conditions influencing settlement, especially the effect of a rising or falling water table. Descriptions of extensometers and their implementation can be found in articles by Charles (1979) and Gale et al. (1983). Accuracy of 1 to 3 mm is easily achieved by using the extensometer correctly. A porous stone adapted to fit onto the bottom of the extensometer allows the extensometer to measure both settlement and water-table position (Charles 1979). Charles also suggests filling the empty space between the borehole wall and flexible tube with dry sand.

2.2.2 Surface Monuments

Ground-surface settlement is easily measured using surface monuments and simple surveying techniques. The PHRP study uses settlement gauges consisting of a base plate welded onto a steel rod. This base plate is dropped to the bottom of a 1 to 2 m deep, drilled hole with a rod extending to or just below the ground-surface, depending on the intended use of the land. A plastic sleeve is dropped over the rod so that the rod is simply an extension of the base plate and records the movement of the ground at the base plate level. Knipe (1979) found little difference in results between this type of surface monument and simple steel rods driven into the ground with an air hammer. Due to the simplicity of installation and cost savings, Knipe suggests that 1200-millimeter long steel rods driven into the ground are adequate for ground-surface settlement measurement. Knipe installed surface monuments at 50-metre centres to form a grid. Where more settlement was apparent, he reduced the spacing between monuments to 25 m or less. However, in regions where frost penetration is significant, simple steel rods may reflect ground movements due to the frost heave action and thus obscure settlement measurement.

Schneider (1977), also used surface movements to monitor vertical displacement of the reclaimed land surface. Elevation stations were laid out in clusters. Three movements were placed on the corners of an equilateral triangle and a fourth in the centre. The middle movements were used to measure total settlement and the surrounding markers used to indicate differential settlement.

2.2.3 Piezometers

Piezometers consist of a porous stone or filter surrounding a slotted sleeve attached to a long tube. A brass or PVC cone at the end of the apparatus allows the instrument to be pushed deep into the ground leaving only the flexible tube protruding from the ground-surface. A low cost, all PVC, hydraulically driven apparatus, developed for use in soft sediment is described by Desauliers (1983). Piezometers of this type were used by the PHRP study.

Piezometers measure the position of the hydraulic head and groundwater table but have been used to perform single-well-response permeability tests (Groenewold and Rehm 1980) and falling head permeability tests (Buist and Dutch 1984). Piezometers are used to correlate groundwater-table movement with collapse settlement (Smyth-Osbourne and Mizon 1984).

2.2.4 Other Field Programs

Various other types of field programs have been undertaken. Winczewski (1977) investigated the influence of stripping methods on settlement behaviour of mine backfill by charting the spoil deposition patterns of a large dragline. In-situ load tests have been performed on mine backfill by several researchers (Charles and Driscoll 1981; Gale et al. 1983). Large-scale, in-situ permeability tests were conducted by Groenewold and Rehm (1980), and general visual observations have been documented by many researchers.

Schneider 1977, monitored the height of a spoil pile from development to a few months old as the pile settlement rate decreased rapidly from 312 to 8 ft/y (95.10 to 2.44 m/y), 20 d later. A one second theodolite was used to measure vertical angles between the top of the spoil pile and a level projection. Reference marks were used to locate the theodolite for each reading. Accuracy was approximately $\pm$0.006 ft (2 mm), a small fraction of the observed settlement.

2.3 LABORATORY PROGRAMS

Laboratory programs generally involve index testing for classification of material types and compression testing for simulation of potential in-situ settlement. Sections 2.1.1 and 2.1.2 described index testing and classification of backfill material so only the compression test and the slake-swell test are discussed here.

2.3.1 Oedometer Tests

Compression, consolidation, and collapse settlement of backfill material can be simulated in the laboratory with the use of the consolidation oedometer. Sizes of 1 m diameter (Charles et al. 1978), 30 cm diameter (Gale et al. 1983), 112 mm diameter (Rangel 1979), 100 mm diameter (Smyth-Osbourne and Mizon 1984), and 73 mm diameter used in the PHRP study have been built. During a consolidation test, the porosity, percent air voids, water content, dry density, and compression can be measured or calculated as a sample is loaded.

