EVALUATION OF MILL TAILINGS DISPOSAL PRACTICES AND POTENTIAL DAM STABILITY PROBLEMS IN SOUTHWESTERN UNITED STATES

GENERAL REPORT

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The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Interior Department's Bureau of Mines or of the U. S. Government."

FOREWORD

This report was prepared by W. A. Wahler and Associates, 1023 Corporation Way, Palo Alto, California 94303, under USBM Contract Number S0110520. The contract was initiated under the Metal and Nonmetal Health and Safety Research Program. It was administered under the technical direction of Spokane Mining Research Center, with Mr. Roy Soderberg acting as the Technical Project Officer. Ms. K. Hughes was the Contract Administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period June 30, 1971 to June 30, 1974. This report was submitted by the authors in January, 1975.

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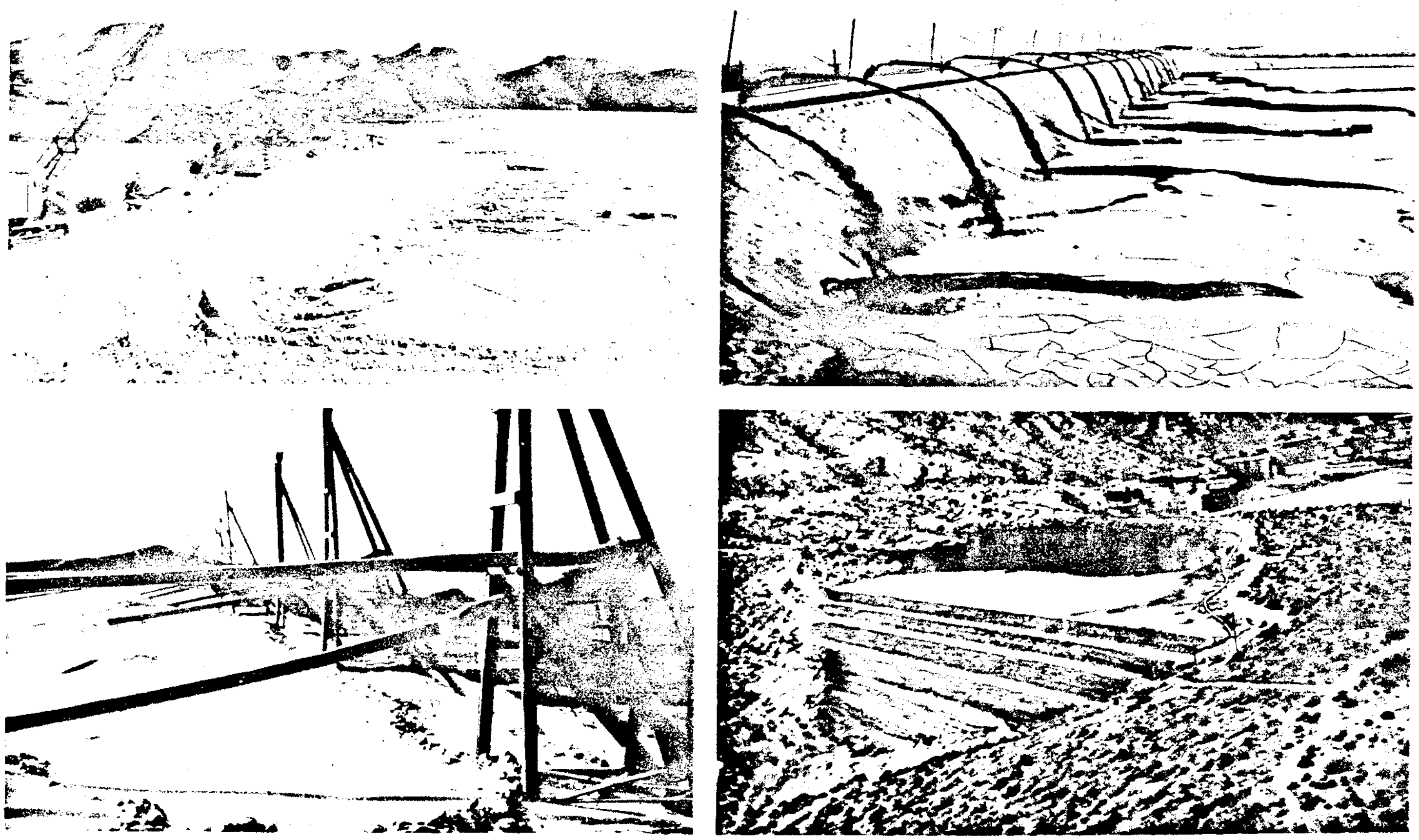
Evaluation of disposal practices and potential problems of
MILL TAILINGS

Undertaken by W. A. Wahler and Associates For the United States Bureau of Mines

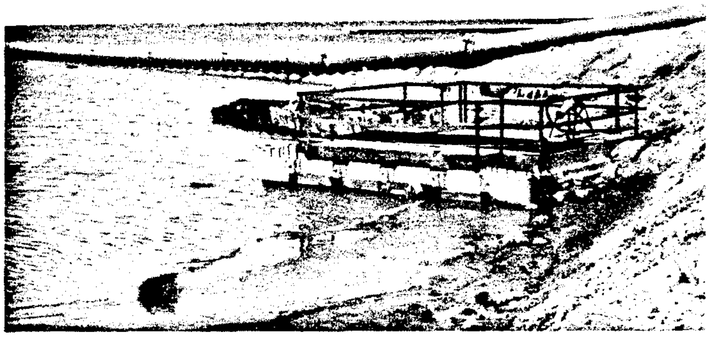
The mining industry throughout the world has been faced with the problem of tailings disposal since the first mill using concentration by flotation methods commenced operation sixty years ago. As the mines today utilize lower grade ore bodies at increasingly higher tonnages, tailings deposits have been growing at faster rates. As these structures grow in size and number, the potential for loss of life and property from failure of tailings dams also increases. Yet, until now, tailings embankment construction has received relatively little discussion in the technical literature of the mining industry.

Recognizing the need for programs to promote safe mine refuse disposal systems, the U. S. Department of the Interior, U. S. Bureau of Mines intensified its existing programs to investigate problems concerning potential structural failure existing with current practices of surface refuse deposits. As a first step in that development, the USBM retained W. A. Wahler and Associates in 1971 to study mill tailings disposal practices and potential tailings dam stability problems. The studies involved a detailed review of the methods of tailings disposal of the copper industry in the southwestern United States and reconnaissance studies of the methods used in other parts of the country and in other mining industries, to compare practices, collect basic data, evaluate construction methods and develop a basis for evaluating the structures studied in detail.

From these studies, W. A. Wahler and Associates has also developed recommended generalized interim investigational, analytical, and inspection procedures for use in regard to mine refuse disposal systems pending future development of a complete tailings technology manual and associated procedures. Significant topics treated in this report are summarized on the following pages.



The above photographs depict various elements of mill tailings disposal. UPPER LEFT, Tailings dam being constructed by typical upstream method; UPPER RIGHT, Tailings being discharged by peripheral spigotting; LOWER LEFT, Tailings being discharged by hydro-separators (cyclones); LOWER RIGHT, Completed tailings dam.



Barge-mounted pump for recycling of reclaimed water

History of the Mill Tailings Disposal Problem

Tailings are a necessary by-product of the mining industry which must be disposed, but, having no immediate value, are often given little consideration. The rate of tailings generation has increased significantly in the past 10 years, and the problems associated with its disposal have also increased. Several mills currently produce up to 50,000 tons per day, and some sites are approaching 100,000 tons per day. Several tailings dams are 250 feet high, and a few dams are being planned to reach 400 to 600 feet in height. Over the next two decades, W. A. Wahler and Associates foresees the construction of many new tailings dams and the continued expansion of existing dams that will rival the world's presently largest earth and rockfill structures.

Recent disastrous failures in tailings embankments and water storage reservoirs throughout the world have influenced consideration of the overall safety of these facilities. Government controls over surface and subsurface water contamination have also become a very real and important consideration to operations, as have the appearance aspects of the deposits in some areas of the world. These factors are influencing tailings disposal objectives and methods, creating a real engineering challenge to assure effective, efficient, economical, safe, and environmentally suitable disposal.

Disposal Systems and Methods

Basic data on mill tailings disposal practices were collected by W. A. Wahler and Associates during extensive field and laboratory investigations at three copper tailings disposal facilities: 1) Phelps Dodge Corporation, Morenci, Arizona–tailings embankment; 2) Kennecott Copper Corporation, Magna, Utah–tailings embankment; and 3) Kennecott Copper Corporation, Chino Mines Division, Hurley, New Mexico–leaching dump. Reconnaissance level investigations of fine-grained refuse disposal practices were also carried out at sixteen additional sites considered typical of the copper, iron, lead and zinc, and phosphate industry methods.

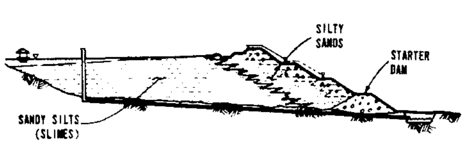
The majority of copper tailings dams in the Southwest are being constructed by a system called the "upstream method", which relies on the principles of natural sedimentation to densify the tailings material. Generally, the deposits are contained by embankments built, where practical, of tailings or a segment of the pulp. The ponds that develop on most tailings deposits provide a settling pond to remove suspended solids from the liquids and to store surplus mill water.

The tailings are commonly transported hydraulically from the mill as a semi-viscous fluid by one of several possible conveyance systems, including concrete launders and various kinds of pipes. Once conveyed to the disposal area, the tailings are discharged to the pond either by means of single or multiple discharge points (spigots) around the periphery, or by cyclones (hydro-separators). The location of decant provisions in the ponds affects the stability of the deposit, principally through control of the position of the ponds with respect to the dam and through the regulation of pond size and depth.

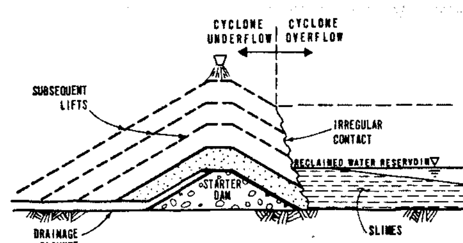
Materials Characteristics and Properties

Since tailings are essentially the by-product of rock crushed for the recovery of valuable minerals, their mineral compositions generally correspond to that of the parent ores, and therefore consist mainly of quartz, feldspars, iron-magnesium minerals, carbonates, and oxides. The individual, silt- to sand-sized particles are very angular, resulting in a material which, when consolidated, has a higher static shear strength than average soils. The dynamic shear strength, however, is sometimes lower than for average soils.

The grain-size distribution of copper tailings material within the dike or pond area can vary widely depending on the method of disposal being used at a particular site. The natural water content and dry density of copper tailings material depends directly on the method of disposal used and the location within the tailings pond. In-place dry densities of materials from the various sites investigated in detail varied from 65 to 108 lb/ft^3, and the water content varied from 17-54%. The average relative compaction of the materials was found to be between 77 and 85%, based on a laboratory maximum density obtained by ASTM–D–1557–70 (modified to 20,000 $ft\text{-}lb/ft^3$ compactive energy) which are low values compared to the average values of 95–100% relative compaction that are usually incorporated into the design of compacted earthfill dams.



UPSTREAM METHOD



CENTERLINE METHOD

Typical Construction Methods

The field and laboratory data regarding deformation characteristics of tailings indicates that horizontal and vertical movements of tailings dams are generally uniform in nature and apparently can be predicted. The shear strength of tailings materials, based on effective stresses, was found to have a remarkably narrow range regardless of materials gradation or natural density. Shear strength parameters based on total stresses had significantly more scatter and reflected the wide range of density possibilities in the tailings material. The shear strengths of tailings material under dynamic loading conditions indicates that these materials when saturated may be susceptible to failure by liquefaction.

Geology, Hydrology, and Seismicity Considerations

The geology at a tailings disposal site may influence both the depositional siting and design and the selection of a disposal method. The type of foundation material underlying the structure will directly influence the settlement, stability, and seepage characteristics of the deposit.

Hydrologic conditions play an important role not only in the siting of mine and mill refuse deposits, but also in their operation and development. Together with topography, vegetative cover, geological materials, and drainage characteristics, the meteorological conditions determine runoff, infiltration, and evaporation characteristics. Many existing tailings deposits have features that would make them vulnerable to overtopping and consequent failure under extreme weather conditions.

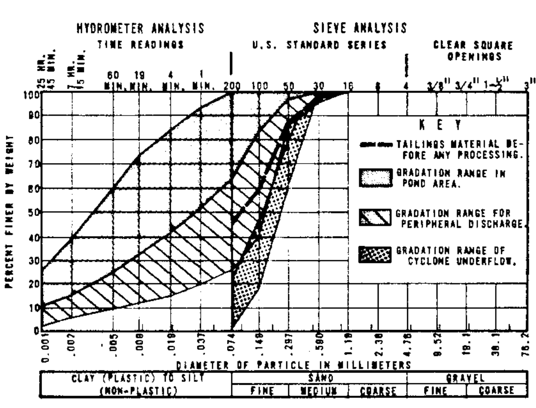
The ever-present threat of an earthquake-induced failure of tailings dams is justification to investigate the potential for earthquakes in any given site area. An earthquake that occurred in Chile in 1965 caused the partial or total failure of 11 tailings dams and the loss of over 200 lives. These failures demonstrate the need for analyzing the problem of earthquakes, their anticipated characteristics, and their influence on existing and planned mine and mill refuse deposits.

Conclusions

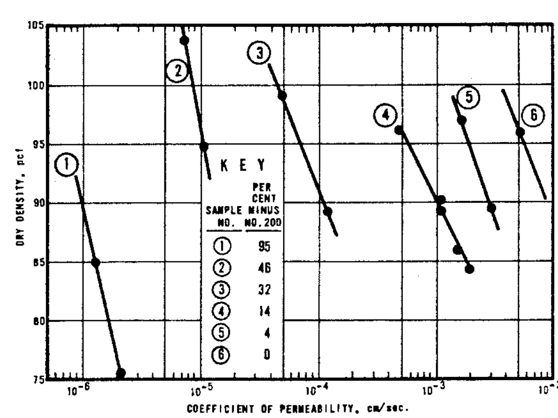
Based on the firm's and its staff's experience, detailed analyses, literature searches, and site reconnaissances performed to develop the basic data for this research program, we have arrived at the following basic conclusions. The report also contains many specific technical conclusions as well as technical data useful to the investigation and design of tailings structures.

Three principal categories of metals and nonmetals mine and mill refuse disposal structures were reviewed for this research project. Included were mine waste dumps, leach dumps and tailings structures. All of these types of structures pose significant safety and environmental problems. The principal focus of the research, however, was on tailings structures.

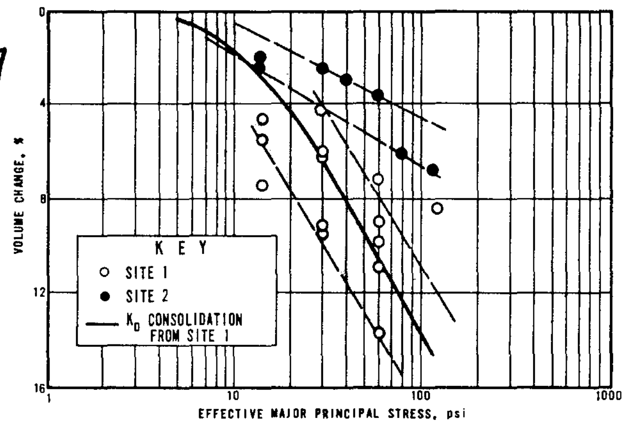
- Tailings structures are generally built of and to retain fine-grained mill or process plant reject materials transported to the structure by hydraulic means. The retention structures are built by hydraulic, semi-hydraulic-mechanical, or mechanical means.
- Tailings structures are variable but represent a distinct class of earthwork. Although they do share some characteristics with other structures built of earth materials and/or which retain water they also differ in some critical aspects.
- Tailings structures have two distinct phases with differing problems—the operational stage and the abandoned stage. The critical aspects of each stage are different from each other and from other earthwork or water retention structures.
- The suitability of tailings structures depends on site conditions such as: topography, geology, seismology and climate; the characteristics of the materials involved; the design of the structure; and its construction and maintenance.
- The site, materials, design, construction, and maintenance conditions throughout the area studied varied considerably. Although some generalizations can be defined on the basis of commonality of location, material type, or other factors, each major operation must be evaluated on a site by site basis to assure the required degree of safety and to preclude absurd economic consequences of inapplicable generalizations.
- The overall suitability and particularly the slope stability of the tailings structures in the area studied varied from "probably" suitable to distinctly marginal. Our work was not intended to be carried out to the degree necessary to evaluate absolute suitability.
- The upstream method of construction appears to be the most critical and the downstream method the most stable of the major construction methods observed.
- Seismically and strain induced liquefaction has been identified as a significant mode of failure for tailings dams. Present evaluation or design practice does not generally consider this potentially most hazardous mode of failure.



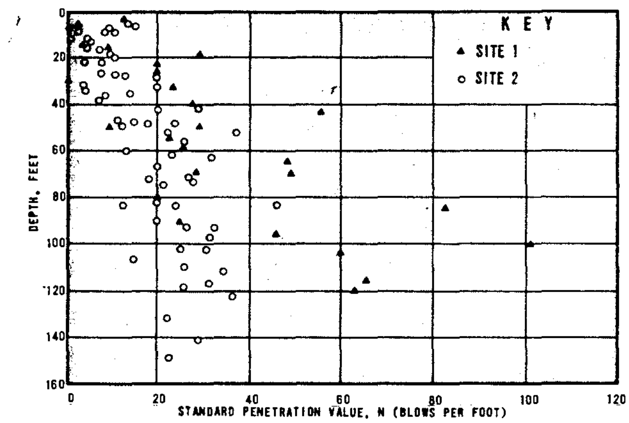
Gradation of Tailings



Permeability versus Dry Density



Consolidation Characteristics



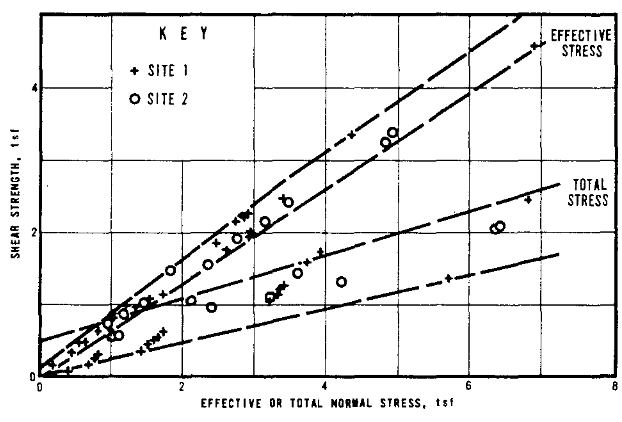
Variation of Blow Count versus Depth

- Most of the techniques needed to evaluate the suitability of existing and the design of new tailings structures exist in soil mechanics, engineering geology, and earth dam practice. However, this technology is not always directly transferable because of special operating conditions, materials or site conditions, or critical criteria not applicable to the structures involved. Care and experience are needed to minimize the probability of mis-transference of nonapplicable standards or "common" practice from one field to the other.
- Many areas of needed future research were identified that are peculiar to tailings structure analysis and design. Techniques need to be developed to lower investigative costs and allow evaluations to be performed on a repetitive basis. Detailed investigation of the insitu stress-strain characteristics of tailings are essential.
- Effective, efficient, economical, safe and environmentally suitable tailings structures can be built with existing multidisciplinary engineering technology. Most existing structures can be modified to improve their suitability at a reasonable cost if proper planning, technology and timed operations are undertaken.

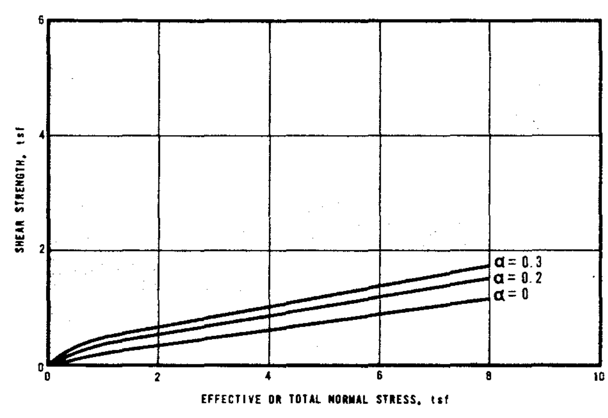
Recommendations

On the basis of the research work reported herein and because of the vast number and size of tailings structures we make the following recommendations:

- Good engineering practice and multidisciplinary technology must be followed to assure construction of suitable tailings structures.
- Regulation of tailings structures must be based on a sound approach recognizing the need for customized consideration of each structure on its own merits.
- Imposition of regulations on tailings structures must be done in an orderly manner permitting sufficient time for administration and implementation of modifications where needed to preclude counter productive and absurdly expensive consequences for both the mining industry and regulating agencies.
- Continuing research is needed to solve some specific tailings disposal problems and to develop more economical means to monitor and evaluate structure suitability.



Static Shear Strength



Dynamic Shear Strength

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EVALUATION OF MILL TAILINGS DISPOSAL PRACTICES AND POTENTIAL DAM STABILITY PROBLEMS IN SOUTHWESTERN UNITED STATES

GENERAL REPORT

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CHAPTER I

INTRODUCTION

A. GENERAL

This report presents the results of a study by W. A. Wahler and Associates of mill tailings disposal practices and potential tailings dam stability problems. The report is the culmination of a research project, undertaken for the United States Department of the Interior, Bureau of Mines, in response to Request For Proposal No. S0110520, dated November 12, 1970.

The Federal Metal and Nonmetallic Mine Safety Act of 1966 (Public Law 89-577) provides that "the Secretary (of the Interior) shall develop . . . and promulgate health and safety standards for the purpose of the protection of life, the promotion of health and safety, and the prevention of accidents in mines which are subject to the Act."

Recognizing the need for improvement in technology and for development of programs to promote safe mine refuse disposal systems, the Bureau of Mines intensified its existing programs to investigate problems concerning potential structural failure existing with current practices of surface-refuse disposal. Further recognizing the long period of time that would be required to develop the technology and practices necessary to significantly improve refuse disposal safety, the Bureau initiated this research effort as a first step in that development.

B. AUTHORIZATION

United States Bureau of Mines Contract No. S0110520, dated June 30, 1971, authorized W. A. Wahler and Associates (WAWA) to proceed with a research program entitled "Evaluation of Mill Tailings Disposal Practices and Potential Dam Stability Problems in Southwestern United States." The work authorized by that contract and subsequent modifications included the studies reported herein.

C. PURPOSE

The basic objectives of the research program, as established by the Bureau of Mines and set forth in Request For Proposal No. S0110520, were to:

(1) develop a base for inspection of tailings dikes, dams, embankments, decant systems, etc.;

(2) begin development of data to provide a basis for establishing mine health and safety inspection standards (as related to tailings disposal); and

(3) define further research needed to improve existing refuse disposal techniques.

D. SCOPE

To accomplish the above objectives, the program included a wide range of activities. Broadly stated, these activities consisted of:

- Limited field, laboratory and office investigations of three selected mine refuse disposal facilities (Phelps Dodge Corporation's Morenci, Arizona, tailings embankments, and Kennecott Copper Corporation's Magna, Utah, tailings embankment and Hurley, New Mexico, leaching dump). For a detailed discussion of the scopes of those three investigations, the reader is referred to Volumes 2, 3, and 4 of this report.

- Reconnaissance-level investigations of fifteen selected tailings disposal facilities throughout the United States (see Volume 5) to determine a cross section of the practices in the field of fine-grained tailings disposal.

- Review and analysis of information and data developed by the above investigations, and of other mine refuse disposal information and data available from WAWA files, those of the U.S. Bureau of Mines, and other sources.

- Summarization of disposal systems and methods, of geologic, seismologic, and hydrologic factors, and of materials characteristics; evaluations of the influence of such factors and characteristics on tailings disposal facilities.

- Evaluation of various possible techniques for the investigation of planned and existing tailings deposits.

- Development of usable interim generalized investigational, analytical and inspection procedures for use in regard to tailings disposal systems pending future development of a complete tailings technology manual and associated procedures.

- Consideration of the general principles involved, and development of an outline for a tailings technology manual.

- Identification of areas of needed future research, and recommendations for specific programs to satisfy research needs in these areas.

- Preparation of this report, including volumes covering specific site and reconnaissance investigations.

E. ORGANIZATION OF REPORT

This report is presented in five separate volumes. Volume 1, this volume, is the General Report, including a summary of conclusions and recommendations resulting from the overall research effort; discussions of disposal systems and methods, geology, seismicity, hydrology, and materials characteristics; evaluations of investigational techniques; discussions of usable interim generalized investigational, analytical and inspection procedures; discussion of general principles and presentation of a tailings technology manual outline; and discussion of needed future research and recommended programs.

Volumes 2, 3, and 4 contain individual evaluation reports covering the field, laboratory, and office studies performed for the Morenci, Magna, and Chino facilities, respectively. Volume 5 contains the report on reconnaissance-level investigations of fifteen disposal facilities throughout the United States.

F. PERFORMANCE

The research program was performed under the direction of Mr. W. A. Wahler, Project Manager, Mr. C. W. Perry, Deputy Project Manager, and Mr. J. G. Wulff, Chief Engineer. Mr. R. L. Volpe served as Project Engineer and was responsible for all engineering analyses and laboratory work and Mr. F. C. Kresse served as Project Geologist. Mr. L. Alvarez served as Field Geologist for the investigations at Morenci and Magna, while Mr. A. S. Buangan served as Field Geologist for the investigation at Chino. Mr. W. D. Martin supervised all laboratory testing.

The report was written by Messrs. Volpe and Alvarez, and personally reviewed by Messrs. Wahler, Perry, Kresse, and Wulff.

G. ACKNOWLEDGMENTS

W. A. Wahler and Associates is grateful to the U.S. Bureau of Mines for their cooperative attitude exhibited during the course of this investigation. We also wish to thank the staff of the Spokane Mining Research Center, in particular Mr. R. L. Soderberg and Dr. C. D. Kealy, for their technical assistance and liaison activities during the investigation.

We would like to express our deep appreciation for the cooperation and support given by the Phelps Dodge Corporation and the personnel of its Morenci Branch, and the Kennecott Copper Corporation, and the personnel of its Utah Copper and Chino Mines Divisions. Without their generous cooperation and assistance, this study would not have been possible. The mine owners and individuals whose cooperative attitude made the Reconnaissance Level Investigations a success are acknowledged in Volume 5.

CHAPTER II

SUMMARY AND CONCLUSIONS

SUMMARY OF INVESTIGATION

CONCLUSIONS OF RESEARCH PROGRAM

RECOMMENDATIONS

CHAPTER II

SUMMARY AND CONCLUSIONS

This chapter presents a summary of the salient portions of W. A. Wahler and Associates' study of mill tailings disposal practices and potential tailings dam stability problems in the Southwestern United States, outlines the principal conclusions which have been drawn therefrom, and briefly describes the areas of needed future research in the field of fine-grained refuse disposal. A thorough understanding of our findings can only be gained by reading the five volumes of the report; however, in order to make our principal findings more readily accessible, they are presented in condensed form below.

A. SUMMARY OF INVESTIGATION

1. Basic data were collected during the field and laboratory investigations at the three selected mine refuse disposal facilities, these investigations being intermittently conducted from December 1971 to September 1972. Office research and analyses were conducted through May 1974.

2. Although not similar in scope, the field investigations of the three selected facilities consisted of field mapping and associated surveying for ground control, subsurface exploration and sampling of materials by means of 14 drill holes (using 4 different types of drill rigs) totaling 2,300 feet, 18 backhoe pits for near-surface exploration and field density testing, 37 field density tests, 412 feet of Slope Indicator casing, 1,154 feet of Dutch Cone penetration sounding, and 7 vane shear probes totaling 380 feet. Also, 18 open well piezometers and 21 surface settlement monuments were installed. A seismic refraction survey to determine shear wave velocities was conducted at one of the sites. Different methods of field exploration and types of instruments were employed in an attempt to determine the best techniques to be used for the investigation of planned and existing refuse disposal facilities.

3. The laboratory investigation consisted of an evaluation of materials characteristics on samples collected during the course of the field investigation and included the following types and number of tests at the various sites:

Type of Test	Number of Tests Morenci	Magna	Chino
Natural Water Content and Dry Density	72	84	10
Grain-Size Distribution	40	90	15
Atterberg Limits	19	26	11
Specific Gravity	19	37	11
Compaction	5	18	13
Permeability	9	3	1
Pore Pressure Dissipation	1	1	--
Static Triaxial Shear			
Unconsolidated-Undrained	--	2	--
Isotropically Consolidated-Undrained	10	15	3
Isotropically Consolidated-Drained	--	2	--
K_o Consolidated-Undrained	--	4	--
Dynamic Triaxial Shear	--	35	--

Tests were conducted both in the WAWA portable field laboratory established in Magna, Utah, and in the main WAWA soils laboratory at Palo Alto, California.

4. Engineering analyses were conducted for the three selected sites to determine the applicability of current geotechnical engineering practice to the general field of mine refuse disposal. Because of budgetary restraints, detailed stability analyses sufficient to define the overall stability conditions for each site were not practical; however, sufficient data were collected to define the validity and applicability of the analytical procedures used and to assess the approximate stability of a unique cross section for each site.

5. Periodic observation of piezometers, Slope Indicator casings, and surface monuments installed during the course of the field investigation was carried out over a period of approximately one year at each site to monitor movements and pressures during typical refuse disposal loading cycles.

6. Reconnaissance-level investigations were performed at 15 sites considered typical of the copper, iron, lead and zinc, and phosphate industry practices in the field of fine-grained refuse disposal. These investigations consisted of site visits, discussions with key personnel at each facility, and compilation of information and data on each facility. The reconnaissance-level investigations, and the sites visited, were selected to represent a cross section of fine-grained refuse disposal practices throughout the United States.

B. CONCLUSIONS OF RESEARCH PROGRAM

DISPOSAL SYSTEMS AND METHODS

1. The vast majority of copper tailings dams in the Southwestern United States are being constructed by a system commonly referred to as the upstream method. This method does not employ conventional earthmoving or compaction equipment and relies on the principles of natural sedimentation to deposit and densify the tailings material.

2. Tailings are commonly transported from the mill as a semiviscous fluid containing 45 to 50 percent solids (by weight) by means of a variety of conveyance systems including concrete launders, or wood-stave, steel, reinforced concrete, Transite, or fiberglass pipe. The rate of tailings disposal has increased significantly in the past 10 years. Although a majority of the mills currently produce less than 10,000 tons of tailings per day, a number of them currently produce between 40,000 and 60,000 tons and one site is approaching 100,000 tons per day.

3. Once conveyed to the disposal area, the tailings are discharged to the pond either by means of single or multiple discharge points (spigots) around the periphery, or by cyclones (hydroseparators). The two principal methods of embankment or dike construction are: 1) to build the embankment as part of the deposit; and 2) to make the embankment a distinct structure behind which the tailings are stored. Although the majority of tailings dams are less than 100 feet high, a number of structures are as high as 250 feet, and several dams are currently being planned to reach heights in excess of 400 feet.

4. The ponds that develop on most tailings deposits serve to provide for collection and storage of water, and to provide a settling pond to remove suspended solids from the tailings before the water is reclaimed. The location of decant provisions affects the stability of the deposit, principally through control of the position of the ponds with regard to the exterior slope of the dam and the regulation of the pond size and depth. In many of the deposits a single decant tower has been found satisfactory for decanting water from the tailings surface. Other methods of decanting include siphons and barge-mounted pumps.

GEOLOGY, SEISMICITY, AND HYDROLOGY

1. Geologic aspects affect the disposal of fine-grained refuse because they may influence both deposit siting and design, and the selection of a disposal method. One of the principal geologic aspects is the type of foundation material underlying

the structure, since the characteristics of this material will directly influence the stability, settlement, and seepage characteristics of the deposit.

2. Another significant geologic factor for a given site is the presence or absence of possible faults that may be the loci of future earthquakes in the site area. Geologic maps showing the location of faults, and an evaluation of the geologic history of the area must form the basis for estimating the probability of occurrence of fault movements that could either affect the structures directly or produce a damaging earthquake. The ever-present threat of earthquake-induced failure of tailings dams is justification to investigate the potential for earthquakes in any given site area. An earthquake that occurred in Chile in 1965 caused the partial or total failure of 11 tailings dams and the loss of over 200 lives. These failures, which should not go unheeded, demonstrate the necessity of analyzing the probability of earthquakes, their anticipated characteristics, and their influence on existing and on planned mine and mill refuse deposits.

3. Hydrologic conditions play an important role not only in the siting of mine and mill refuse deposits, but also in their operation and development. The regional meteorological conditions govern the magnitudes and frequencies of storms, precipitation, and snow depth. Together with topography, vegetative cover, geologic materials, and drainage characteristics, the meteorological conditions determine runoff, infiltration, and evaporation characteristics. All of these factors must be considered when analyzing an existing refuse deposit or when designing a new structure. Many existing tailings deposits have features that would make them vulnerable to overtopping and consequent failure under extreme weather conditions. The major deficiency in deposits of the cross-valley type is the lack of water control or diversion facilities to handle storm runoff.

MATERIALS CHARACTERISTICS AND PROPERTIES

1. Since tailings are essentially the by-product of rock crushed for the recovery of valuable minerals, their mineralogical composition generally corresponds to that of the parent ore material. Tailings consist mainly of mixtures of quartz, feldspars, ferromagnesium minerals, carbonates, some oxides, and minor amounts of other minerals. The fact that tailings are the by-product of crushed ore materials also provides insight to the resulting soil structure of the material when deposited. Individual particles usually are very angular, thus resulting in a material having a higher static shear strength than average soils when the material is consolidated.

2. The grain-size distribution of copper tailings material within the dike or pond area can vary widely depending on the amount of fines in the mill product, the pulp density of the distributed tailings, and the method of disposal being used at a particular site, but generally will result in the material being classified either as silt, a nonplastic sandy silt, a silty sand, or a relatively clean sand. In general, the material as it leaves the mill has no particles larger than the No. 16 sieve (0.6 mm) and has slightly less than one-half of the material coarser than the No. 200 sieve (0.074 mm). The use of cyclones is necessary to reduce the amount of fines (less than 0.074 mm) to between 3 to 20 percent with the lower figure generally requiring the use of multiple-staged cyclones.

3. The natural water content and dry density of copper tailings material depends directly on the method of disposal used and the location within the tailings pond. Two tailings dams were investigated in detail during the course of this research program; one used a peripheral and the other a form of the single point discharge method. Therefore, the resulting density variations observed were the result of natural sedimentation processes. In-place dry densities were found to vary from 65 to 108 pounds per cubic foot (1.04 to 1.73 ton/m^3), and the water content (based on dry weight) varied from 17 to 54 percent. More importantly, however, the average relative compaction of the materials was found to be between 77 and 85 percent based on a laboratory standard determined by ASTM D1557-70, modified to 20,000 ft-lb/ft^3 compactive energy. The low relative compaction values referenced above are considered typical for all sites using either peripheral or single discharge methods. These values should be compared with average values of 95 to 100 percent relative compaction (using the same laboratory standard) which are usually incorporated into the design of compacted earthfilled dams. Also, there is some indication that extremely fine-grained tailings materials distributed by peripheral or single point discharge methods do not fully consolidate for up to 20 years after deposition. The resulting state of underconsolidation seems to adversely influence the in-situ undrained shear strength of the tailings.

4. Permeability characteristics of copper tailings were evaluated only by laboratory methods and were found to range between 5.7×10^{-7} cm/sec (0.6 feet per year), and 3.5×10^{-5} cm/sec (36 feet per year) for the two methods of disposal previously referenced. Because the coefficient of permeability, or more precisely the difference in permeability for the various materials involved, has a direct influence on the developed location of the phreatic surface within a tailings dam, it is important to note that the coefficients of permeability for the two sites investigated, which cover a reasonable range in gradation possibilities for most sites using peripheral discharge methods, did not differ significantly. The common assumption that permeability of materials using

peripheral methods increases towards the exterior face of the dam was not clearly demonstrated for those samples tested. In fact, a review of published permeability data indicates that cycloning is necessary in order to significantly increase the permeability characteristics of tailings materials. The coefficient of permeability of cycloned tailings underflow can vary from 7 x 10^{-4} cm/sec (720 ft/yr) to 1.7 x 10^{-2} cm/sec (17,600 ft/yr) depending on the method of cycloning used.

5. The field and laboratory data regarding the deformation characteristics of tailings indicates that horizontal and vertical movements of the exterior face of tailings dams are generally uniform in nature and apparently their time rate and magnitude can be predicted. Additional research is needed, however, using nonlinear finite element techniques, to verify the predictability of embankment movements and assess the significance of these movements with regard to the development of mobilized strength and the overall stability of the dam.

6. The shear strength of tailings material, based on effective stresses, was found to have a remarkably narrow range regardless of materials gradation or natural density. The angle of internal friction (ϕ') was found to vary from 33 degrees to 37 degrees with a minimal cohesion (c') of less than 0.1 ton per square foot (1.0 ton/m^2). Shear strength parameters based on total stresses had significantly more scatter and reflect the wide range of density possibilities in the tailings material.

7. The shear strengths of tailings material under dynamic loading conditions indicate that these materials can be susceptible to a liquefaction mode of failure. Although dynamic triaxial test results were obtained only from one site during this research program, dynamic tests performed by WAWA for other tailings dams indicate that tailings material existing at a dry density representing a relative compaction less than about 90 percent (20,000 ft-lb/cu.ft. compaction standard), regardless of the method of discharge, will, when saturated, exhibit low resistance to liquefaction. Obviously, the severity of this deficiency in resisting dynamic or rapid static load application is dependent on the seismicity of the site, saturation conditions within a deposit, and specific test results. The expected performance of tailings material under earthquake loading condition is an area of needed future research.

EVALUATION OF INVESTIGATIONAL TECHNIQUES

1. One of the principal conclusions drawn from this research program is that the same basic concepts of geotechnical engineering and engineering geology used for the exploration of earth or rockfill dams are directly applicable to the field of mine refuse disposal.

The application of such concepts, however, must be made on the basis of the actual case involved and general "rules of thumb" do not necessarily apply.

2. Geologic mapping is essential in the field of mine refuse disposal in order to provide a background for the engineering analysis for a given deposit and to assess the influence of local and regional geologic characteristics.

3. Although four different types of drilling equipment were used during the course of our investigations, WAWA has concluded that conventional rotary drilling equipment, using mud to keep the holes open, was the most practical equipment for exploration of existing tailings dams. Although hollow-stem auger drilling is also a viable alternative, if used in areas of very wet tailings, the creation of high seepage forces at the base of the hollow stem has a tendency to liquefy the tailings, thereby increasing the difficulties associated with sampling. Special drilling equipment, such as the Swedish Foil Sampler, requires special handling techniques, and did not improve the rate of drilling. In the opinion of WAWA, such equipment is not justified for use in copper tailings exploration. A Becker hammer drill rig was successfully used for the exploration of the investigated leach dump. As a result of the large particle size encountered in a leach dump, the use of conventional rotary equipment would not, in the opinion of WAWA, produce desired results.

4. Conventional instruments, such as piezometers, slope inclinometers, and surface monuments, which are used extensively in the monitoring of each dam performance, were successfully used during the present research program and their use in future similar investigations is recommended.

5. Dutch Cone penetration and vane shear equipment was used for the field investigations and was found to provide valuable information regarding the penetration resistance and undrained shear strength characteristics for the tailings material. The vane shear test is extremely valuable in obtaining in-situ, undrained shear strength for soils where undisturbed samples are difficult to obtain or where the materials exhibit a high degree of sensitivity. The use of the vane shear instrument for tailings dam investigations, however, is somewhat limited to those areas of the pond that contain materials with at least 70 percent or more finer than the No. 200 sieve (0.074 mm).

6. The laboratory testing procedures used throughout this research effort were those conventionally used in the field of soil mechanics and no unusual problems associated with the tailings materials were encountered except for the extremely loose condition of some samples. Comparative triaxial tests were performed on dual samples, one series being performed on-site in the WAWA

portable laboratory and the other series at the main WAWA laboratory in Palo Alto. The results of the comparative tests indicated no appreciable difference in the density, modulus, or shear strength due to deterioration of the samples during transport.

EVALUATION OF TAILINGS DAM STABILITY

1. As a result of the detailed analyses performed during this research program, the observations made during the reconnaissance investigations, correlations of construction methods, and field and laboratory test results from other tailings dams investigated by WAWA, we conclude that the overall mass stability of the majority of existing tailings dams in the southwest is marginal, when compared with current safety standards for earth dams. Furthermore, the mass stability of tailings dams is apparently very sensitive to any adjustments or additions to the normal loading conditions, such as excavation on a berm for pipe relocation, discharge of waste material over a slope, a buildup of high pore pressure due to an increased rate of construction, or the inadvertent construction of an "impervious" layer, which could lead to an overall mass stability problem. Although there have been no fatalities directly related to a tailings dam failure in the Southwestern United States, at least six major structures using the upstream method of construction have experienced some form of failure within the past five years.

2. The utilization of materials, construction methods, and continued maintenance conditions throughout the areas studied varied considerably. Although some generalizations can be defined on the basis of commonality of location, material type, or some other factor, the overall safety of each major operation must be evaluated on a site-by-site basis to assure a required degree of safety and to preclude absurd economic consequences of inapplicable generalizations.

3. Tailings structures are variable and represent a distinct class of earthwork. Although they do share some characteristics with other structures built of earth materials and/or which retain water, they differ markedly in certain critical aspects that influence overall safety, such as the method, total time, and rate, of construction.

4. If the shear strength of the tailings material is considered to adhere to the same principles as other fine-grained materials, with regard to gradation and density characteristics, it would be expected that the undrained shear strength would: 1) decrease with increasing distance from the point of discharge because of the commensurate increase in fines; and 2) increase with increasing depth because of the commensurate increase in density. Although this variation in shear strength was not clearly established

during this research work, because of the inability due to budgetary considerations to perform the required type and number of field and laboratory tests at a sufficient number of sites, the trends in gradation and density variation were demonstrated. WAWA concludes, therefore, that the stability of any tailings dam being constructed by the upstream peripheral discharge method, incorporating typical fluid densities of 45 to 50 percent solids by weight, decreases as the dam height increases. The reason for this reduction in stability is directly associated with a persistently high uncontrolled phreatic surface relative to the exterior face of the dam, and the configuration of potential failure arcs which continuously encroach on weaker materials within the pond as the dam height increases.