Often laboratory measurements of compression characteristics of a spoil do not agree with settlements measured in the field. Smyth-Osbourne and Mizon (1984) and Charles (1984) suggest that this discrepancy may result from compaction of samples during drive sampling and subsequent extrusion. Groenewold and Rehm (1980) mention that obtaining representative samples of spoil material is extremely difficult because often the spoil commonly consists of fragments of overburden ranging in size from sand-size grains to 3 m blocks. A 70 to 100 mm diameter sample, thus, commonly yields a sample of undisturbed overburden from a large block. Truly representative sampling, thus, requires much larger sampling equipment.

2.3.2 Slake-Swell Tests

Extensive testing has been performed on the water sensitivity of overburden at the Battle River mining area (Dusseault et al. 1984c, 1985). It was found that the transitional materials from the Plains regions of Alberta show volume change characteristics when in contact with water, because the soil contains little mineral cementation and contains significant quantities of swelling clay minerals. Ingles and Aitchison (1969) suggest potentially slaking soils should be examined by consolidation testing for susceptibility to collapse subsidence when unsaturated material is inundated.

3. MECHANISMS OF SETTLEMENT

3.1 AREA-WIDE SETTLEMENT

Area-wide settlement, as Groenewold and Rehm (1980) call it, or 'creep' as Charles (1983) refers to it, is the movement that occurs under conditions of constant water content and constant self-weight induced stress. Creep compression for many backfills shows a linear relationship when plotted against the logarithm of time (Charles 1983). A parameter, alpha, defined by Charles (1983), gives quantitative measurement of this compression. Alpha is defined as the strain of the backfill occurring over one log cycle of time. Alpha values are used to express strains in domestic refuse backfill sites and range from 0.2 percent to 10 percent. Many other researchers have noted a linear relationship between self-weight compression and log time (Leigh and Rainbow 1979; Riker et al. 1978; Hankins 1984). This type of settlement continues longer in the top layers of spoil since, here, ground stresses are not large enough to accelerate settlement (Ferguson 1984). Area-wide settlement of surface coal mine spoil has been observed to continue for as much as 20 years at some European mine sites (Bell 1977; Golosinski et al. 1984).

3.2 COLLAPSE SETTLEMENT

Collapse settlement can result in the formation of large depressions, and is caused by an increase in the water content of the spoil material. Groenewold and Rehm (1980) note depressions as much as 15 m in length and 3 m deep. Depressions of approximately half these dimensions have been noted to form on the backfill at Diplomat Mine within the first one to five years after leveling. Collapse settlement can occur when precipitation infiltrates through the ground-surface or when the groundwater table fluctuates. Charles and Burland (1982) suggest that susceptibility of land to collapse settlement can be tested simply by excavating a shallow trench, filling it with water, and monitoring the level of the ground-surface by precise leveling. Settlement strains of as much as 4.5 percent, resulting from inundation, have been noted by Charles (1984). Even greater strains have been noted in laboratory tests of the PHRP. Groenewold and Rehm (1980) report that collapse settlement is a short-term problem usually expiring in 12 to 15 months from initial leveling of spoil, however, Charles (1984) notes that backfill may be susceptible to large settlements on inundation irrespective of the time that has elapsed since reclamation. Collapse settlement has created a problem in New Mexico where geological deposited young, unconsolidated alluvium developed large subsidence depressions when the land was inundated (Johnpeer 1986). Observations at Diplomat and Vesta Mines as part of the PHRP study confirm that the collapse mechanism also occurs in unconsolidated mine spoil.

The susceptibility of a spoil to collapse settlement will depend on the initial water content, initial porosity, and on the water sensitivity of the spoil. In Figures 1 and 2, Charles et al. (1978) and Charles (1984) show that the amount of potential compression increases as the initial water content decreases and as the initial air voids increase. Booth (1975) presents a graph (Figure 3) that relates both initial dry density and initial water content to the amount of compression on saturation. The effect on the potential for settlement of altering: (1) soil density by compaction, and (2) initial water content by flooding, is clearly described with this plot. By increasing the clay density from 1.5 g/cm^3 to 1.6 g/cm^3, at a water content of 8 to 12 percent, the potential strain of material decreases from 7 to 15 percent; by increasing the water content from 8 to 16 percent at a density of 1.5 g/cm^3, the potential strain of the material decreases from 7 to 1 percent.