5. Tailings materials are extremely susceptible to erosion, especially that associated with water. One tailings dam in the southwest barely escaped having a major failure when water was inadvertently discharged on the downstream slope. Within a very short period of time, a large cavity measuring tens of feet across was formed. It is extremely important that safeguards be taken to preclude excessive discharge of water directly over an existing slope. This requires that intermediate benches be sloped to properly collect and discharge rainfall or melted snow water.

6. Water which collects in the pond area prior to decanting can also pose potential stability problems. If the decant system is underdesigned, improperly located, clogs, or otherwise malfunctions, water may encroach dangerously close to the edge of the dam. The resulting water loading and increase in pore pressure near the edge of the bank could lead to failure. At least one tailings dam has failed in such a manner.

7. The applicability of using either the effective or undrained shear strength for stability analysis purposes, under static loading conditions was not clearly developed during this research work. In order to incorporate a shear strength based on effective stresses, as determined in the laboratory by consolidated drained or undrained triaxial shear tests, the variation of internal pore water pressure must either be obtained from installation of piezometers (pore pressure monitoring instruments), or accurately determined from theoretical seepage (flow net) analysis. As a result of the extended period of time associated with tailings dam construction, the magnitude of internal pore water pressure is constantly varying (both increasing and decreasing) which complicates their correct assessment for stability analysis purposes. In addition, there is strong evidence (see Volume 3 of this report) that major sections of the pond areas of most tailings dams are not fully consolidated under their own weight and that it may take up to 20 years for such consolidation to occur.

8. Under "pseudo-static" loading conditions (commonly applied to account for earthquake forces), the stability may be analyzed with two different shear strengths, effective and total stress, for the material below the assumed saturation level. The effective stress strength analysis assumes that drainage could occur rapidly enough that the saturated material would not develop any excess pore pressures during shear failure. On the other hand, the total stress strength analysis assumes that no drainage could occur during shear failure and the material would develop full shearing pore pressures. In reality, however, pore pressure developed in tailings under a seismic load may or may not lie within this range of pore pressures and is dependent on the soil type, its relative density, and its load characteristics. The factors of safety calculated assuming both zero and full excess shearing pore pressures would, therefore, give the upper and lower bounds of probable actual safety factors except when possible liquefaction of the material under dynamic loading is considered.

9. Seismically and strain-induced liquefaction has been identified as a potentially significant mode of failure for tailings dams. Present evaluation and design techniques do not generally consider these potentially most hazardous modes of failure. In the opinion of WAWA, the potential for catastrophic liquefaction to occur during an earthquake, if major portions of the dam are saturated, may be the most significant deficiency of tailings dams. Fortunately, a major earthquake has not occurred in the Southwest during recent years. This fact, however, does not minimize nor mitigate the hazard. Few regions of the United States are free from earthquakes. Therefore, it is necessary to undertake investigations of the seismic activity in relation to tailings dams and other refuse deposits.

NEEDED FUTURE RESEARCH

1. As a result of the experience gained by WAWA during the detailed investigations associated with this research, it became evident that new methods of developing, compiling, and analyzing in-situ engineering properties of tailings material are needed. We are of the opinion that the Dutch Cone Penetrometer could possibly be developed into a valuable field testing device to provide rapid and repeatable data on in-situ characteristics for engineering analysis.

2. Results obtained during this research indicate that embankment movements as a result of tailings emplacement follow a uniform and apparently predictable trend. With the development of computer programs to solve nonlinear finite element analyses, the analytical techniques are now available to accurately model the stress-strain relationships of most soils. Because of the

demonstrated ability to collect meaningful field data with regard to slope movements, an in-depth evaluation should be undertaken to determine the correlation of observed field movements with those that are theoretically predicted.

3. The need exists to compile a complete list and description of all mine and mill refuse deposits that exist throughout the United States. The results of such an inventory would provide a means of correlating and cross-referencing all types of deposits as a function of, for example, ore product, embankment size, and method of construction.

4. From an earthquake hazard standpoint, dams and mine refuse deposits with water-retention capabilities constitute one of the greatest single categories for potential wide-spread destruction existing in our modern society. As a result of this potential hazard, the need clearly exists for a research program to investigate the relationship between spatial and time distribution of earthquakes in the conterminous United States, and to develop a uniform system for rating seismic hazards associated with dams and reservoirs, so that the potentially most hazardous structures can be recognized at an early date and can then be assigned the highest priorities for the performance of more detailed investigations related to seismic safety.

5. A laboratory research program should be carried out to define the dynamic response characteristics of tailings material.

6. With the development of ground-water litigation in progress near Tucson, Arizona, it has become increasingly more obvious that the amount of degradation of ground water from tailings pond seepage is not clearly understood by the mine owner, ground-water basin management or the geotechnical engineering profession. This very important pollution problem requires more study.

C. RECOMMENDATIONS

- The quantity of primary refined copper ore produced in the United States during 1970 was estimated at 1.72 million tons. By the year 2000, it is estimated that 6.4 billion tons of copper will be refined, thereby generating 1.3 billion tons of tailings per year. The approximate fourfold increase in tonnage of fine-grained refuse between now and the year 2000 will require construction of many new disposal structures and impose a critical burden on the stability of existing tailings dams. An obvious result of this increased production will be to build higher tailings disposal structures at faster rates. The consequences of continued use of invalid design assumptions and/or improper construction techniques could be serious. This mining management problem should be studied in depth to determine the need for, and possible approaches to, influencing better future design and construction of tailings deposits.

- Since the inception of the research project which forms the basis for this report, the regulation of metals/nonmetals mine and refuse disposal sites has been separated from the USBM Health and Safety group and a new regulatory agency, MESA, created. While the MESA Office of Technical Support has, and will continue to have, a research oriented interest in mill tailings disposal technology, the prime area of interest for the MESA group will be the development, promulgation, and enforcement of mining health and safety regulations. Complicating the regulatory aspect of metal/nonmetal mine and refuse disposal is the fact that more than one Federal agency may be involved at a particular site as a regulator (the Environmental Protection Agency, the Bureau of Land Management, the Forest Service, and others), along with State agencies (Water Resources, Mining Agencies, Fish and Game groups, and others). WAWA considers it imperative that all agencies be coordinated to achieve the single goal of economic construction of safe and environmentally acceptable disposal facilities.

- Regulation of the design, construction, and abandonment of tailings dams and other types of refuse disposal facilities, if required, must be based on a sound approach recognizing the need for different considerations for each structure. Imposition of regulations on tailings dams and other types of refuse disposal facilities must be done in an orderly manner, permitting sufficient time for administration and implementation of modifications where needed. Timely implementation procedures should be used to preclude the possibility of counterproductive and/or absurdly expensive consequences for both the mining industry and regulatory agencies.

- Unknown numbers of new tailings dams are either in the planning stages or just starting construction. Indications are that presently planned heights of some tailings dams may be neither prudent nor geotechnically sound if constructed with current methods and procedures. At present, there are no established guidelines for the design and construction of new tailings structures or modification to existing dams. WAWA recommends that the necessary funding be made available to develop these urgently needed guidelines which should, in our opinion, be similar in scope to the requirements that currently exist in the field of earth dam engineering, as set forth in the Tailings Technology Manual Outline, presented in Chapter VIII of this report. Prior to the development of more comprehensive guidelines, interim generalized investigational, analytical, and inspection procedures, along the lines set forth in Chapter VII of this report, are available for use.

- Because of the vast number and size of existing or planned tailings dams and other types of refuse disposal facilities within the United States, and because the questionable overall safety of some of these structures will continue to pose a potential threat to nearby residents, WAWA strongly recommend that the needed future research outlined in Chapter IX of this report be given serious consideration. This research is needed, in our opinion, to advance a basic understanding of the technical aspects associated with mill tailings disposal practices and potential tailings embankment stability problems.

CHAPTER III

DISPOSAL SYSTEMS AND METHODS

INTRODUCTION

GENERAL PRINCIPLES OF TAILINGS DISPOSAL

TAILINGS CONVEYANCE

TAILINGS EMBANKMENT CONSTRUCTION

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CHAPTER III

DISPOSAL SYSTEMS AND METHODS

A. INTRODUCTION

Both Webster and the 1974 edition of the American College Dictionary indicate that in the context of mining and milling, the word tailing must be spelled with an "s" at the end of the word to be used as a plural noun. However, in the mining industry, there is no universally accepted standard. In the taconite mining industry in Minnesota, for example, the term is tailing. In the rest of the metals industry, it is tailings. In the phosphate industry of Florida, the word is tailings but is restricted to indicate the sandy residue of the flotation process, as opposed to the fine-grained residue which is called slimes. Throughout this report we have adopted the term tailings and use the word in its plural sense.

The mining industry thoughout the world has been faced with the problem of tailings disposal ever since the first mill using concentration by flotation methods commenced operation. As the mines today improve their extraction efficiency and, through the use of new equipment and techniques, develop lower grade ore bodies at increasingly higher daily tonnages, the problem of tailings disposal has become even more acute.

As the quantity of ore milled per day has increased, tailings deposits, along with their peripheral embankments (dams), have been built ever higher and at increasingly faster rates. The tailings which are deposited hydraulically both on level surfaces and in valleys today require embankments which have begun to rival major earth dams (for water reservoirs) in height and often in the quantity of material required. While earth dam engineering has evolved with development of a large body of published theory and practice, tailings embankment construction has received relatively little discussion in the technical literature of the mining industry.

We have reviewed in detail the methods of tailings disposal of the copper industry in the southwestern United States and made reconnaissance-level studies of the methods used in other parts of the country and in other mining industries. This was done to compare practices, collect basic data, evaluate construction methods and develop a basis for evaluating the structures studied in detail.

The tailings deposits reviewed in detail are the Magna, Utah, deposit of the Utah Copper Division, Kennecott Copper Corporation, and the Morenci, Arizona, deposit of Phelps Dodge. Furthermore, an investigation was performed of the leach dump of the Chino Mines Division of Kennecott Copper Corporation at Hurley, New Mexico. The reconnaissance-level investigations, the report for which is contained in Volume 5 of this report, included the following 15 sites of the copper, iron, lead and zinc, and phosphate industries:

TABLE III-1

RECONNAISSANCE-LEVEL INVESTIGATION

Industry	Site Name	Location
Copper Mining	Kennecott Copper Corp., Ray Mines	Hayden, Arizona
	ASARCO, Mission Unit	Mission, Arizona
	Cyprus Pima Mining Co.	Pima, Arizona
	White Pine Copper Co.	White Pine, Michigan
Iron Mining	Erie Mining Co.	Hoyt Lakes, Minnesota
	The Hanna Mining Co. Groveland Mine	Channing, Michigan
	Pilot Knob Pellet Co.	Pilot Knob, Missouri
Lead and Zinc Mining	AMAX Lead Company of Missouri	Boss, Missouri
	Cominco American Inc.	Bixby, Missouri
	St. Joe Minerals Corp.	Bonne Terre, Missouri
	New Market Unit	New Market, Tennessee
Phosphate Mining	Monsanto Co.	Columbia, Tennessee
	Swift Chemical Co.	Bartow, Florida
	International Minerals & Chemical Corp.	Bartow, Florida
	Brewster Phosphates Brewster Plant	Bradley, Florida

Although a majority of the field and laboratory procedures used for the detailed investigations are applicable to both tailings dams and leach dumps, it is difficult to extend any discussion regarding geotechnical engineering techniques or analyses to both types of deposits. As a result, a major portion of the remaining sections of this chapter is devoted to tailings dams, which, in the opinion of WAWA, possess a more critical stability potential than those of leach dumps. The last section of this chapter presents a discussion of the unique characteristics of leach dumps.

B. GENERAL PRINCIPLES OF TAILINGS DISPOSAL

Tailings are a necessary by-product of the mining industry which must be disposed, but, having no immediate value, are often given little consideration. Attempts are made to keep all expenditures associated therewith to a minimum. In the early days of the mining industry, the individuals responsible for tailings disposal could take advantage of the area near the mine property and deposit tailings in streams or upon open, uninhabited tracts of land. In regions where floods were uncommon, the tailings could be impounded in valleys or canyons at a relatively low cost. If tailings should contaminate surface or subsurface waters, there were few laws and seldom other strong interest groups to raise objections. Failures in the past were not considered serious unless there was loss of life, since there was ample space to receive the flow and a failure could always be repaired or remedied by starting a new deposit at another site.

Failures in tailings embankments and water storage reservoirs throughout the world in recent years have influenced consideration of overall safety because of the significant loss of life and property associated therewith. Government controls over surface and subsurface water contamination have also become a very real and important consideration to operations, as have the appearance aspects of the deposits in some areas of the world. These factors are influencing tailings disposal objectives and methods.

Experience has shown that tailings disposal must be safe and economical. Other considerations depending upon the area and conditions, such as stream or ground-water contamination and/or embankment beautification, must be put in proper context. Thus, tailings disposal is a real engineering challenge.

Economics dictate that disposal be made: 1) as close as practical to the concentrator; 2) where possible, downgrade from the concentrator so that power requirements are nonexistent or at least minimal; 3) so that the embankment necessary to retain the tailings can be as low and small as possible; 4) so that water can be reclaimed or disposed easily and with the least adverse effect on the deposit; and 5) so that the site will have no serious consequences of failure.

Safety considerations dictate: 1) that the slimes settling pond be as small and remote from the embankment as possible; 2) that the water be removed from the pond as completely as practical to minimize the extent of the saturation of tailings; 3) that the embankments be kept unsaturated to the degree practical to enhance stability; 4) that the embankment foundation be sound--equal or superior to the embankment with regard to strength, compressibility, and permeability; 5) that the embankment be constructed of the coarsest, strongest, least compressible, and most permeable material available, placed in proper zones to proper densities; 6) that the weaker and more compressible material (portion of pulp, slimes, etc.) be kept as far as practical from the embankment; and 7) that the embankment slopes be flat enough to be stable depending on embankment height and the characteristics of the materials used in its construction.

Construction schedules and techniques must also be given consideration. Available time, equipment, and personnel (numbers and training) must be considered principally from an economic standpoint. From a safety standpoint, present availability of equipment and personnel must be considered.

Pollution control and area beautification are serious considerations. Although these factors are relative, they are being incorporated with increasing frequency into economic and safety considerations, especially since the implementation of legislative and regulatory measures to avoid or correct pollution.

C. TAILINGS CONVEYANCE

One of the basic problems in tailings disposal is the transportation of tailings from the mill to the disposal area. The methods by which tailings are transported and distributed depend on several important factors. These include: 1) the type and quantity of tailings flow anticipated; 2) the distance, topography, and slope (or head) from the mill to the disposal area; 3) effect of weather--floods, freezing, wind, etc.; 4) the characteristics of the foundation support of the embankments; and 5) the cost and availability of local labor and materials.

Because there is a variety of conditions encountered in tailings disposal, the pulp is transported hydraulically in a number of different ways, some of the more important of which are discussed in the following paragraphs.

1. Concrete Launders

Concrete launders are used where the cost of pipe would be excessive or its use impractical, or where tailings are discharged directly into the impoundment. This type of launder is in use at the Morenci deposit, where an open concrete launder is used to transport tailings from the mill to the tailings ponds. The open concrete launder discharges into a reinforced concrete pipe which is then used to distribute the tailings to the embankments. The concrete launder is fabricated at the site using standardized forms, and is shown on Photoplate 1-A.

2. Wood-Stave Pipe

Wood-stave pipe, although somewhat unusual today, is still extensively and successfully used at the Chino mine. The pipe has spigots at regular intervals so the tailings can be distributed around the perimeter of the tailings pond. The wood-stave pipe in use at Hurley is shown on Photoplate 1-B.

3. Steel Pipe

Steel pipe is also used in tailings transportation and distribution. When it is lined wear characteristics have proven to be satisfactory and the pipe performs well when the tailings are transported under pressure. Although long lasting and durable, steel pipe is not as common as some other types, mainly due to the weight and difficulty of handling, which contributes to a high overall use cost. Mortar-lined spiralweld steel pipe is used at the Kennecott tailings pond at Magna. The pipe

(Photoplate 1-C) has spigots every 40 feet (12.2 meters) for discharging the tailings. Mortar-lined steel pipe (Photoplate 1-D) is also used to transport tailings from the mill to the tailings pond.

4. Reinforced Concrete Pipe

Reinforced concrete pipe is sometimes used in tailings disposal. It is relatively heavy and difficult to handle and thus is used only when large volumes of tailings must be transported under high pressure. Large diameter reinforced conrete pipe (Photoplate 2-A) has and is being used for the header pipes at the Morenci tailings disposal structures.

5. Transite Pipe

Transite pipe is used at many locations throughout the Southwestern United States. This type of pipe is desirable because it is noncorrosive, easy to handle, and relatively durable. Problems do occur, however, if very high pressures develop in the pipe. Excessively high pressures are controlled by providing drop structures at regularly spaced intervals. Various diameter Transite pipe is used depending upon the volume of tailings to be transported. Photoplates 2-B and 2-C, and 3-A show typical uses of Transite pipe at the Pima Mine, and at the Mission and Silver Bell sites, respectively.

6. Fiberglass Pipe

Fiberglass pipe has recently been installed in some tailings disposal systems on a trial basis. It has the favorable qualities of Transite pipe and is even more lightweight. This pipe is being used in some sections of the peripheral discharge pipe of the Magna tailings deposit.

D. TAILINGS EMBANKMENT CONSTRUCTION

Tailings deposits usually require retaining embankments or "dams" to confine them to a given area. In hydraulic engineering, the term "dam" is reserved for the situation where an embankment is built across a principal water course or deep valley. The term "dike" is used to define the structure built across low areas or locations other than major water courses. The term "levee" has a meaning similar to dike, but a levee is not used to define a structure which retains part of a reservoir, the use being restricted to the confinement of rivers or streams to their channels. Many tailings embankments are dams in the true sense, and the term "dam" is commonly used in the mining industry for this purpose.

Generally, the types of deposits which have evolved over the years in the mining industry are constrained by embankments built, where practical, of tailings or a segment of the pulp--usually the coarser part. This has been done for several reasons, including the availability of the materials and need to dispose of it, and because the facilities for transporting and handling these materials are also required, for the most part, in the disposal process. Therefore, these materials are and must be given consideration as a construction material for any of the necessary embankments.

The techniques used to construct tailings embankments are based on various hydraulic fill procedures. The most suitable techniques use "better" methods of separating the coarser portion of the pulp from the finer-grained or "slime" materials. The less suitable techniques use less effective methods of separating (classifying) the coarse and slime materials. The coarse materials are used for the construction of the embankment, and the slimes are deposited behind the embankment. This separation process is one of the key aspects of successful construction of high embankments.

Separation of fine-grained from coarse-grained tailings is generally accomplished by using natural sedimentation principles. The tailings pulp or slurry is discharged through spigots onto the deposit where its flow is determined by the thickness or viscosity of the pulp and the available hydraulic gradient. The coarser-grained particles settle out first, close to the discharge point, while the finer-grained materials are transported longer distances toward the pond, where they finally settle and from which the water is decanted. Depending upon the position of the discharge point and the settling pond, water and fines will either be close to the embankment or a considerable distance from it.

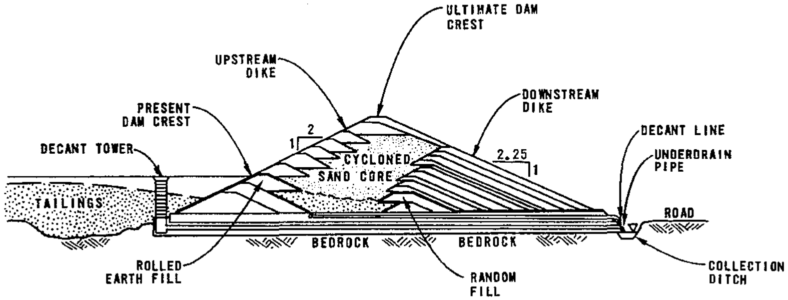
A control of grain-size distribution within the deposit is obtained by a planned positioning of the discharge points and by discharging at different times in different sections. The usual practice is to discharge tailings from the crest of the embankment to prevent water from being close to the exterior face of the dam and to provide a supply of coarser dam-building material close to the crest. However, in deposits contained by designed embankments constructed of earth or rock materials other than tailings, this procedure may not always be necessary.

The other method of separating grain sizes is through the use of hydroseparators or cyclones. Construction methods using cyclones are described later in this section.

Depending upon the general layout used, the deposits used for tailings disposal can be classified as cross-valley (dams), side-hill, or diked deposits, depending on whether the peripheral embankment or embankments block a relatively narrow valley, exist on two or three sides of the deposit, or completely contain a deposit. Examples of typical tailings deposits cross sections are presented on Drawing No. III-1.

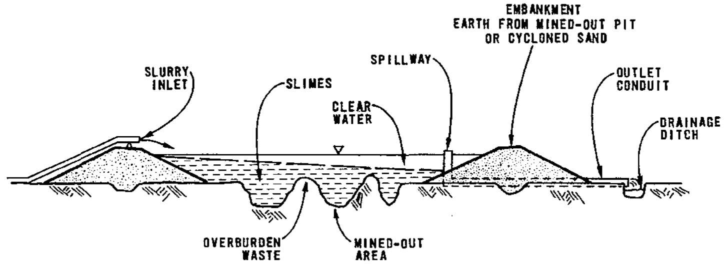
In most cases, when a new tailings deposit is begun, a starter dike is built of natural materials at the toe of the proposed structure. The starter dike is constructed, depending upon the deposit's general layout classification, on one, several, or all sides of the proposed deposit.

DATA SOURCE:



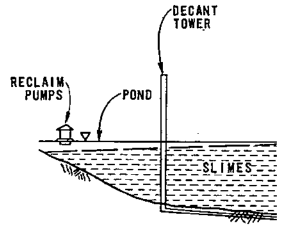
MICHIGAN: WHITE PINE

SIDE-HILL IMPOUNDMENT
DOWNSTREAM METHOD



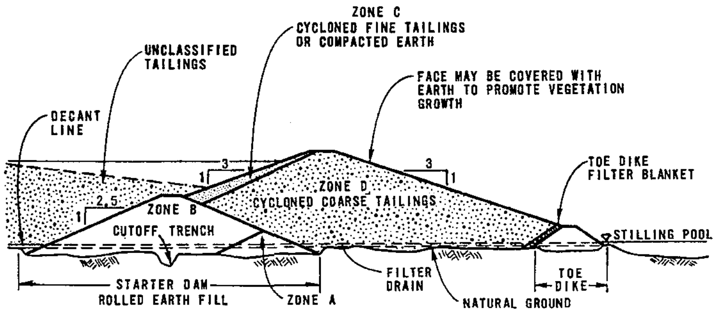
FLORIDA: PHOSPHATE INDUSTRY

DIKED POND
SPECIAL EMBANKMENT



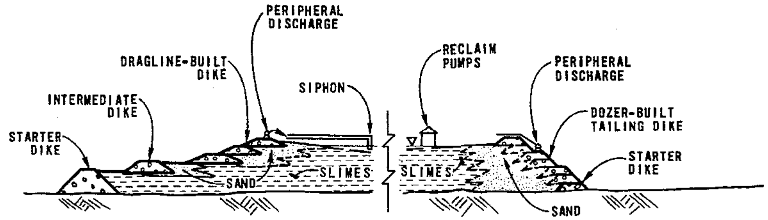
CROSS-V.

WITH DECANT TOWER
ARIZONA: MORENCI
CYPRUS PIMA
MISSION
TENNESSEE: NEW MARKET



MISSOURI: NEW LEAD BELT

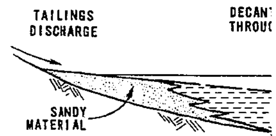
CROSS-VALLEY IMPOUNDMENT
DOWNSTREAM METHOD



UTAH: MAGNA, KENNECOTT COPPER CORP.

ARIZONA: HAYDEN, KENNECOTT COPPER CORP.

DIKED POND
UPSTREAM METHOD



MISSOURI: PILOT KNOB PELLE

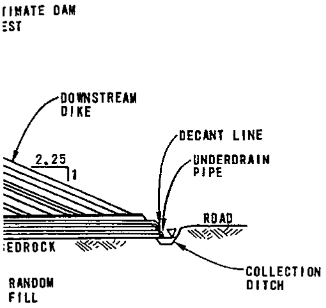
C

NOTE: THESE SKETCHES ARE NOT TO SCALE.

W.A. WAHLER & ASSOCIATES
U.S. BUREAU OF
GENERAL REPC
PALO ALTO • NEWPORT BE

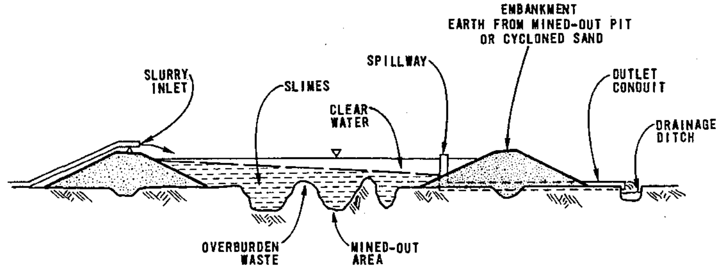
39-A

DATA SOURCES: (1) BUREAU OF MINES INFORMATION CIRCULAR 8404 (1969).
(2) 2ND INTERNATIONAL TAILING SYMPOSIUM, TUCSON, ARIZONA (1972).
(3) DESIGN DRAWINGS FROM SEVERAL MINING COMPANIES.
(4) SITE VISITS.



MICHIGAN: WHITE PINE

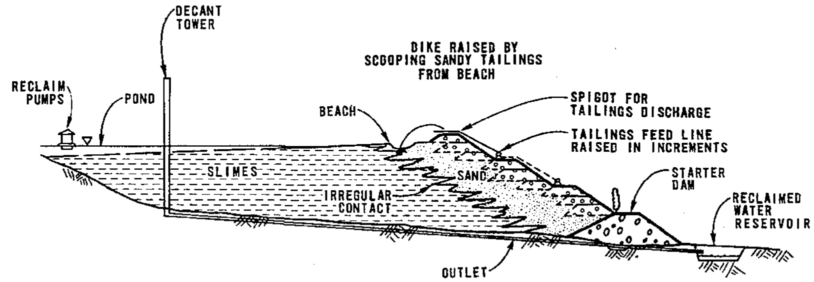
MENT



FLORIDA: PHOSPHATE INDUSTRY

DIKED POND

SPECIAL EMBANKMENT



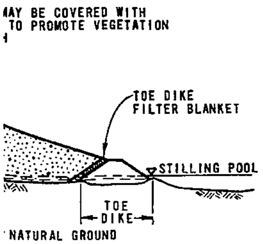
CROSS-VALLEY OR SIDE-HILL IMPOUNDMENT

UPSTREAM METHOD

WITH DECANT TOWER
ARIZONA: MORENCI
CYPRUS PIMA
MISSION
TENNESSEE: NEW MARKET

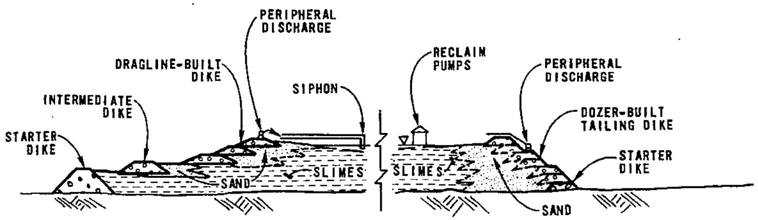
WITH RECLAIM PUMPS
ARIZONA: MORENCI
MINNESOTA: ERIE MINING CO.

S



MISSOURI: NEW LEAD BELT

MENT



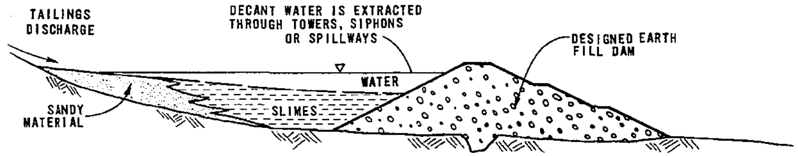
UTAH: MAGNA, KENNECOTT COPPER CORP.

ARIZONA: HAYDEN, KENNECOTT COPPER CORP.

DIKED POND

UPSTREAM METHOD

NOTE: THESE SKETCHES ARE NOT TO SCALE.



MISSOURI: PILOT KNOB PELLET

TENNESSEE: MONSANTO

CROSS-VALLEY IMPOUNDMENT

SPECIAL EMBANKMENT

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	TYPICAL TAILINGS DEPOSITS CROSS SECTIONS		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. III-1

39-B

These embankments are then raised using the coarser fraction of the pulp in one of the ways described below. The two principal classes of embankment construction procedures are: 1) to build the embankment as part of the deposit; and 2) to make the embankment a separate and distinct structure behind which the tailings are stored.

The first type is generally built along with the deposit. The latter type can be built as a unit ahead of the deposit. Each of the types of construction have advantages and disadvantages. The "build as you go" embankments have the advantage of low initial investment and "pay as you go" cost. The preconstructed embankments are built as discrete structures and require a substantially higher initial investment, but they can provide the greatest security from a stability standpoint and may result in the lowest total cost.

The three principal types of "build as you go" embankments are constructed following the upstream method, the centerline method, or the downstream method. The resulting embankments are almost always built of the coarser fraction of the tailings pulp. A discrete embankment constructed of tailings using hydraulic methods can also be built on an "as you go" schedule. A preconstructed embankment can be built of select tailings, of native materials, or of mine strippings. The tailings in this latter case may not be distributed around the periphery of the embankment but may be allowed to flow into the disposal area from a central location without size separation.

1. Upstream Method

In the upstream method, the lifts of the peripheral embankments are carried up, advancing in a general upstream direction. Most of the small tailings deposits have been built in this manner with the inclination of the downstream face generally at the natural angle of repose. The larger deposits usually have berms at regular intervals of height, thus possessing downstream slopes with gentler inclinations. When utilizing this method of tailings embankment construction, the slopes have inclinations that permit maximum storage within a given area as the deposit is raised.

A major drawback to the upstream method of construction is the inability to control the location of the phreatic surface. Depending on the actual methods of construction employed, which are discussed in more detail below, the phreatic surface develops in a manner similar to that in a homogeneous dam, thereby causing saturation of a major portion of the dam. As the upstream portion of each embankment segment (lift) is placed, it is founded on a mixture of fine sands and silts (slimes). The lift construction usually proceeds only after the pond area has dried sufficiently to allow access of light-weight construction equipment. The dried pond surface and base of each lift constitute potential planes of weakness and areas of concentrated seepage.

Several different building techniques are utilized in the conventional upstream method of embankment construction. The four major methods used in the areas considered are discussed below.

a. Hand-Built Embankments - At some of the smaller mines where the daily tailings output is relatively small, successive hand-built dikes are used to retain the tailings. The inclination of the slopes of these dikes is generally the angle of repose of the material used. The construction procedure consists of building a dike approximately 1 foot (0.3 meter) high. The area behind the dike is filled with tailings utilizing simple gravity separation (sedimentation principles) to develop a layer of coarser material adjacent to the deposit's perimeter. As the area behind the dike fills, the coarser material near the dike's inside slope is hand excavated and utilized to build the next successive dike. This method of embankment construction results in a very thin, steep sloped outer shell of more pervious and higher strength materials retaining a large near-fluid mass. A typical example of hand-built dikes to raise tailings deposits is at the Superior mine in Arizona (Photoplate 3-B and 3-C).

b. Dragline-Built Embankments - Where large daily quantities of tailings are deposited, draglines are often used to construct the peripheral embankment of the tailings deposit. The tailings are deposited by spigots and separated by gravity flow toward the center of the deposit. The coarser materials near the edge of the existing embankment are excavated by a dragline and shaped with dozers and/or scrapers into a new dike to retain the next raise. The trenches left upstream of the new raise by the excavation process are either divided into compartments with small lateral dikes which direct new tailings toward the center of the deposit, or they are reshaped into flat areas by dozers. In this way, the natural separation process continues with minimal amounts of fines depositing behind or near the peripheral embankment. Embankments constructed using draglines normally have berms at regular intervals and slopes which vary from 1½:1 (horizontal to vertical), to 2½:1 and gentler. Draglines are presently being used to construct tailings embankments at a number of sites throughout the United States (Photoplates 4 and 5).

c. Cyclone-Built Embankments - Cyclones are in use at many tailings deposits constructed by the upstream method throughout the United States. The cyclones vary in size from portable ones mounted on wooden frames which are subsequently buried as at San Manuel and Mineral Park in Arizona to the large units which require a permanent setup as at the new Morenci deposit. At San Manuel some 42,000 tons of tailings (1971) are deposited daily through 370 - 12-inch cyclones spaced around the various deposits. These units produce about 13,000 tons per day of the coarser tailings (underflow) utilized in embankment construction. The overflow is piped further out onto the tailings deposit. When tailings embankments are constructed solely by cyclones as at San Manuel, the slopes are relatively gentle, about 3:1 or flatter, due to the gentle inclination that the wet underflow assumes. The cones that form as a result of the cyclones being used are usually steepened and trimmed using tractors. Photoplate 6-A through C, and Photoplate 7-A show typical cyclone setups and the sand cones that are formed. Both the San Manuel and Mineral Park tailings deposits are of the side-hill variety, while the new Morenci deposit is a cross-valley type.

d. Tractor and Scraper-Built Embankments - In some regions of the southwestern United States, large earthmoving equipment is used to build peripheral embankments for raising the tailings deposits. With this method, several small deposits or one very large deposit need to be in continuous operation. If several small deposits exist at a site, a minimum of three are required. Of these three, one should be receiving tailings, one drying, and one under construction. Where the individual deposits are large, two areas are sufficient. When disposal is transferred from one to another, adequate time is available for drying and embankment construction. Typical examples of mechanical earthmoving equipment were observed in Arizona.

A self-loading scraper, together with bulldozers, is used at one site. There, the coarse tailings materials which are deposited and separated by gravity are excavated by the scraper and deposited along the edge of the existing embankment. One or two bulldozers are used in conjunction with this scraper to shape and track-roll the new embankment as it is being constructed. Approximately 100 lineal feet (30.5 meters) of 10- to 15-foot (3.0 to 4.6 meters) high embankments can be built a day. The coarser tailings used for embankment construction have moisture contents which, during most of the year, are high enough to make the material easy to handle. During the summer months, however, the tailings need to be prewetted before handling (see Photoplate 7-B and C showing embankment construction operations).

2. Centerline Method

The centerline method of tailings dam construction is generally limited to the use of cyclones. The method involves the initial construction of a starter dam and then subsequent raises of the dam by equally distributing materials on both sides of the original starter dam centerline. The coarse-grained cyclone underflow is distributed in a downstream direction for dam construction and the fine-grained overflow is distributed upstream where retained water may be reclaimed. Cyclone separation of material, if properly designed and maintained, is usually effective in preventing saturation of the downstream half of the dam.

3. Downstream Method

The method least commonly used for construction of peripheral embankments for tailings deposits is known as the downstream method. This is a method of building tailings deposits where the embankment is raised by placing coarser fractions of the separated tailings on the crest and downstream face of the peripheral embankment. The main advantage of utilizing this method, which is similar to the centerline method, is that the slime layers are not allowed to mix into the peripheral embankment to constitute planes of weakness to horizontal forces. Consequently, the embankment is not raised on weaker foundation material as in the case with the upstream method. One drawback to the downstream method is that the exposed sand on the downstream face is subject to water and wind erosion and the sand that is being continually deposited across the face of the embankment is not at complete equilibrium. A metastable downstream slope condition may exist throughout the period that the disposal area is in operation. Another drawback to this method is that each successive lift requires proportionately more material for construction than the previous lift.

In the conventional downstream method, the distribution system is raised as the deposit is raised, but in an upward and outward direction from the existing deposit. The retaining embankment, therefore, progressively moves in a downstream direction. The tailings used for embankment construction are usually separated either through the use of cyclones or some other type of classifiers. The deposits of the lead-zinc industry in Missouri and the White Pine deposit in Michigan use this method partially in combination with designed embankments.

4. Embankments Constructed of Natural Materials

One of the safest ways of containing tailings is the use of retaining embankments constructed of natural rock or soil materials. These embankments can be built across valleys as regular earth dams such as the Monsanto deposit near Columbia, Tennessee, or as side-slope embankments where large quantities of overburden must be disposed of, as at the Twin Buttes open pit copper mine near Sahuarita, Arizona.

The earth embankments constructed at Twin Buttes are 200 feet (61 meters) high and wide enough at the existing crests so they could be raised another 100 feet (30 meters). These embankments have been constructed from alluvial stripping material with berms on the downstream face for maintenance and beautification purposes and have slopes at an approximate 1½:1 inclination. Hauling equipment routing was used to compact the embankments. Photoplate 8-A and B show these earth-retaining embankments.

E. SETTLING PONDS

The ponds that develop on most tailings deposits serve multiple functions: to provide for collection and storage of water in water-short areas, and to provide a settling pond to remove suspended solids from the tailings before the water is reclaimed or disposed.

These are the useful aspects of the ponds. There are also a number of undesirable aspects to them, including the following: 1) in the event of an embankment failure, the ponds provide a quantity of liquid to enlarge the volume of material flowing downstream, thereby providing greater erosion and carrying capacity to the material involved; 2) the more water involved in a flowing mass, the further it can flow; 3) the pond provides a constant source of water for saturation of the mass of tailings and, in many cases, at least partial saturation of the containing embankment. This increases the probability of liquefaction failure under adverse conditions and lowers the strength of the embankment below the phreatic surface even under normal conditions; 4) the disposal capacity of a structure is reduced by the volume required for the pond; 5) the consolidation of the materials below the phreatic surface is reduced due to the buoyant effect of water below the surface of saturation (phreatic surface); and 6) the pond provides a source of water that can infiltrate into the ground degrading naturally-occurring ground water.

F. DECANTING METHODS

The water used for transporting tailings from the mill to the tailings deposit must be reclaimed or otherwise removed from the deposit because of the necessity to reuse the water, for safety and environmental considerations, or simply to prevent the loss of storage space when accumulating too large a reservoir of water. Several methods to drain ponds have evolved and are presently in use.

In many stockpile type deposits and some of the side-slope deposits, a single tower, located in the center of the pond area and constructed either of wood, steel, concrete, brick and mortar, or reinforced concrete, with openings at various elevations, has been found satisfactory for decanting water from the tailings surface (Photoplate 9-A through D). In other deposits, particularly those located in valleys, there may be a series of towers (Photoplate 10-A). The towers are connected at their bottoms to an outlet conduit which usually discharges the decanted water into a small reservoir from which it is either recycled or otherwise disposed (Photoplate 10-B).

Siphons and barges are two other types of decanting methods worth mentioning even though they are not in extensive use. At the Magna tailings deposit, two steel siphons have been erected for the purpose of decanting the water from this very large tailings deposit. A small vacuum pump is provided with each of these setups so the siphons can be de-aired and the lift capacity initiated and maintained (Photoplate 10-C).

Barges can be used to support a pump and hose line to decant the water from the tailings deposit. An important advantage for a barge installation is that the location of the decant point can be varied. Disadvantages include freezing problems in winter and power supply to the barge pumps. Barges with pumps are used at San Manuel and at Mineral Park (Photoplate 10-D). These tailings deposits are of the side-slope variety. The barges themselves are located at the upstream edges of the deposits (Photoplate 11-A and 11-B).

The location of the decant provisions affects the stability of the deposit, principally through control of the position of the pond and regulation of the pond size and depth. Other important safety considerations involve the actual structural design of the towers and conduits. They must be designed to resist the lateral and vertical forces which are placed thereon by the tailings and water, and for seismic loads in earthquake zones. Structural integrity is necessary to permit the tower to perform its function and to prevent an uncontrolled drawing from the pond of water and solids in the event that a breach occurs in the decant system.

G. COMBINED AND SPECIAL METHODS

Not all tailings deposits are being or have been built utilizing only one construction method. In fact, most of the older structures were started with one method and raised with a different method or methods.

The Magna, Utah, tailings deposit was initiated as a retaining peripheral embankment constructed of mine waste rock hauled and dumped from railroad cars. After this method, a new peripheral embankment was constructed of mine waste rock hauled and dumped from trucks. This embankment was founded inside the previous one and upon the settled tailings material. This method was followed by embankments built of sandy gravel hauled and placed by trucks initiating an upstream method with a single discharge point. The method now being used is the upstream method, using draglines to raise the dike, dozers to shape it, and peripheral spigotting to build a sand beach next to the crest of the raised embankment from which the dragline excavates the material necessary to raise the dike.

The tailings deposit at Hayden, Arizona, was a diked pond type of deposit built with dozers and with a single-point discharge. The construction method was changed to the use of cyclones and peripheral discharge a few years ago.

The method of construction of embankments to contain tailings in the new lead-zinc belt of Missouri combines earth dams built using mechanical compaction procedures with cycloned embankments. This combination is also used at the White Pine Copper Company disposal site near White Pine, Michigan. In the phosphate industry of Florida, slimes are contained by peripheral dams built of mine waste placed by dragline. The dams are raised in some cases with cycloned sands to provide more storage volume for the slimes pond.

Decanting methods are also combined in many deposits. Water is extracted through decant towers in most cases, but in a few deposits, the towers are supplemented when necessary with pumps and/or siphon installations. At Morenci, barge-mounted pumps are used when insufficient water is being decanted through the tower decant system.

H. GENERAL PRINCIPLES OF LEACH DUMPS

Copper has been recovered from copper ore for more than 200 years in various parts of the world by leaching, and during recent years as much as 12 percent of the total copper production in the United States has been obtained by leaching. Four principal leaching techniques, dump, heap, in-place, and vat leaching, are used to recover copper from ore materials. Dump leaching, which is far more common, differs from the other three because it involves recovery from low grade and waste material produced usually from open pit mines. The dump leaching method is usually a much larger operation than the other three methods and also involves a much longer leaching cycle, often years in length.

Copper leaching is an excellent example of a process which is simple in principle, but complex in practice. A large body of literature has accumulated concerning the chemistry of various ores leached in the laboratory and/or in pilot columns. The most common method of acid leaching uses a weak solution of sulfuric acid which is allowed to percolate downward through a pile of low grade copper ore, dissolving the soluble copper salts in its path. The pregnant liquid is collected by various means at the bottom of the dump and the copper recovered, usually by precipitation with iron scrap.