Soils of different grain-size distributions, shown by three different sloping lines in Figure 3, but with the same initial air voids and water content undergo varying amounts of compression. Soils with more clay-size particles will compress more than soils with more silt and sand-size particles. This is, again, clearly

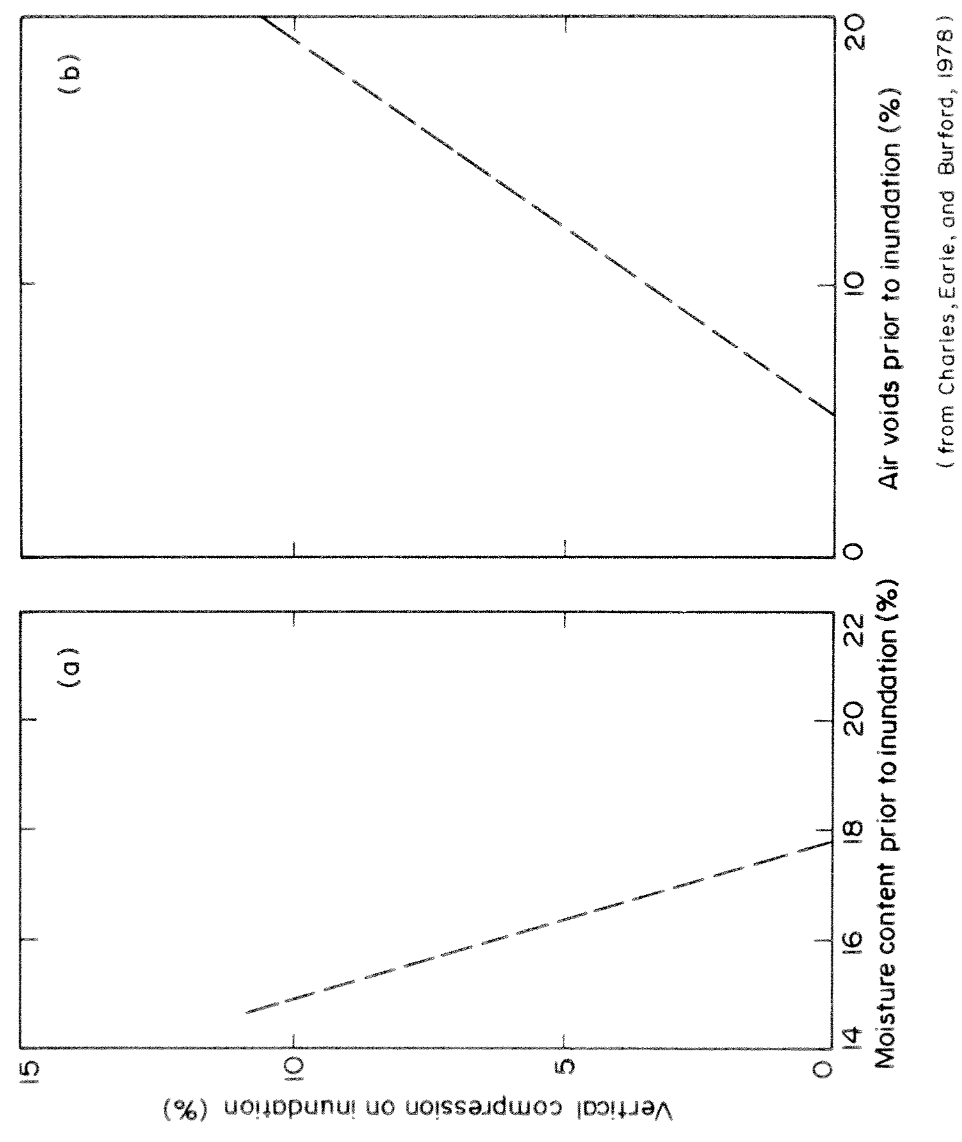


Figure 1. Compression of cohesive fill on inundation in the one metre diameter oedometer.

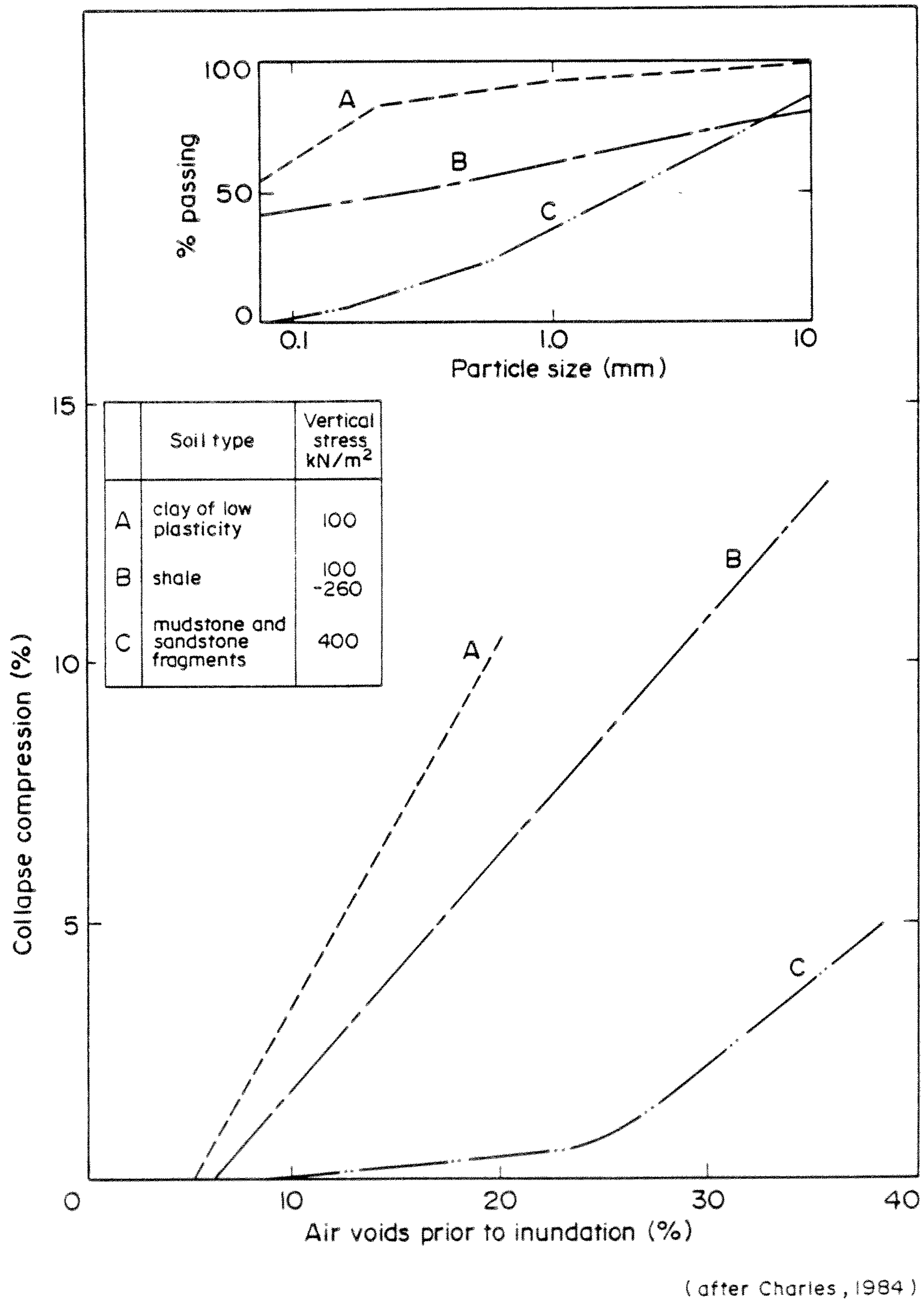
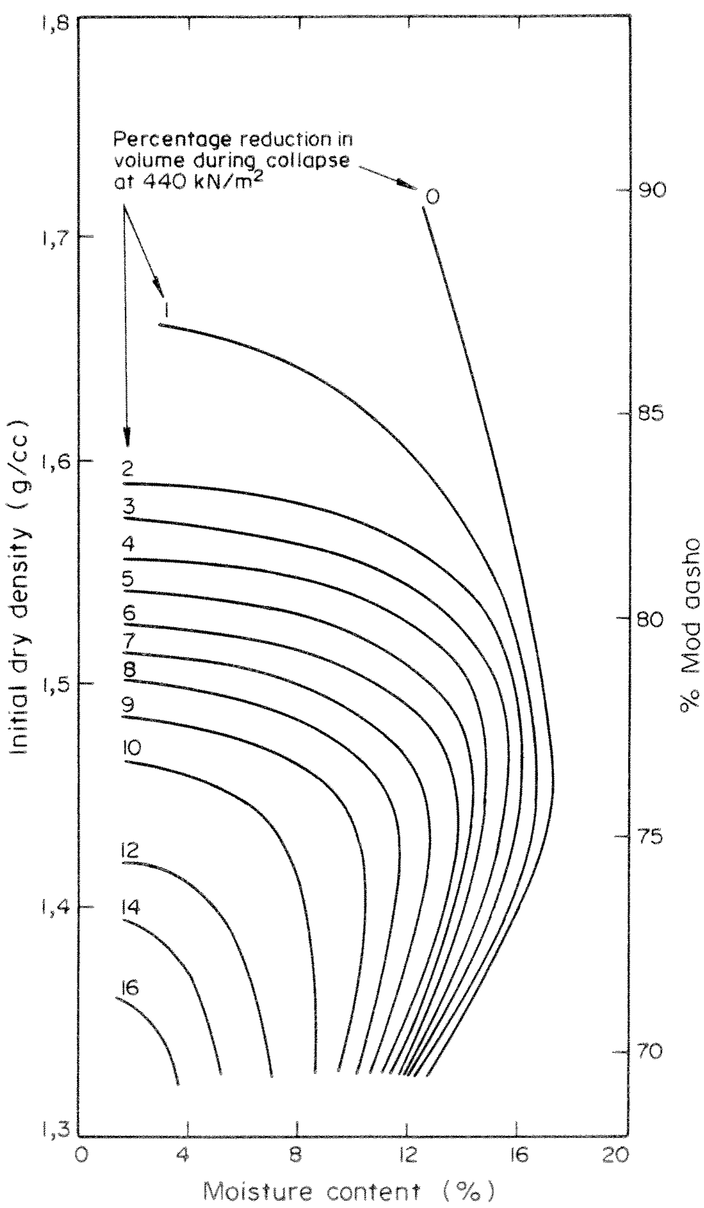