1. Mineralogy and Chemical Reactions

Copper in the western United States is produced from low grade ore bodies found predominantly in igneous host rocks, chiefly quartz monzonite, quartz porphyry, monzonite porphyry, granite porphyry, and quartz diorite. The principal copper sulfide minerals in the host rocks are chalcopyrite and chalcocite. Although not a part of our research studies, a basic understanding of the chemical alterations and balances set up within a typical leaching dump is necessary to evaluate their influence on the engineering materials properties. The basic chemical reactions that occur within a leaching dump are the result of the copper ore minerals of chalcocite, chalcopyrite, and nonsulfide copper minerals such as malachite, azurite, and native copper. The chemical reactions by which these specific copper minerals are dissolved in leaching by sulfuric acid and ferric iron are given by Sheffer, et.al., 1968, as follows:

<u>Pyrite</u>

$$2FeS_2 + 7O_2 + 2H_2O \rightleftharpoons 2FeSo_4 + 2H_2SO_4$$

$$4FeSO_4 + 2H_2SO_4 + O_2 \rightleftharpoons 2Fe_2(SO_4)_3 + 2H_2O$$

<u>Chalcocite</u>

$$Cu_2S + Fe_2(SO_4)_3 \rightleftharpoons CuS + CuSO_4 + 2FeSO_4$$

$$Cu_2S + 2Fe_2(SO_4)_3 \rightleftharpoons 2CuSO_4 + 4FeSO_4 + S$$

<u>Chalcopyrite</u>

$$CuFeS_2 + 2O_2 \rightleftharpoons CuS + FeSO_4$$

$$CuS + 2O_2 \rightleftharpoons CuSO_4$$

<u>Malachite</u>

$$Cu_2(OH)_2CO_3 + 2H_2SO_4 \rightleftharpoons 2CuSO_4 + CO_2 + 3H_2O$$

<u>Copper Recovery</u>

$$CuSO_4 + Fe \rightleftharpoons Cu + FeSO_4$$

$$Fe + H_2SO_4 \rightleftharpoons FeSO_4 + H_2\uparrow$$

The above expressions represent only a few of the many and complex chemical reactions that take place within a leach dump on a continuing basis. Added to this complexity is the need for various bacteria living within the dump to convert the ferrous sulfate to ferric sulfate, especially in the reduction of the chalcocite and covellite minerals. From the foregoing, it is easily concluded that an extremely complex balance of flow, leaching, replacement, and in-place weathering is taking place within a given dump, all of which influence its engineering properties.

2. <u>Methods of Dump Placement</u>

Most leach dumps are deposited upon the existing topography in a convenient area near the open pit. The criteria used in selecting the site location is based on the need for an impermeable ground surface and proper dump location to effectively utilize the natural slopes of ridges and valleys for the recovery and collection of the pregnant liquors.

The material to be leached is generally hauled from the open pit to the leach dump by trucks or trains. Bulldozers are used to level the surfaces and edges of the dumps. The larger dumps are usually raised in lifts of 50 to more than 100 feet (15 to 30 meters) (Photoplate 12-A) with the intent of optimizing haulage cost and to form a porous dump favorable for percolation of leach solutions. The exterior slopes of the dumps are generally quite steep (Photoplate 12-B and 12-C) with an inclination corresponding to the maximum angle of repose of the material which ranges from about 28 to 45 degrees. Some sorting of the material is accomplished as the coarser fragments (cobbles and boulders) roll down to the bottom of the depositional slope and the finer materials accumulate near the top of the lift. This characteristic of deposition, particularly noticeable at the Chino leach dump, formed the basis of identifying the top and bottom of lifts during the drilling exploration carried out during this study. Because of the restricted nature of deposition of each individual truck load originating from different source areas and of different material types, there is no uniform layering or lateral continuity of material types within the dump. Compaction of the top layers of each lift by heavy equipment results in a relatively impervious layer. A typical profile within the dump, therefore, would consist of alternating lifts of generally coarser materials near the bottom and finer materials near the top. The internal zoning within typical leach dumps, however, is an extremely heterogeneous mixture of soils and rocks, characterized by irregular, discontinuous, permeable layers mixed together with zones of relatively impervious layers.

The sizes of major dumps in the western states vary widely both in the heights of structures and volumes (tonnages) of dumped material. Although slightly outdated, information compiled by Sheffer and Evans in 1968, reprinted in Table III-2, presents pertinent data regarding tonnage and geometry of some major dumps.

TABLE III-2

DATA FROM COPPER LEACHING AND PRECIPITATION OPERATIONS IN THE WESTERN UNITED STATES

Company	Source materials		Leaching operation						
			Type of leaching	Leach material					Method of introduction of leach solution
				Quantity 1,000 tons (est.)	Geometry		Ground preparation	Method of emplacement	
	Host rock	Principal copper minerals			Area, 1,000 sq.ft.	Maximum height, ft.			
American Smelting and Refining Co., Silver Bell unit, Silver Bell, Ariz.	Alaskite, dacite porphyry, monzonite.	Chalcocite and chrysocolla.	Dump....	[1] 30,000	5,650	200	Leach material is deposited on the existing topography.	Leach material is hauled and dumped by trucks. Edges and surfaces of dumps are leveled by bulldozer.	Ponding and trenching
The Anaconda Company:									
Butte, Mont.	Quartz monzonite.....	Chalcocite...........	 ...do....	10,000 [2] 23,000	390 860 400	195 175 50	The main dump is underlain by an impervious pad. See complete description in body of report under ground preparation for dump emplacement.	................do.................	Solutions introduced through perforated plastic pipes spaced 100 ft apart on grid.
Yerington mine, Weed Heights, Nev.	........do............	Chrysocolla.........	Dump and vat.	30,000	20	165	The leach dumps have been deposited on a dry lake bed which was leveled by bulldozer and compacted by sheepsfoot rollers.	................do.................	Spraying...............
Bagdad Copper Corp., Bagdad, Ariz.	Monzonite porphyry...	Chrysocolla, malachite, azurite.	Dump [1]..	40,000	2,390	240	Leach material is deposited on the existing topography.	................do.................	........do.............
Duval Corp.:									
Esperanza mine, Sahuarita, Ariz.	Quartz monzonite, rhyolite flows, quartz diorite.	Chalcocite, some chalcopyrite.	...do....	19,000	830	220	.............do...............	................do.................	........do.............
Mineral Park, Ariz..........	Quartz porphyry and quartz monzonite.	Chalcocite...........	...do....	[1] 5,500	340	250	.............do...............	................do.................	........do.............
Inspiration Consolidated Copper Co., Inspiration, Ariz.	Schist and granite porphyry.	Chrysocolla, azurite, malachite.	Dump, inplace, vat.	30,000	750	200	.............do...............	................do.................	Spraying, ponding, and trenching.
Kennecott Copper Corp.:									
Utah Copper Division, Bingham Canyon, Utah.	Quartz monzonite.....	Chalcopyrite.........	Dump....	4,000,000	31,000	1,200	.............do...............	Leach material is hauled and dumped by trucks and train. Edges and surfaces of dumps are leveled by bulldozer.	Solutions introduced into strips or channels.
Chino Mines Division, Santa Rita, N. Mex.	Granodiorite porphyry..	Chalcocite...........	...do....	425,000	28,000	300	.............do...............	................do.................	Ponding and trenching
Ray Mines Division, Ray, Ariz.	Schist and diabase....	........do..........	Dump and inplace.	94,000 31,000 44,000 [3] 17,500	12,000 2,000 6,000 NA	125 80 85 NA	.............do...............	Leach material is hauled and dumped by trucks. Edges and surfaces of dumps are leveled by bulldozer.	Ponding...............
Miami Copper Co., Miami, Ariz.:									
Castle Dome unit.........	Quartz monzonite and granite porphyry.	Chalcopyrite and chalcocite.	Dump....	48,000	NA	NA	.............do...............	................do.................	Spraying and ponding.
Copper Cities unit........	Quartz monzonite....	........do..........	...do....	NA	NA	150	.............do...............	................do.................	Spraying
Miami Unit...............	Schist and granite porphyry.	Chalcocite	Inplace..	NA	NA	NA	Surface topography on which solutions are introduced is a depression resulting from block-caving operations beneath.	Copper minerals remain in block-caved stopes, pillars, and capping.	Spraying of surface above block-caved areas.
Phelps Dodge Corp.:									
Bisbee, Ariz.	Quartz monzonite and conglomerate.	Chalcocite, some azurite and malachite.	Dump....	47,000	3,850	170	Leach material is deposited on the existing topography.	Leach material is hauled and dumped by trucks. Edges and surfaces of dumps are leveled by bulldozer.	Ponding...............
Morenci, Ariz.............	Quartz monzonite porphyry.	Chalcocite..........	...do....	NA	NA	NA	Strip material is sometimes deposited on pre-existing dumps that were deposited on the existing topography.	Leach material is hauled and dumped by side-dump railroad cars.	...... do..............
Ranchers Exploration and Development Corp., Bluebird mine, Miami, Ariz.	Granite porphyry......	Malachite and azurite	Heap....	500	100	80	Ground is dressed, soil is cemented and covered with diluted tar for curing and sealing purposes.	Leach material is hauled by bottom-dump scrapers to the heaps. Motor grader levels the heap area.	Percolated through plastic pipes spaced 8 ft apart on surface of the heaps.
J. H. Trigg Co., Tyrone, N. Mex.:									
Property No. 1.............	Quartz monzonite.....	Chrysocolla and azurite.	...do....	150	20	75	Leach material is deposited on the existing topography.	Blasted material is loaded by scoopers into dumpsters. The dumpsters unload the material on a pile. Bulldozer levels the dump material.	Ponding...............
Property No. 2	........do...........	Malachite...........	...do....	100	30	40	..............do...............	...................do................	NA
Zontelli Western Mining Co., Page, Ariz.	Sandstone............	Malachite, azurite, chrysocolla.	...do....	500	300	40	A special pad is prepared. See complete description in body of report under ground preparation for dump emplacement.	Leach material is hauled and dumped by trucks. The surfaces of the heaps are leveled by bulldozer.	Ponding...............

NA, Not available.

[1] In 2 dumps
[2] Main dump is divided into high and low dump sections.
[3] Total for other three dumps.

Data taken in part from Table 1 of IC 8341 Bureau of Mines, SHEFFER and EVANS, 1968.

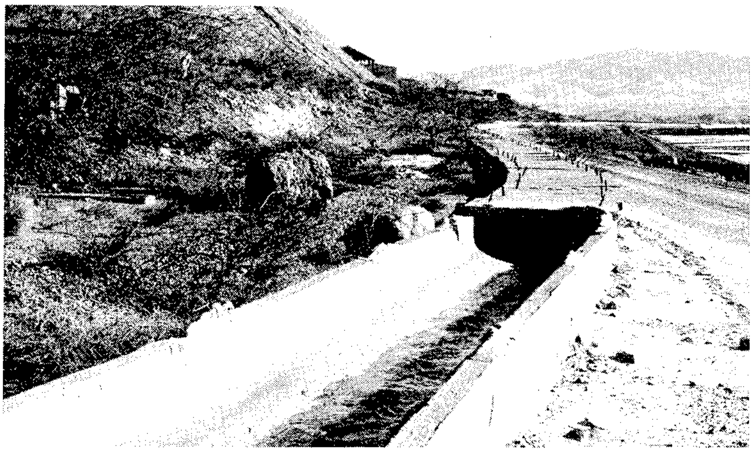


PHOTO A. TYPICAL CONCRETE LAUNDER USED AT MORENCI, ARIZONA FOR TRANSPORTING TAILINGS.

PHOTO B. WOOD-STAVE PIPE USED FOR TAILINGS TRANSPORTATION AT KENNECOTT'S CHINO MINES DIVISION, HURLEY, NEW MEXICO.

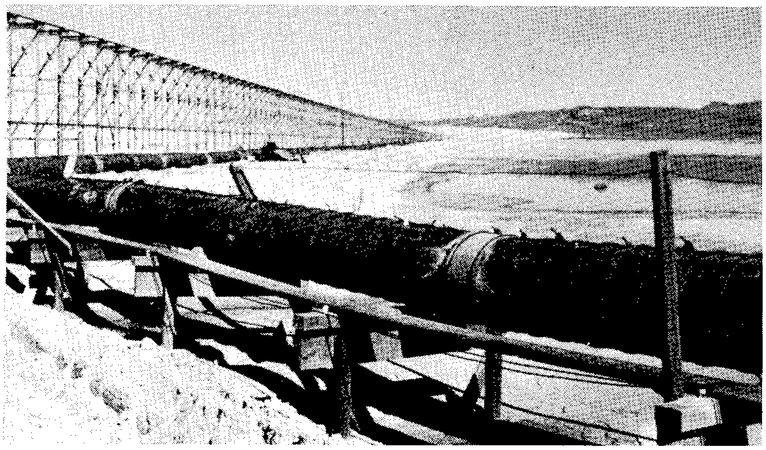
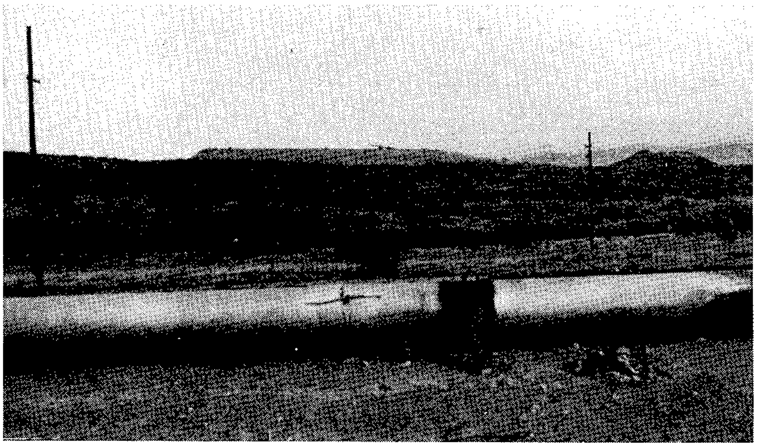


PHOTO C. VIEW OF CEMENT-LINED SPIRALWELD STEEL PIPE USED FOR TAILINGS DISTRIBUTION AT KENNECOTT'S TAILINGS DEPOSIT NEAR SALT LAKE CITY, UTAH.

PHOTO D. VIEW OF CONCRETE-LINED STEEL PIPE USED TO TRANSPORT TAILINGS PULP FROM THE MILL TO THE TAILINGS DEPOSIT.



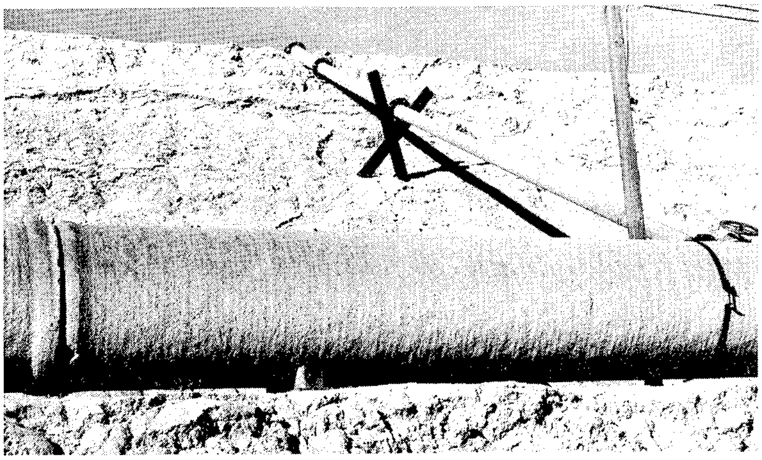
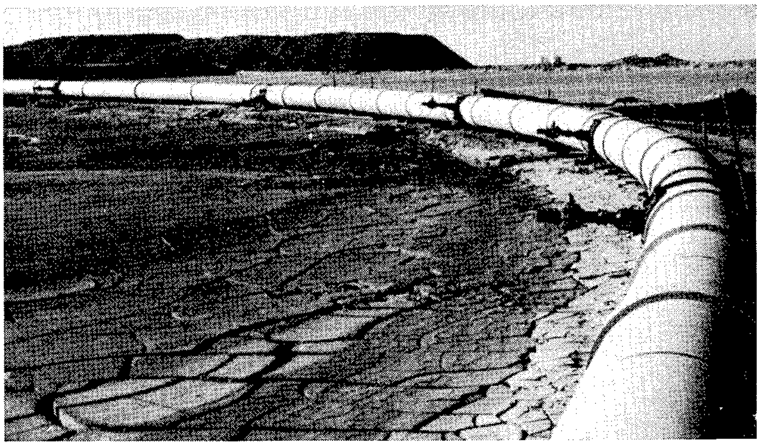


PHOTO A. LARGE DIAMETER, REINFORCED CONCRETE HEADER PIPE AT MORENCI, ARIZONA.

PHOTO B. TRANSITE PIPE WITH SPIGOTS USED IN DISTRIBUTING TAILINGS AT PIMA, ARIZONA.



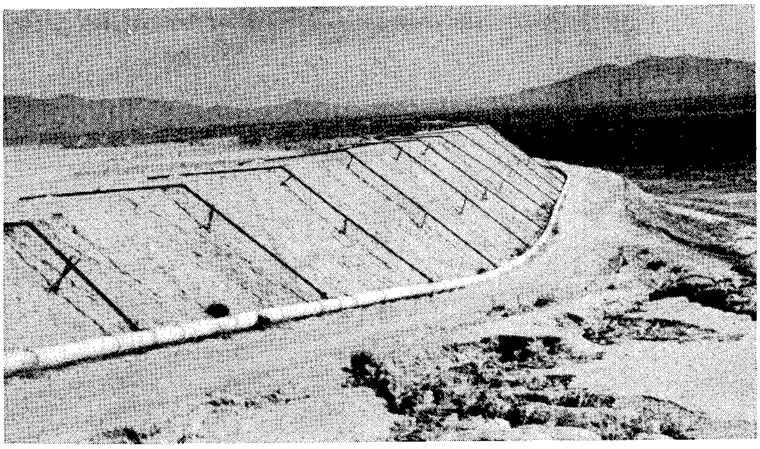


PHOTO C. TRANSITE HEADER PIPE WITH LATERALS USED IN DISTRIBUTING TAILINGS AT THE MISSION UNIT OF THE AMERICAN SMELTING AND REFINING COMPANY, ARIZONA.

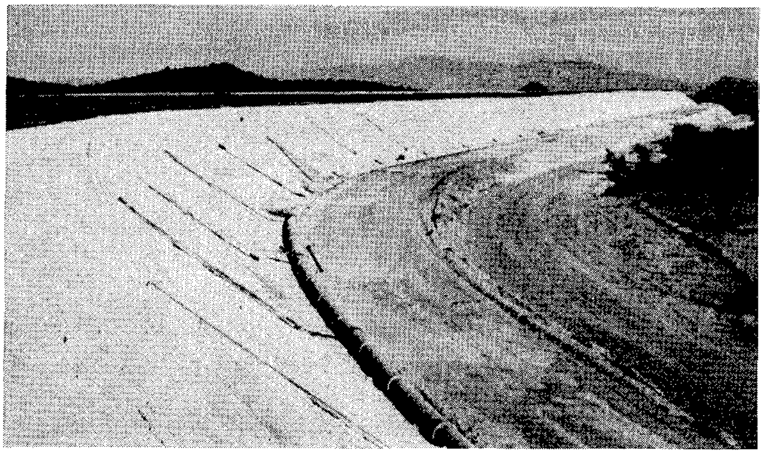
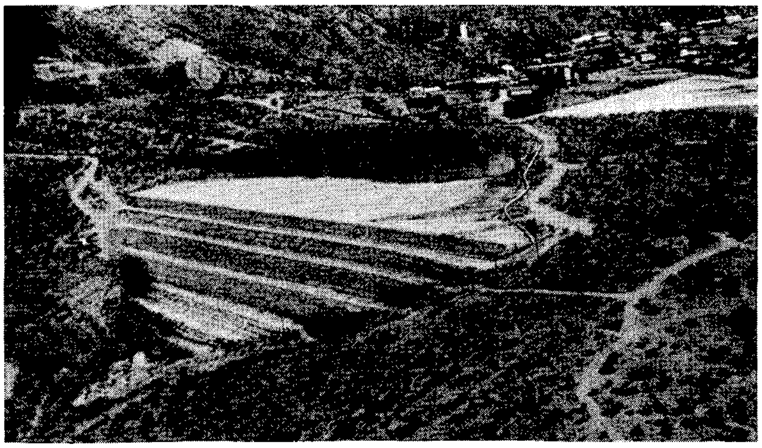


PHOTO A. TRANSITE HEADER WITH PARTIALLY BURIED LATERALS AT THE SILVER BELL UNIT OF THE AMERICAN SMELTING AND REFINING COMPANY, ARIZONA.

PHOTO B. VIEW OF NEW TAILINGS DEPOSIT AT SUPERIOR, ARIZONA.