Figure 2. Compression of three different mine spoils on inundation.



(after Booth, 1975)

Figure 3. Percentage collapse at different initial dry densities and moisture contents.

illustrated in Figure 4 where Rangel (1979) plots results of consolidation tests. As the sand content increases, settlement potential decreases dramatically.

Two factors, essential for collapse subsidence to occur, are substantial porosity and lessening of interparticle bond forces (Ingles and Aitchison 1969). Ingles and Aitchison also state that clayey sands which have not been previously wetted to saturation may exhibit the collapse phenomena upon wetting. They also recognized that soils which resist compactive effort, i.e., heavy clays in an unsaturated state, are particularly susceptible to large pores built into the soil structure. Both the sandy tills and the heavy clay bedrock materials of the Alberta Plains region would fall into the categories mentioned by these authors.

The effect of prewetting and preloading on collapse compression is discussed by Charles et al. (1984). An open pit mine at Horsley left a lagoon area and a large spoil pile. Total settlements were less in these areas where the spoil was subjected to prewetting or preloading. The effect of prewetting was also noted in Methil, where backfill was end tipped into standing water (Charles 1984). Both prewetting and preloading reduce the potential for collapse settlement.

Extensive research on the mechanisms causing collapse settlement has been reported by Barden et al. (1973) and Nowatzki (1980). Nowatzki describes the collapse as a breakdown of weak cementation bonds as a soil intakes water. Barden investigated the soil structure with an electron microscope and suggests that collapse can occur on saturation by three processes: (1) net negative pore pressure or capillary suction is destroyed decreasing the interparticle friction; (2) clay buttresses supporting larger grain structure is softened allowing more movement of soil grains; and (3) chemical bonds formed by agents, such as, iron oxide or calcium carbonate are eroded when saturated. It is not known if these mechanisms are instrumental in the collapse of mine spoil materials found in Alberta.

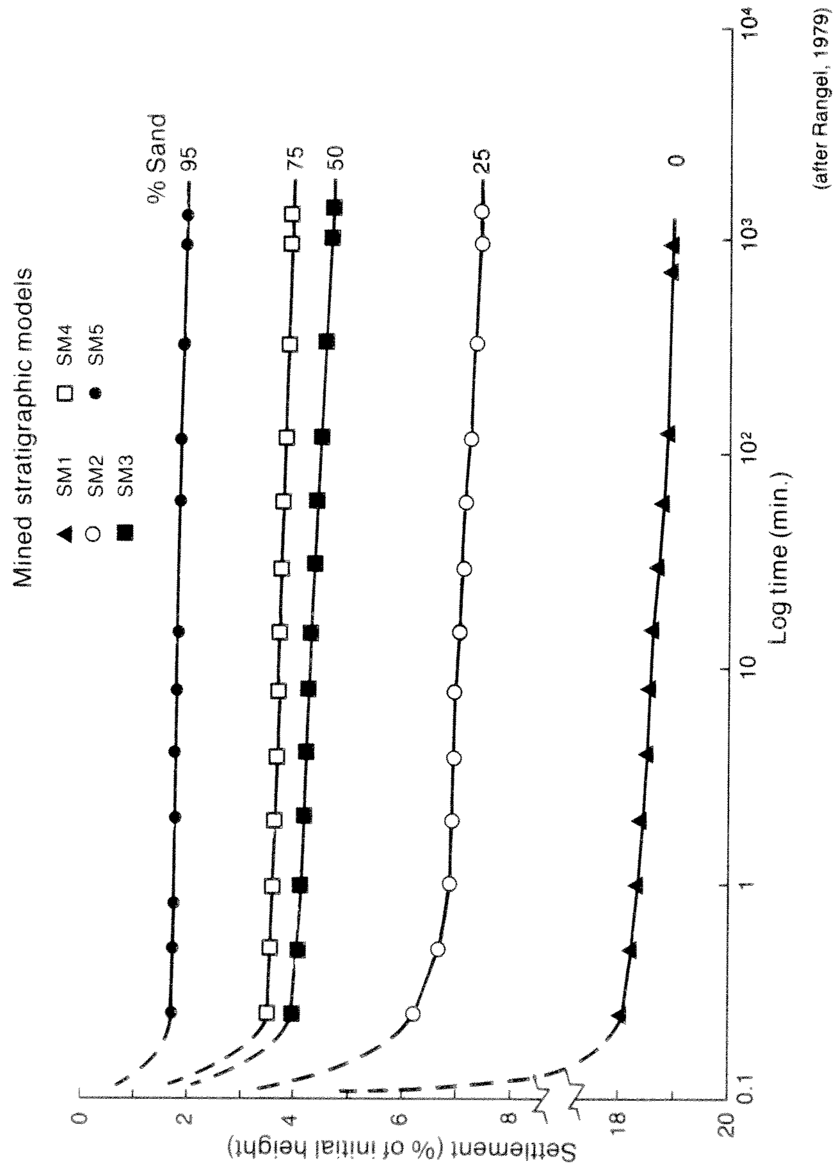


Figure 4. Settlement vs log time for stratigraphic models at various sand contents.

3.3 PIPING

Sinkholes can develop long after reclamation has been completed and surface settlements have diminished. The mechanism forming these sinkholes is called piping by Groenewold and Rehm (1980) and is the most dramatic instability phenomenon. Groenewold and Rehm (1980) note piping features as much as 3 m in diameter and 1 m deep. There are different views on what exactly takes place during piping. Groenewold and Rehm (1980) describe it beginning as cracks either on the surface of exposed spoil or at the topsoil-spoil interface. The cracks allow access for large volumes of surface runoff to flow into the subsurface spoil if the subsurface spoil is fractured or poorly compacted. The water washes the topsoil and subsoil into the pore space of the subsurface spoil. Groenewold and Rehm (1980) and Winczewski (1977) conclude that areas of poorly compacted spoil, resulting from dozer-contouring or zones between differently compacted areas, are most susceptible to piping especially if the reclaimed surface contains standing water.

Dusseault et al. (1984a) explain the sinkhole development by a completely different mechanism. Sinkholes do not develop by subsurface dispersion of water transporting soil, nor do they develop by melting blocks of frozen material, rather they develop through arching and stoping mechanisms.

Large voids in the subsurface spoil are formed by leveling of spoil, by melting of frozen blocks of spoil, or by compaction of spoil from inundation. The spoil above such a void arches so little ground-surface deflection is noted. The void migrates up through the spoil by a stoping mechanism as the spoil slakes and collapses into the void. The surface layer is commonly more compact from reclamation traffic and, thus, forms a beam-like layer spanning the void. When the layer becomes sufficiently undermined it shears and falls into the void leaving a distinct hole in the ground-surface. The sides of the sinkhole stoping toward the intact spoil and the pattern of tension cracking surrounding the sinkhole indicate these mechanisms. Sinkholes develop where large settlements of at least

600 mm occur in valley locations and only if stoping action concentrates the voids centrally.