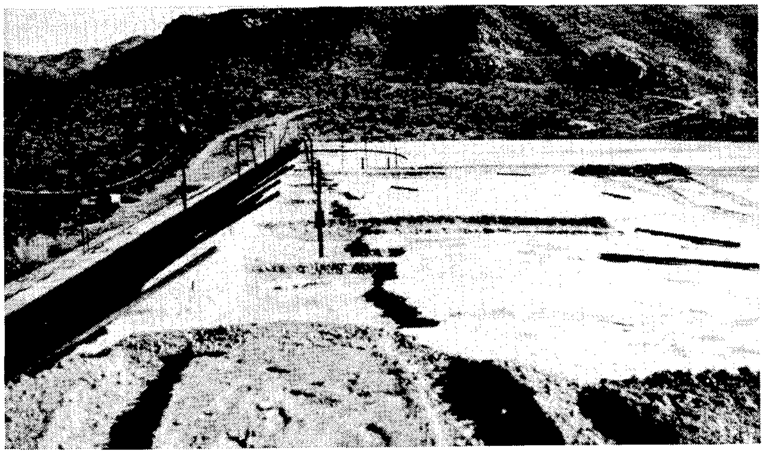


PHOTO C. THE NEW TAILINGS DEPOSIT AT SUPERIOR, ARIZONA SHOWING PITS EXCAVATED TO OBTAIN MATERIAL FOR HAND-BUILT DIKE AT EDGE OF DEPOSIT IN LEFT PORTION OF PHOTO. STEEL LATERAL PIPES PARTIALLY OBSCURE THE DIKE ITSELF. THE DEPOSIT IS NOW READY TO RECEIVE ANOTHER RAISE.

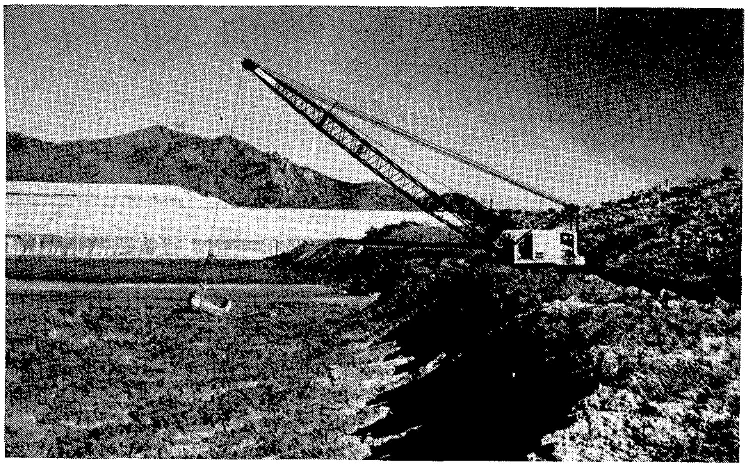
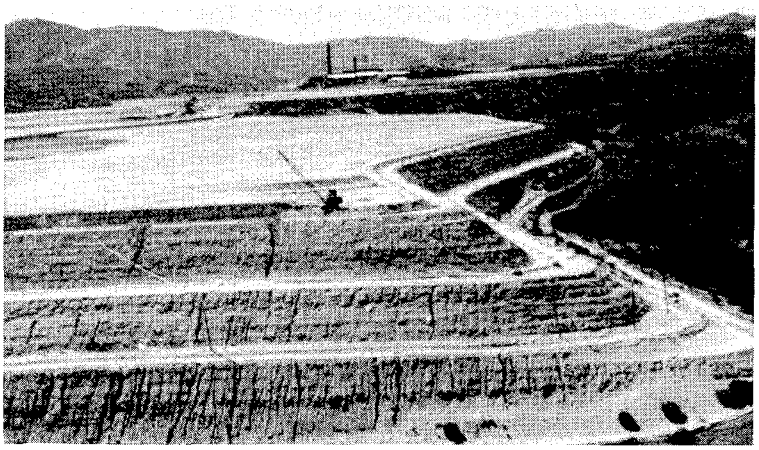


PHOTO A. DRAGLINE AT MORENCI, ARIZONA.

PHOTO B. TAILINGS DEPOSIT AT INSPIRATION, ARIZONA. PERIPHERAL EMBANKMENT IS BEING RAISED BY BY DRAGLINE.



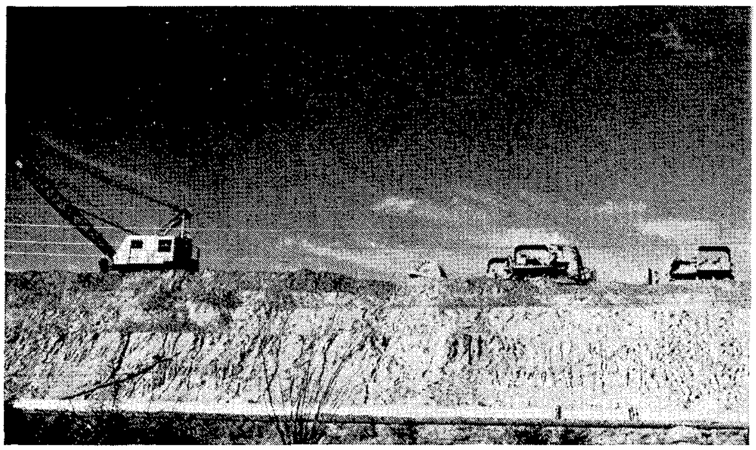
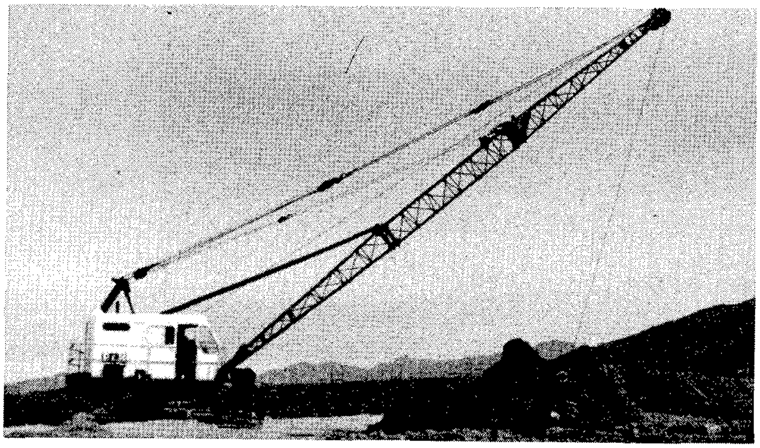


PHOTO C. DOZER AND SHEEPSFOOT ROLLER COMPACTING RAISED EMBANKMENT.

PHOTO D. DRAGLINE WORKING ON TAILINGS EMBANKMENT.



W.A. WAHLER
& ASSOCIATES

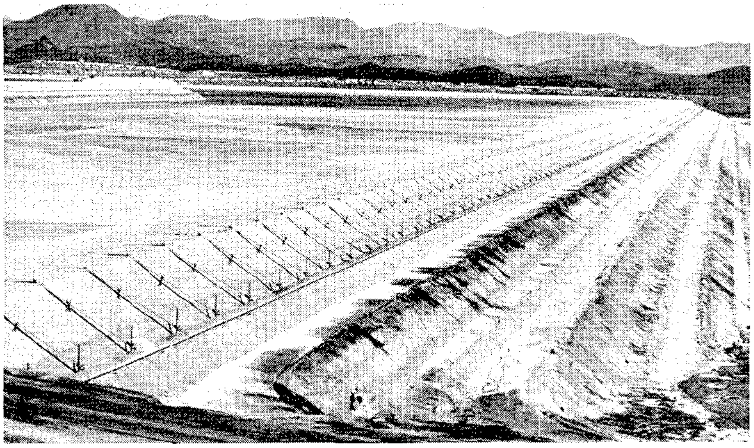


PHOTO A. View showing headers and laterals placed after embankment has been raised by dragline at Morenci, Arizona.

PHOTO B. View of trench left upstream of raised embankment by dragline excavation at the Mission Unit of the American Smelting and Refining Company, Arizona. Note lateral dikes for directing slimes to center of deposit.

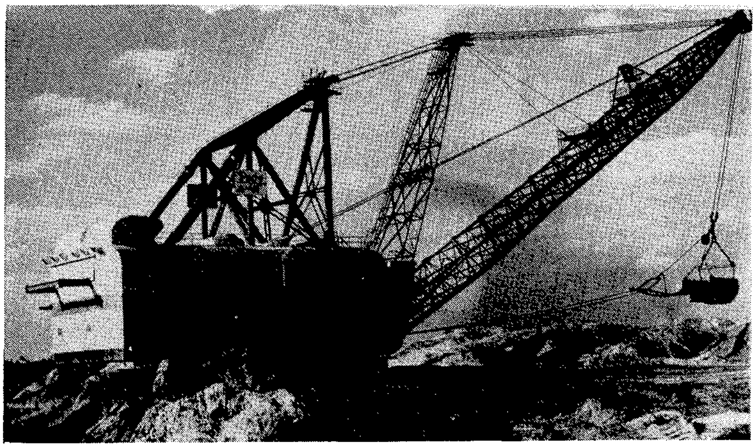
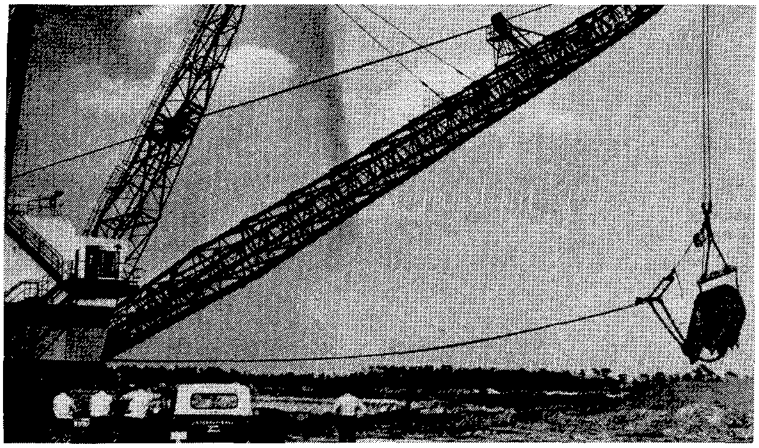


PHOTO C. Dragline operating in phosphate mine of Swift Co Florida.

PHOTO D. Dragline casting waste material for embankment, Florida.



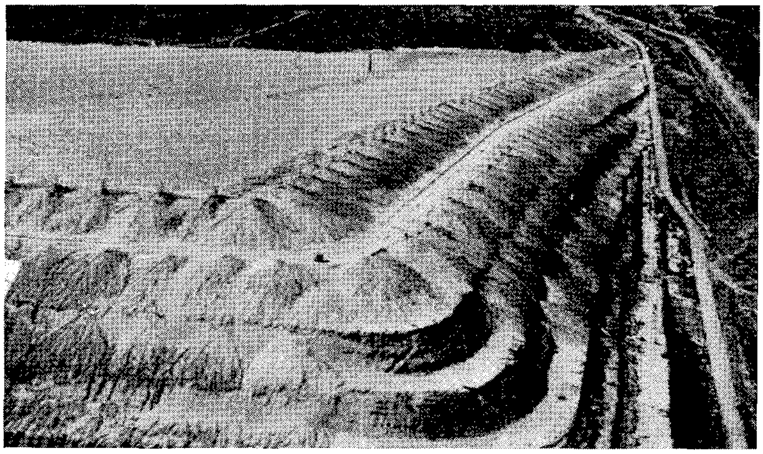
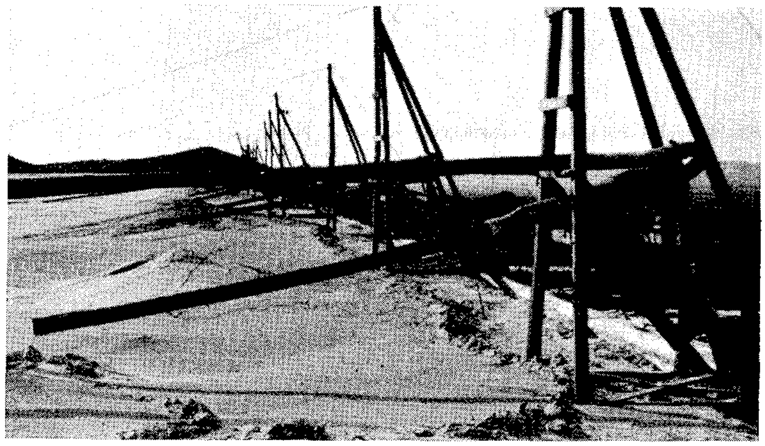


PHOTO A. VIEW SHOWING CONES OF TAILINGS DEPOSITED AROUND INDIVIDUAL CYCLONES AT SAN MANUEL, ARIZONA. NOTE NUMBER AND SPACING OF CYCLONES.

PHOTO B. TYPICAL CYCLONE OPERATION. THE FEED LINE CANNOT BE SEEN BUT THE UNDERFLOW CONVEYANCE IS THE SHORT BOTTOM PIPE, WHICH DISCHARGES THE COARSE MATERIAL FOR BERM CONSTRUCTION, AND THE OVERFLOW CONVEYANCE, WHICH CARRIES SLIMES TO THE POND AREA, IS THE UPPER PIPE.



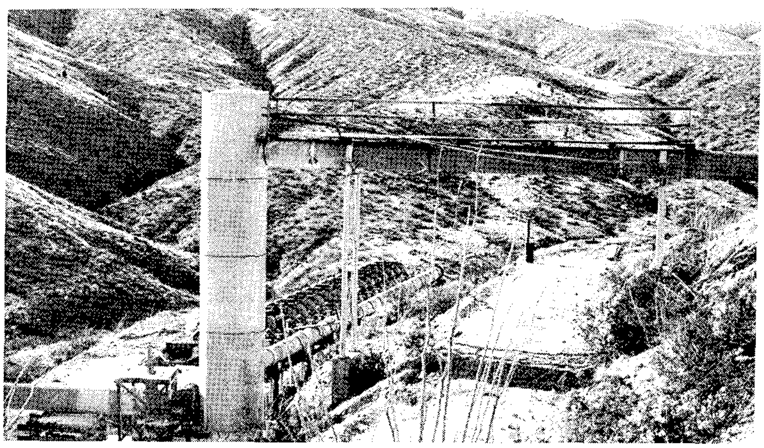


PHOTO C. VIEW SHOWING BANK OF CYCLONES AND ASSOCIATED HEADER PIPES SITUATED ON THE LEFT ABUTMENT OF THE NEW TAILINGS DEPOSIT AT MORENCI, ARIZONA.

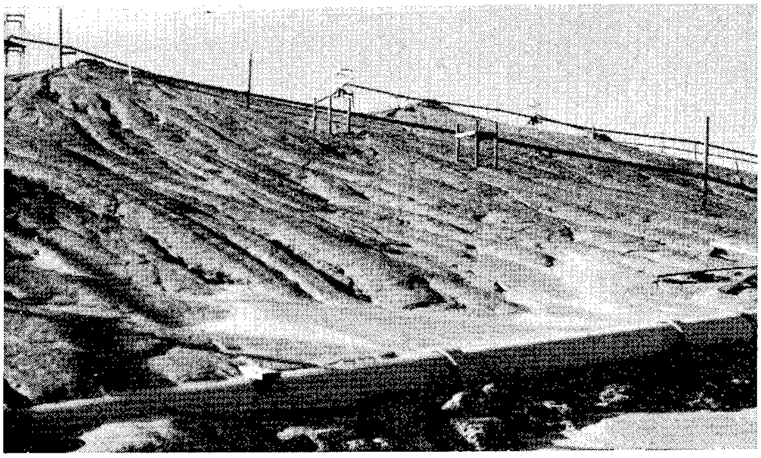


PHOTO A. CONES OF TAILINGS DEPOSITED AROUND CYCLONES AT SAN MANUEL, ARIZONA. THESE CONES ARE LATER TRIMMED AND STEEPENED BY TRACTOR.

PHOTO B. TYPICAL PERIPHERAL DISCHARGE BY SPIGGOTING. THE TAILINGS ARE SEPARATED BY GRAVITY YIELDING COARSER MATERIALS NEAR THE PERIPHERY AND SLIMES AT THE CENTER OF THE DEPOSIT.

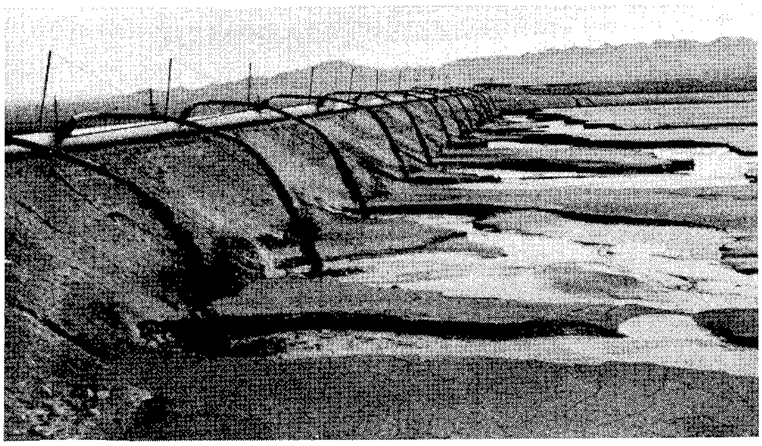


PHOTO C. VIEW SHOWING ELECTRIC SELF-LOADING SCRAPER EXCAVATING COARSEST TAILINGS FOR CONSTRUCTION OF PERIPHERAL EMBANKMENT.

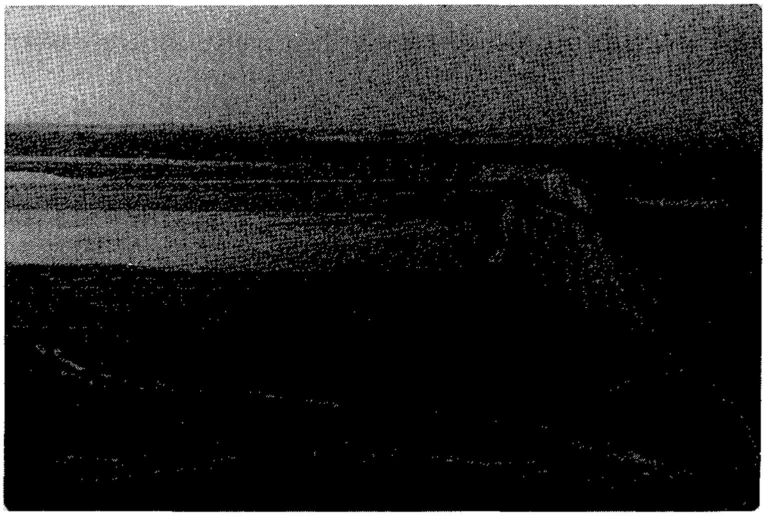
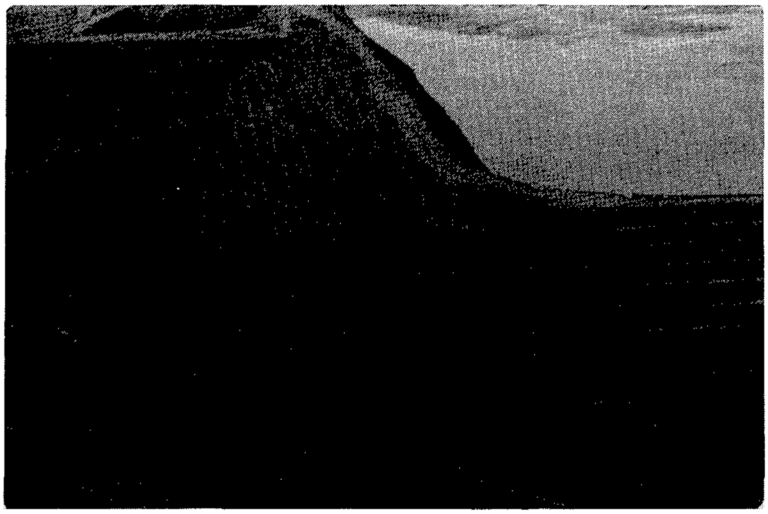


PHOTO A. EARTH EMBANKMENTS FOR IMPOUNDING TAILINGS AT ANACONDA'S TWIN BUTTES OPEN PIT COPPER MINE, ARIZONA

PHOTO B. CORNER OF TAILINGS RETAINING STRUCTURE AT TWIN BUTTES, ARIZONA.



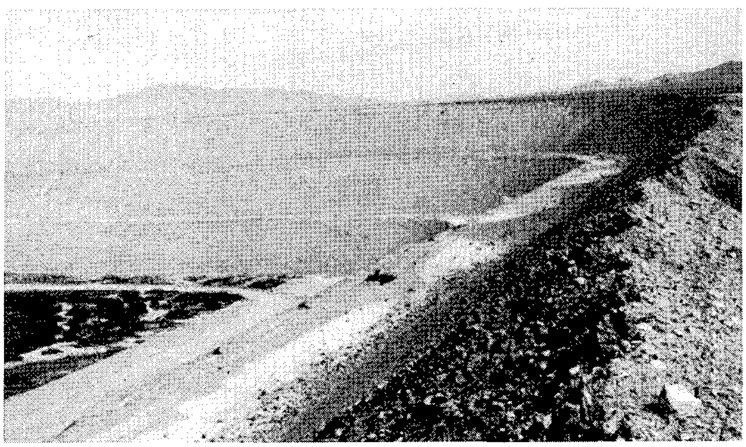


PHOTO C. INSIDE CORNER OF DIKE PRIOR TO FILLING WITH TAILINGS, TWIN BUTTES, ARIZONA.