3.4 DIFFERENTIAL COMPACTION

Open pit coal surface mines, typically, are long narrow pits. Overburden is cast to the side of the pit forming large parallel windrows as much as 20 m above the original ground level (Thomson and Schultz 1984). These windrows are flattened by bulldozing the peaks into adjacent valleys. The end result leaves spoil in the precontouring peak location compacted both by dynamic compaction as the windrow was built, and by the surcharge load of the peak material, whereas spoil in the valley location is subjected to compaction only from the bulldozing operation. This differential compaction causes the spoil to settle differentially which results in a corrugated land surface with distinct ridges and troughs reflecting original windrow topography (Dusseault, Scott and Moran 1985). Water often ponds in the low areas and can cause additional collapse settlement and piping features in the first years after leveling. The thin layer of topsoil, which is initially spread evenly over the reclaimed land after severe subsidence features are releveled, may migrate from ridge areas to lower trough areas as the land is cultivated year after year. The potential agricultural productivity of the land could be lessened from that of the original reclaimed landscape by the two-fold effect of topsoil migrating from ridge areas into lower areas and of lower areas ponding water thus flooding the cropland that has the deepest topsoil.

Other conditions leading to differential settlement include varying reclamation techniques and varying depths of fill. Contouring one area with scrapers and the adjacent area with dozers creates an interface between areas that is particularly susceptible to differential settlement and instability problems (Winczewski 1978). Varying depths of fill material that undergo the same percentage strain result in varying total surface settlements. A mining scheme that creates a preloaded area where a spoil pile once existed next to an undercompacted dozer-filled area where the spoil pile was pushed into a valley, results in differential settlement pattern where the ground-surface in the preload area heaves and the ground-surface in the precontoured valley area settles. Heave of 100 mm was observed in an area where spoil piles were removed and used for backfill near Dudley, Great Britain (Knipe 1979).

4. REMEDIAL MEASURES

Remedial measures, if warranted, can be accomplished by adapting the mining method to produce a more uniformly compacted backfill, by taking care during reclamation procedures to compact or otherwise alter low density spoil, or by treating low density areas that are settling with post-reclamation ground treatment techniques. It is acknowledged that a more economic and effective choice may be to use adaptive mining and reclamation schemes because post-reclamation ground treatments are moderately to excessively costly or ineffective (Norton 1983). Contouring the land surface so that positive drainage is maintained even after long-term settlement expires, may be an economic solution to the damaging effects of settlement.

4.1 RECLAMATION METHODS

It is generally confirmed that placing backfill by scraper in thin lifts produces a more dense spoil than by pushing spoil with a dozer or by end tipping spoil in thicker lifts with trucks. Winczewski (1978) points out that pan scrapers reduce clast size of spoil material as well as compact sediment by transit of the scraper over the sediment. Charles (1984) compares the dry density of open drive samples of spoil placed by scrapers with spoil placed in high lifts by trucks and leveled with dozers. Spoil placed by scrapers averages a dry density of 1.68 g/cm^3, whereas spoil placed in high lifts average 1.56 g/cm^3. Groenewold and Rehm (1980) state that settlement is significantly less in scraper contoured areas than in dozer contoured areas. Thomson and Schulz (1984) note that precontoured peak locations will not be as susceptible to settlement as precontoured valley locations because spoil piles are subjected to dynamic compaction from the falling spoil of the dragline operation. Expending this dynamic compaction uniformly over the backfill area would decrease the differential compaction characteristic of the dragline spoil. This might be accomplished by depositing the dumped material in an arching action, which would change the spoil pile shape slightly. In some mining layouts, this would result in a reduced pit width, reducing the productivity of a given machine and, therefore, would not be considered an economic solution.

4.2 POST-RECLAMATION GROUND TREATMENT

Charles et al. (1978) compared the effectiveness and costs of three ground treatment methods (Table 3). The most effective ground treatment was the preload. Depending on the accessibility of preload soil, it can also be reasonably economic (Charles et al. 1978). They point out that the preload need not remain in place a long time, as most of the compression occurs almost immediately. Therefore, a continuous earth moving operation can be implemented with great benefit. Dynamic consolidation, consisting of dropping a heavy (15 t) weight from a height of 10 to 20 m, has been accomplished on several sites in England, and on an area near Wabamun. Charles and his associates have investigated the effectiveness of dynamic consolidation in several papers (Charles et al. 1978; Charles 1979; Charles et al. 1981; Charles 1981). Johnpeer (1986) also recognizes that this treatment may be viable for small areas of land on which buildings are to be constructed.