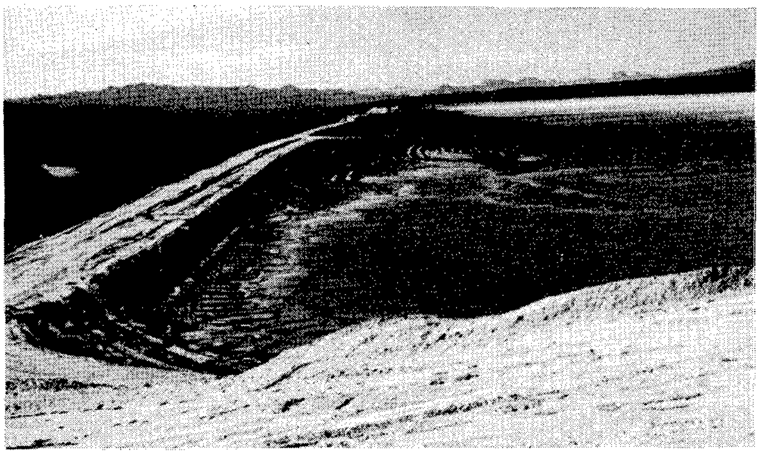
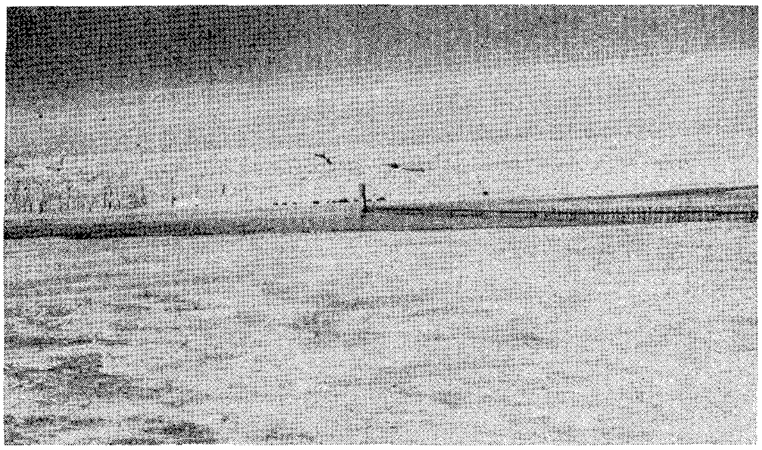


PHOTO A. VIEW SHOWING REINFORCED CONCRETE DECANT TOWER NEAR THE EDGE OF THE EMBANKMENT AT HAYDEN, ARIZONA.

PHOTO B. STEEL DECANT TOWER IN THE CENTER OF THE DEPOSIT AT AJO, ARIZONA.



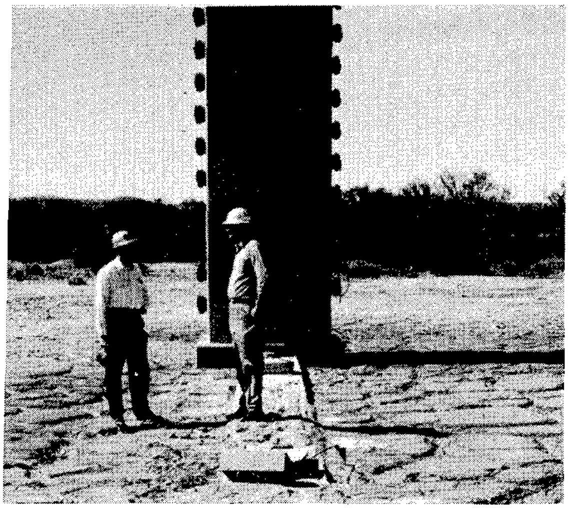
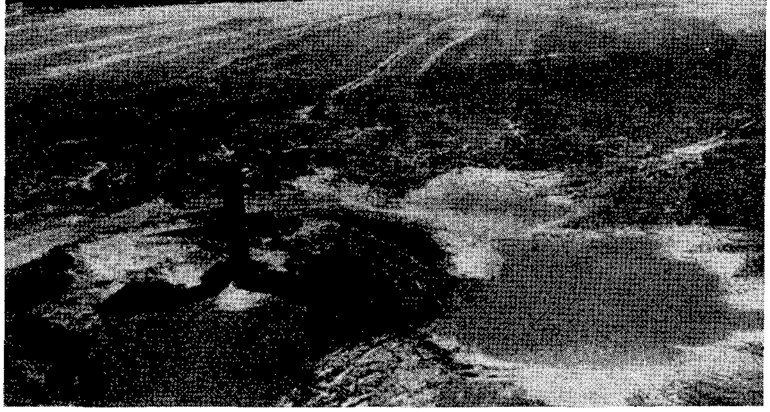


PHOTO C. REINFORCED CONCRETE DECANT TOWER AT THE MISSION UNIT OF AMERICAN SMELTING AND REFINING COMPANY.

PHOTO D. AERIAL VIEW SHOWING REINFORCED CONCRETE DECANT TOWER AT MORENCI, ARIZONA.



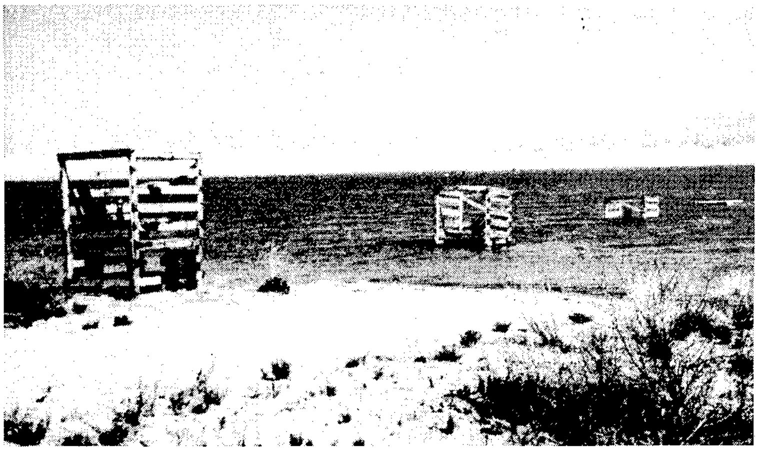
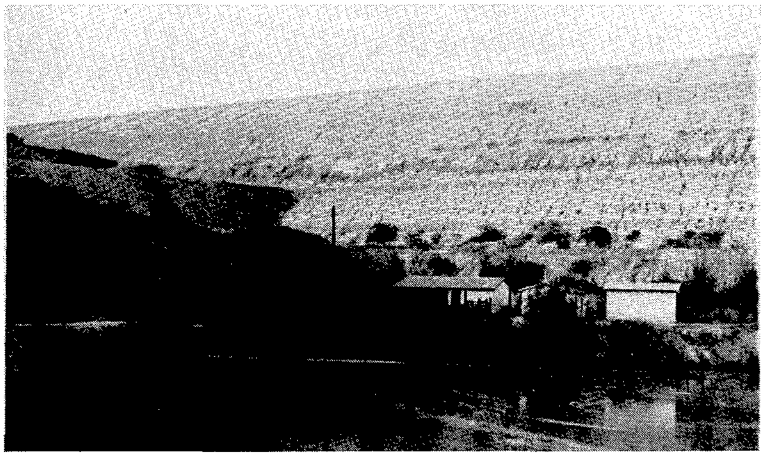


PHOTO A. SERIES OF SMALL STEEL DECANT TOWERS AT SAN MANUEL, ARIZONA.

PHOTO B. STILLING BASIN AT MORENCI, ARIZONA.



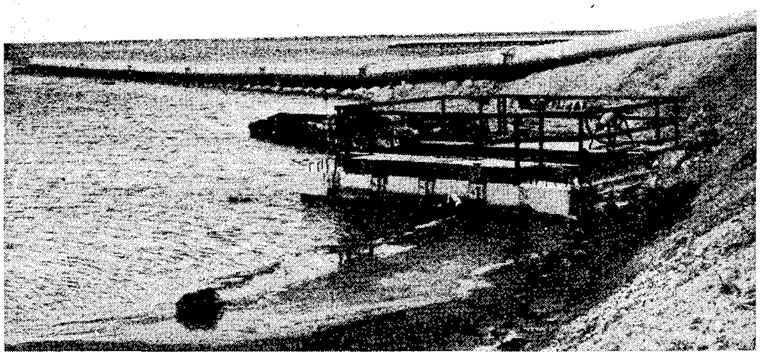
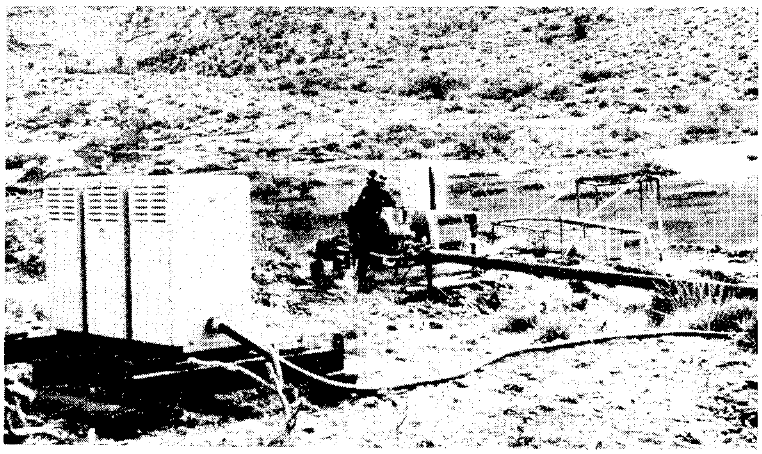


PHOTO C. VIEW OF DECANT SIPHONS AT KENNECOTT'S TAILINGS DEPOSIT NEAR SALT LAKE CITY, UTAH.

PHOTO D. VIEW OF PUMPING APPARATUS USED TO RECOVER WATER FROM THE TAILINGS POND AREA.



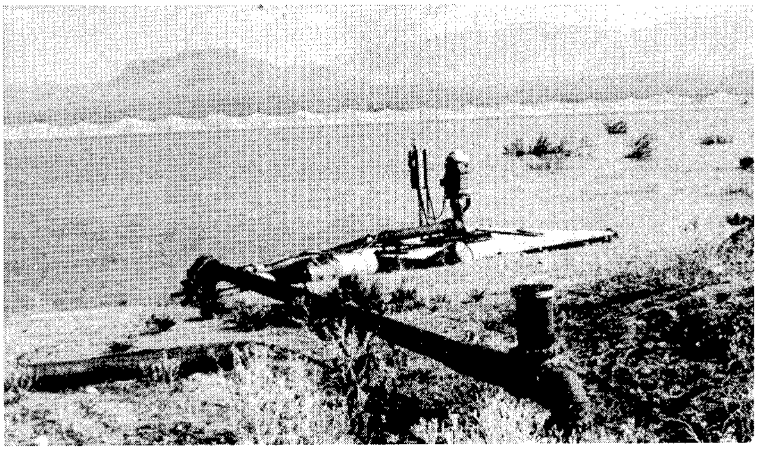
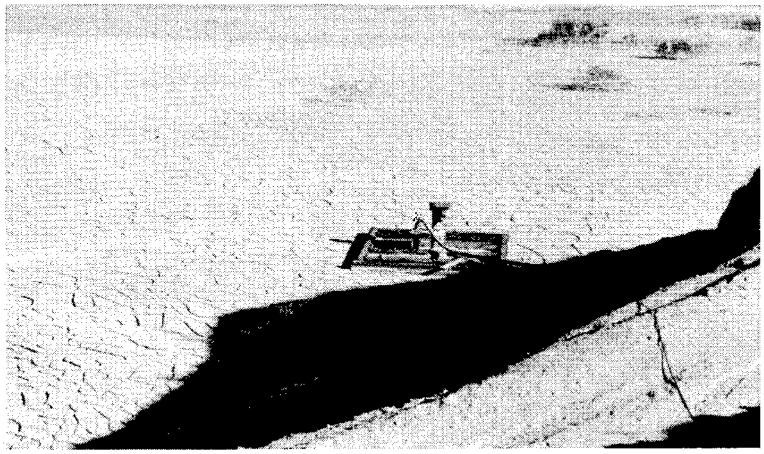


PHOTO A. DECANT BARGE AT UPSTREAM EDGE OF DEPOSIT AT SAN MANUEL, ARIZONA.

PHOTO B. DECANT BARGE AT PIMA, ARIZONA.



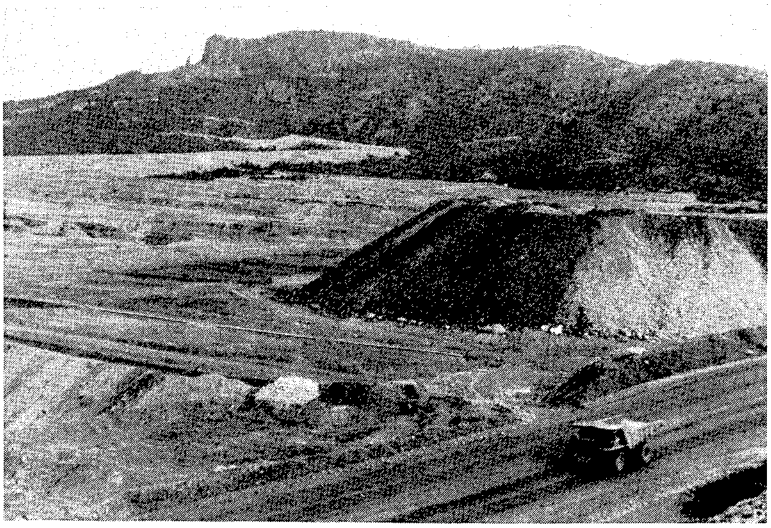


PHOTO A. A 75-FOOT LIFT DEPOSITED BY END DUMPING (RIGHT, CENTER). NOTE THAT COARSER MATERIALS ROLL DOWN DEPOSITIONAL SLOPES. CHINO LEACH DUMP, HURLEY, NEW MEXICO.

PHOTO B. MAIN EMBANKMENTS AT CHINO LEACH DUMP. NOTE THE DRILL RIG ON BENCH TO THE RIGHT.

PHOTO C. TOE OF DUMP IN FOREGROUND OF PHOTO B. NOTE BOTH THE COLLECTION OF ACID SOLUTION AND MAN IN FOREGROUND FOR SCALE.

CHAPTER IV

GEOLOGY, SEISMICITY, AND HYDROLOGY

GEOLOGY

SEISMICITY

HYDROLOGIC CONSIDERATIONS

CHAPTER IV

GEOLOGY, SEISMICITY, AND HYDROLOGY

A. GEOLOGY

The investigation at the Magna, Morenci, and Chino deposits included a relatively detailed review of the geologic and seismic characteristics of each site. The geologic aspects of the sites control many characteristics of the deposits. This was also recognized at the sites visited during the reconnaissance-level investigation.

Because they may influence deposit siting and design, and the selection of disposal methods, geologic aspects are of importance for the disposal of mill or mine waste products. One of the main geologic aspects to be considered is the type of foundation material underlying the structure, since it has a direct influence on the stability, settlement, and seepage characteristics of the deposits.

The types of foundation materials found under refuse deposits and their significance can be classified in general as follows:

1. Organic Soils

Organic soils should be removed before placement of refuse deposits due to their low strength, which is detrimental to stability under conditions of fast rates of construction. Settlements caused by the high compressibility of such materials are also critical and can endanger the stability of the structure since cracks can develop between masses settling at different rates. Seepage through organic soils can be very high if the soil has low density and could produce piping (internal erosion) that may lead to failure.

2. Granular Soils

Soils that are mainly granular include those derived from river sedimentation, beaches, etc. If they are too loose, these soils may be subject to liquefaction, particularly if they have a uniform, relatively fine gradation. Settlements of these soils can be very high and usually will occur during construction. Since the permeability of this type of soil is generally high, the rate of seepage through it can also be very high. Therefore, the danger of washing fine-grained material from such deposits by high seepage velocities is a problem that should be investigated; the problem can usually be solved by employing adequate protective filters, or by taking measures to control seepage rates through the deposits.

Filter layers to control seepage forces are especially important under the dam or embankment portion of a tailings deposit since these forces are detrimental to the basic stability of the containing structure.

However, the use of filters does not seem to be widespread throughout the mining industry. Only a few tailings deposits visited during this investigation had provisions for filters (example: White Pine, New Lead Belt of Missouri).

3. Cohesive Soils

Cohesive soils exist under many tailings deposits. Their properties as foundation materials vary widely. Stability will depend on the rate of construction of the deposit and the shear strength of the foundation materials. Settlement caused by the imposed weight of a deposit is a slow process and the magnitude will depend on the thickness and compressibility of the foundation material. Therefore, differential settlements may occur where such materials exist in deposits of significantly varying thickness, or where they occur adjacent to bedrock or other less compressible foundation materials. Seepage through this type of soil may not be important and depends on the stratification characteristics.

Since permeability varies with direction in a stratified deposit, determination of this direction becomes important. If the cohesive foundation soil is too impervious, the tailings deposit may have to include drainage provisions to prevent undesirable water accumulation within the deposit. This, of course, depends on the water requirements of the mill or other mine or mill facilities. In arid areas, for instance, where water is scarce, an impervious foundation which would minimize water losses may be desirable.

4. Rock

Although rock is generally the best foundation material, few deposits of mine and mill refuse are founded directly on rock. Rock, in itself, is generally strong, incompressible, and impervious. However, if the rock is very fractured, strongly jointed, or has solution cavities, secondary permeability (that of the rock mass as a whole) may be great and seepage control measures might be required.

In one case, a solution cavity in carbonate rock was used to dispose of some tailings. The cavity, a sinkhole at the New Market site in Tennessee, was filled with tailings before a new tailings deposit was developed over it. At that site there is no seepage control.

The categories of foundation materials described above are broad and at many sites there are a variety of foundation conditions which depend on the geologic setting and history of the site. The climate at the site also influences the geologic characteristics and the design of the structures. For instance, organic soils are more likely to be present in a humid environment than in arid places. Therefore, organic soils are less likely in Arizona or New Mexico than in Michigan or Missouri.

The other importance of geologic characteristics of the sites is the presence of faults that may be the loci of future earthquakes. Geologic maps that show the location of faults and an evaluation of the geologic history of the area are the basis for estimating the probability of occurrence of fault movements that could affect the structures directly or produce a damaging earthquake. The geologic evaluation also will indicate other hazards to the structure from such phenomena as landsliding, flooding, subsidence due to underground fluid withdrawals, solubility or reactivity of soils and rocks, etc. All these geologic considerations are necessary to design a safe new structure, or to evaluate hazardous conditions associated with existing structures.

B. SEISMICITY

The ever-present threat of earthquake-induced failure of structures is justification to investigate the potential for earthquakes in a site area. An earthquake occurred in Chile in 1965, causing the partial to total failure of 11 tailings deposits and the loss of over 200 lives. Another earthquake occurred in the same region in 1971 and again induced the failure of many tailings dams. These failures demonstrate the necessity of analyzing the probability of earthquakes, their anticipated characteristics, and their influence on existing and on planned mine and mill refuse deposits. The three deposits investigated in some detail for this project were analyzed as to their seismic setting according to the general procedure discussed below.

To arbitrarily assign a seismic coefficient which expresses a horizontal force in terms of a percentage of the force of gravity when analyzing the seismic stability of a structure does not represent the current state-of-the-art in earthquake engineering. Experiences with earthquakes and their effects, the concern of many engineers and geologists who have had to deal with earthquake-related problems, and the increased availability of computer programs which permit the solution of more sophisticated engineering analyses, have led to the development of new concepts and techniques for the analysis of site seismicity and for the evaluation of seismically-induced ground motions.

Typically, the investigative procedures required to estimate the probable earthquake parameters for a site include the following:

1. Investigation of the geology and earthquake history of the project region to provide a statistical probability of earthquake occurrence based on the occurrence and characteristics of previous earthquakes in the region.

2. Detection and delimitation of active or potentially active faults or other suspect structures by geologic mapping, surface and subsurface exploration, remote sensing and geophysical exploration techniques.

3. Monitoring earthquake motions, and natural and artificial ground vibrations to define the elastic properties of the soil and rock materials at the site.

4. Testing selected samples of foundation and embankment materials in the laboratory under static and dynamic conditions and analyzing mathematical models to define the dynamic behavior of the site.

Few regions of the United States are free from earthquakes. We are reminded quite often that our planet is not quiet and that part of its restlessness is manifested in the form of earthquakes that may be directly attributed to known active faults such as in the western part of the country, or to less well defined, but nevertheless active, seismic areas such as in the eastern and southeastern states. It is, therefore, necessary to undertake investigations of the seismic activity in relation to tailings dams and other refuse deposits. These investigations will generally include the following sequential phases:

1. A review of available information on regional and local geologic conditions as they relate to seismicity and potential ground shaking at the site. These data are compiled and tabulated to allow a preliminary earthquake engineering evaluation. The steps involved in the geologic and engineering analyses are:

   a. Determination of the location of potentially active faults and of the probable magnitude of the maximum credible earthquake on such faults.

   b. Study of the site characteristics with respect to possible amplification or attenuation of ground motion.

   c. Estimation of ground motion parameters, such as the maximum level of bedrock acceleration at the site resulting from earthquakes.

   d. Study of the probability of occurrence of various levels of bedrock acceleration during the design life of the structure.

2. Seismic design criteria are established based upon a comprehensive evaluation of ground response resulting from one or more different magnitude earthquakes. The steps involved in the evaluation are:

   a. Selection of an accelerogram for design based on the probability of occurrence and other factors.

   b. Preparation of response spectra of ground motion for the project site.

c. Consideration of damping and structure-foundation interaction for the design.