If spoil is sensitive to collapse settlement on inundation, treatment can exist in the form of saturating the ground by surface infiltration. Trenches may be needed to hold water as the permeability of the spoil is commonly low. Where permeability of the spoil is very low, boreholes drilled into the trenches can help water infiltrate the ground (Charles et al. 1978). Inundation produces large settlements and was the most effective ground treatment for unconsolidated alluvium in New Mexico (Johnpeer 1986).

Other treatment techniques, discussed briefly by Charles et al. (1978) and Buist and Dutch (1984), are vibro-compaction, grouting and stone columns, all of which seem to be less effective and/or more expensive than preloading.

Table 3. Average settlements produced by ground treatment and cost of treatment.

	Dynamic Consolidation	Inundation	9 m High Surcharge
At surface	240 mm	100 mm	410 mm
At 4 m depth	90 mm	40 mm	230 mm
At 10 m depth	10 mm	10 mm	40 mm
Cost	15 000	2 500	12 000

All costs are for treatment of 2500 m^2 at late 1974 prices in English pounds. Dynamic consolidation could have been considerably cheaper if a larger area had been treated. Average haul distance for surcharge treatment was 100 m.

(From Charles, Earle and Burford 1978).

5. CONCLUSIONS

The following are the more pertinent conclusions or recommendations mentioned by the various authors reviewed. They are listed in the order in which they appear in the discussion.

1. Larger diameter sampling and compression testing equipment is needed to adequately simulate mine spoil subsidence in the laboratory (Groenewold and Rehm 1980).
2. Classification of spoil makes it possible to predict spoil characteristics through a knowledge of excavation equipment, excavation technology, and overburden material properties (Borbely 1986).
3. The cone penetrometer and SPT have been used effectively to provide density profiles of cohesive heterogeneous backfill materials (Armstrong 1986; Charles 1984; El-Moursi et al. 1978).
4. The potential for collapse settlement increases with decreased initial water content and increased initial air voids. Finer textured soils are susceptible to more collapse compression upon inundation than coarser textured soils (Charles et al. 1978; Ingles and Aitchison 1969; Rangel 1979).
5. Area-wide settlement has been observed to continue for as much as 20 years after reclamation (Bell 1977; Golosinski et al. 1984). Settlement has frequently been observed to continue linearly with the logarithm of time (Leigh and Rainbow 1975; Charles et al. 1978; Hankins 1984).
6. Prewetting and preloading of mine backfill reduce the potential for collapse settlement (Charles et al. 1984).
7. Sinkholes or piping features as much as 3 m in diameter and 1 m deep have been observed on reclaimed mine backfill (Groenewold and Rehm 1980).

8. Differential compaction resulting from the dragline back-casting method leads to differential settlement resulting in a corrugated land surface (Dusseault et al. 1985).
9. Remedial measures in the form of adaptive mining and reclamation schemes may be less costly and more effective than post-reclamation ground treatment. Measures for settlement control should take the form of prevention rather than cure, greatly reducing costs (Norton 1983).
10. Preloading of mine backfill by a continuous earth moving operation is more effective and economic post-reclamation ground treatment for reducing the settlement potential of more granular spoils than are methods dynamic compaction and inundation (Charles et al. 1978).

The following conclusions are not found in the discussion but come from the papers that were reviewed and are closely related to the objectives of the PHRP study.

1. Agronomic, geologic, hydrogeologic, and geochemical variability from one mine site to the next suggest that each mine must be treated individually. Blanket laws that require highly specific performance standards of all mining reclamation are inadequate (Groenewold and Rehm 1980).
2. Behaviour of untreated backfill is highly variable because of the uncontrolled method of placement. Building on such fill may be susceptible to structural distress caused by collapse settlement during resaturation and by creep settlement caused by self-weight of the backfill (Charles et al. 1978; Charles et al. 1984).
3. A rigid adherence to conventional mining practices may limit technical advances in mining and

reclamation operations and, therefore, new mining schemes involving new mining patterns and equipment should be imaginatively and conscientiously investigated (Coates 1973).

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