It should be emphasized that an exhaustive evaluation of the earthquake situation, carried through to completion of all activities listed above, will not always be warranted. Likewise, it will not always be necessary to perform sophisticated dynamic laboratory testing or dynamic stability analyses. The decision on how far to carry any investigation must be made on an individual basis, depending on the findings of the investigation as to what may be the earthquake-related problems at the specific site under study. However, to make this determination, it would seem essential that, as a minimum, steps 1.a. through 1.d., above, always be carried out.

The following covers each activity required for a thorough earthquake engineering evaluation and delineates considerations required to achieve the desired results.

1. <u>Seismicity Analysis and Selection of Design Earthquake</u>

A design earthquake or earthquakes must be chosen to properly simulate ground motions that could be developed at the site by an actual earthquake. If the magnitude and location of a unique earthquake can be relatively well defined as related to the site, that earthquake will be the design earthquake. If various magnitudes of earthquakes can be expected to occur at various distances from the site, it may be necessary to analyze the structure utilizing more than one earthquake.

Literature review and field investigations are made to determine the structural geology and seismic history of the region, area, and local site of each critical structure, as a basis to define the site seismicity. The size, frequency of occurrence, and approximate locations of earthquakes that can be expected to affect the site are determined and design earthquakes and related parameters developed.

A study of regional geologic maps is necessary to define general characteristics of geologic materials and their geologic history, as well as fault locations and characteristics. These data provide the basis for analyzing the seismic setting of an area in relation to the project features.

The seismic history is most desirably developed for an area on the basis of instrumental records supplemented by available historical records. When instrumental records are not available, seismic histories are developed on the basis of study and interpretation, by a qualified seismologist or geologist, of written accounts of historical earthquakes. These historical data can be converted to approximate equivalents of instrumental earthquake records.

The basic seismicity data are evaluated and a basement rock accelerogram is generated either from an existing record, or it is constructed based upon known dynamic parameters. This accelerogram is used directly as input for a computer-programmed dynamic stability analysis, or is used to develop ground motion response spectra.

2. Foundation Response Analysis

Response analysis relates probable ground or foundation level motions to the design earthquake. Whether a bedrock motion is amplified or attenuated at the surface depends upon the dynamic characteristics of the site, depth of alluvium, etc. Important parameters are natural periods of vibration and damping. These data are obtained through evaluation and integration of geophysical survey data, subsurface drilling information, field and laboratory testing data, and consideration of local geologic features. The ground motion response spectra are developed by combining computer techniques with geotechnical information and seismicity data.

The basement rock accelerogram, which is a signature of the design earthquake, represents motions in the basement rock; those motions are then propagated up through the foundation materials. Since soil and rock foundations do not always behave elastically during an earthquake, it is necessary to use finite element techniques and a computerized analysis to generate the displacement, velocity, and acceleration response spectra for the structure foundation.

Where structures are placed directly on foundations of basement rock, the accelerogram developed during the study is used directly for response analysis.

3. Geophysical Exploration

Geophysical exploration work, particularly seismic refraction surveys, is sometimes necessary to determine the velocities of shock waves and the dynamic moduli characteristics of the site foundation. Special ambient vibration and seismic refraction surveys are generally made on the surface; however, seismic refraction surveys may also be performed in holes drilled for foundation exploration. These programs are usually performed in conjunction with the geologic and subsurface exploration programs that normally are needed to determine foundation characteristics. In this way, the needed data may be developed in the most effective and economical manner.

Seismic refraction surveys are made to measure compression and shear wave velocities of the materials at the site. These data are analyzed to determine the dynamic moduli values and elastic properties needed for the earthquake analysis of foundation materials. Ambient vibration studies are made to establish low strain natural frequency and period of vibration characteristics of project foundations. The ambient vibration surveys may also provide characteristic mode shapes, frequencies, and damping factors for use in the earthquake analyses.

4. Laboratory Testing of Dynamic Response

When complex subsurface conditions are encountered at the site, laboratory investigations may be made to determine the seismic response characteristics of typical foundation materials, including "liquefaction" potential and control factors for analytical and design purposes.

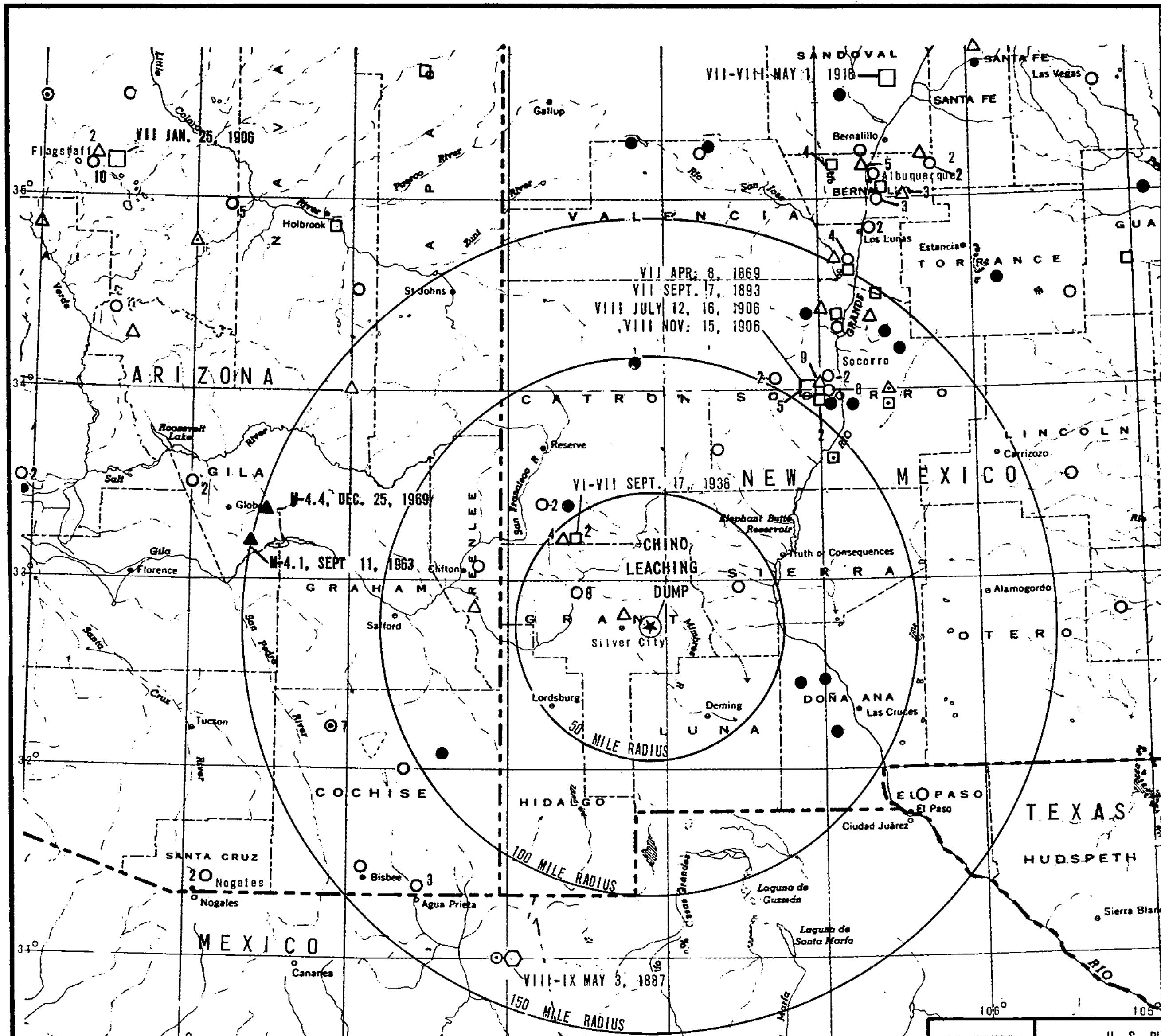
Programs of dynamic triaxial testing are implemented to simulate the effects of earthquakes on soils by superimposing cyclic loads on samples which have been either isotropically or anisotropically consolidated to selected static stress conditions. Dynamic response testing programs are developed on the basis of the geologic and subsurface investigation results combined with the results of standard laboratory testing of foundation and construction materials. Only materials representing major or critical elements of design are tested. Test results are used to establish the dynamic response characteristics needed for analytical and design purposes.

A limited earthquake engineering evaluation of the Magna tailings deposit was developed for this project following, in general, the procedure and the phases described above, and including a dynamic analysis of the deposit. The results of it are presented in Volume 3 of this report which covers the Magna site and laboratory investigation.

The locations of the three deposits investigated in detail are shown in relation to regional historical earthquake epicenters on Drawing Nos. IV-1, IV-2, and IV-3, and, in a more general way, on Drawing No. IV-4, which is a map of the United States depicting the larger historical earthquakes. From these maps, and the location map which locates all sites visited during our reconnaissance report (Drawing No. 1, Volume 5), it can be seen that many of the deposits lie in seismically active regions where earthquakes can and will occur. It is, therefore, important to consider the probability of seismically induced failure of existing deposits and, where applicable, to design future deposits to resist seismic ground shaking. Maps depicting location of epicenters aid in the determination of how seismically active a particular area is. Combining this knowledge with geologic and soils engineering considerations, mine and mill refuse deposits can be made reasonably resistant to earthquakes.

C. HYDROLOGIC CONSIDERATIONS

Hydrologic conditions play an important role in the siting of mine and mill refuse deposits, as well as in their operations and development. The regional meteorological conditions govern the magnitudes and frequencies of storms, precipitation, and snow depth. Together with topography, vegetative cover, geologic materials, and drainage characteristics, the meteorological conditions determine runoff, infiltration, and evapotranspiration. All these factors have to be considered when analyzing an existing refuse deposit or when designing a new structure.



BASE FROM MAP 2-A, UNITED STATES, SCALE: 1:2,500,000, U.S. GEOLOGICAL SURVEY, 1961 EDITION.

EXPLANATION

SYMBOL	INTENSITY* M.M
○	I-IV
△	V
□ (small)	VI
□ (large)	VII-VIII
⬡	IX-X

SYMBOL	MAGNITUDE**
●	2.0-3.9
▲	4.0-4.9
■	5.0-5.9
⬢	6.0-6.9

○-6 6 EPICENTERS

*INTENSITY SYMBOLS WITH CENTERED DOT DENOTE INSTRUMENTALLY LOCATED EPICENTERS.

**EARTHQUAKES WITH KNOWN MAGNITUDES WERE INSTRUMENTALLY LOCATED.

NOTE: THIS SEISMICITY MAP INCLUDES ALL KNOWN EARTHQUAKE EPICENTERS BOTH INSTRUMENTALLY AND NON-INSTRUMENTALLY LOCATED IN ARIZONA (1850-1969) AND NEW MEXICO (1868-1968).

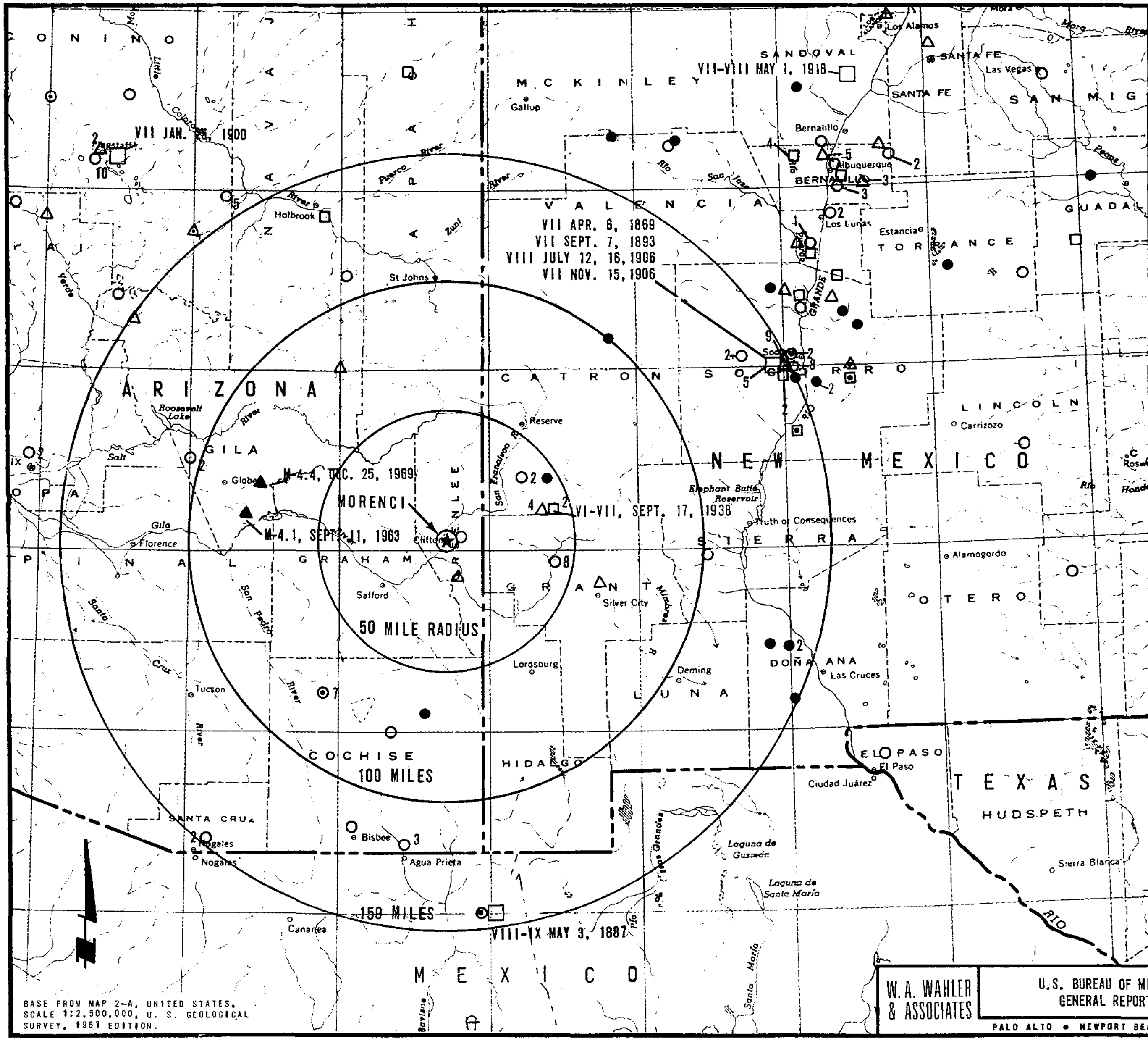
DATA SOURCES

1. HECK, N.H. AND EPPLEY, R.A., 1958, EARTHQUAKE HISTORY OF THE UNITED STATES-PART 1-CONTINENTAL UNITED STATES AND ALASKA (EXCLUSIVE OF CALIFORNIA AND WESTERN NEVADA): U.S. GEOD. SURVEY PUB. NO. 41-1.
2. U.S. DEPARTMENT OF COMMERCE, 1928-1969, UNITED STATES EARTHQUAKES, ANNUAL REPORT PUBLICATIONS: U.S. COAST AND GEODETIC SURVEY.
3. SANFORD, ALLAN R., 1965, AN INSTRUMENTAL STUDY OF NEW MEXICO EARTHQUAKES: N. MEX. INST. MIN. AND TECH., STATE BUR. MINES AND MINERAL RES., CIRC. 78.
4. SANFORD, ALLAN R. AND CASH, DANIEL J., 1964, AN INSTRUMENTAL STUDY OF NEW MEXICO EARTHQUAKES, JULY 1, 1964, THROUGH DEC.31, 1967: N. MEX. INST. MIN. AND TECH., STATE BUR. MINES AND MINERAL RES., CIRC. 102
5. SANFORD, ALLAN R. ET AL., 1972, SEISMICITY OF THE RIO GRANDE RIFT IN NEW MEXICO: N. MEX. INST. MIN. AND TECH., STATE BUR. MINES AND MINERAL RES., CIRC. 120.

SCALE
40 0 40 MILES

W.A. WAHLER & ASSOCIATES	U. S. BUREAU OF MINES GENERAL REPORT	SEISMICITY MAP CHINO LEACHING DUMP		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. IV-1

70



EXPLANATION

SYMBOL	INTENSITY* M.M	SYMBOL	MAGNITUDE**
○	I-IV	●	2.0-3.9
△	V	▲	4.0-4.9
□ (small)	VI	■	5.0-5.9
□	VII-VIII	⬢	6.0-6.9
⬡	IX-X		

6 EPICENTERS

*INTENSITY SYMBOLS WITH CENTERED DOT DENOTE INSTRUMENTALLY LOCATED EPICENTERS.

**EARTHQUAKES WITH KNOWN MAGNITUDES WERE INSTRUMENTALLY LOCATED.

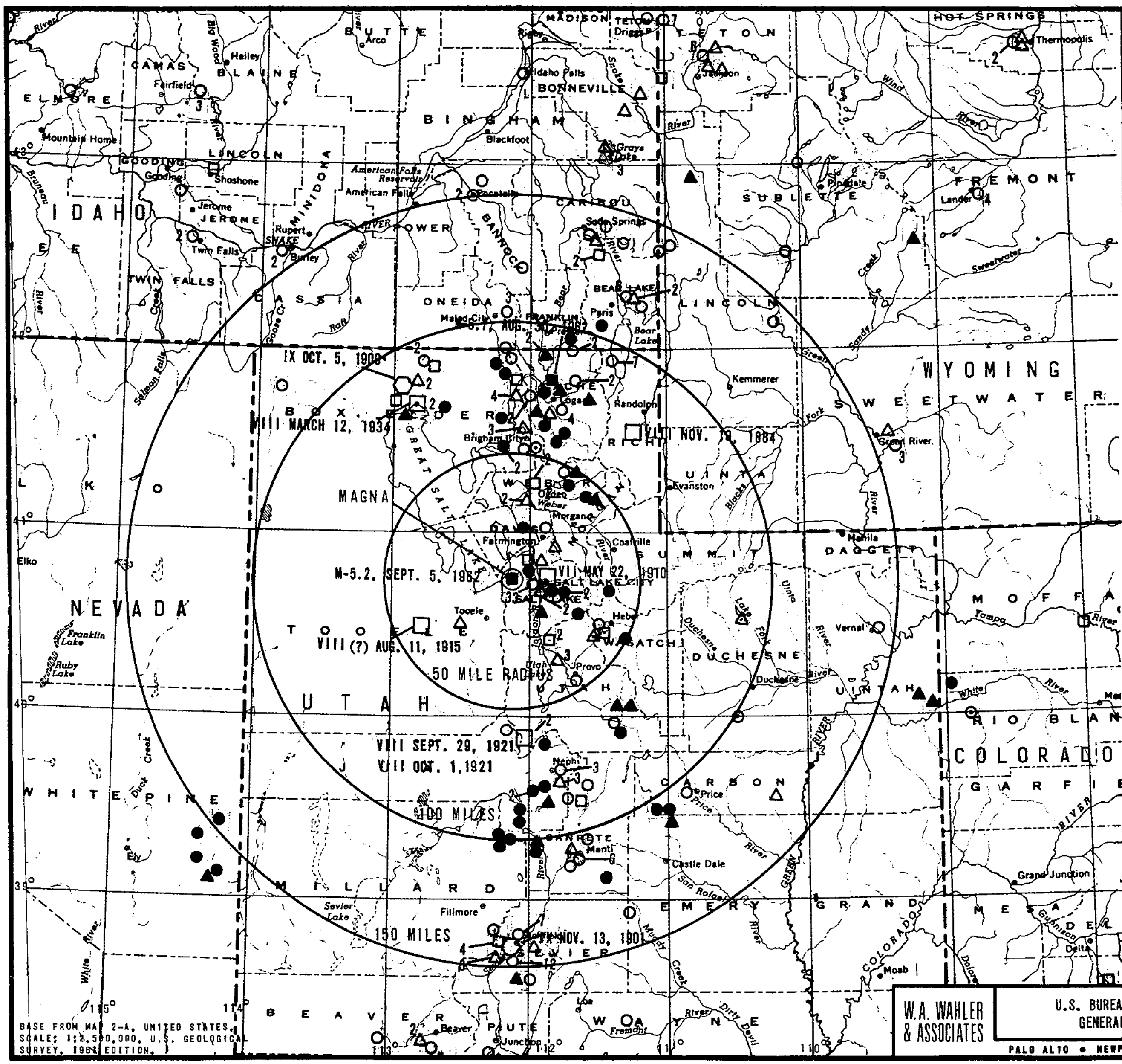
NOTE: THIS SEISMICITY MAP INCLUDES ALL KNOWN EARTHQUAKE EPICENTERS BOTH INSTRUMENTALLY AND NON-INSTRUMENTALLY LOCATED IN ARIZONA (1850-1969) AND NEW MEXICO (1868-1968).

DATA SOURCES

1. HECK, N. H. AND EPPLEY, R. A., 1958, EARTHQUAKE HISTORY OF THE UNITED STATES-PART 1-CONTINENTAL UNITED STATES AND ALASKA (EXCLUSIVE OF CALIFORNIA AND WESTERN NEVADA): U. S. COAST GEOD. SURVEY PUB. NO. 41-1.
2. U. S. DEPARTMENT OF COMMERCE, 1928-1969, UNITED STATES EARTHQUAKES, ANNUAL REPORT PUBLICATION: U. S. COAST AND GEODETIC SURVEY.
3. SANFORD, ALLAN R., 1965, AN INSTRUMENTAL STUDY OF NEW MEXICO EARTHQUAKES: N. MEX. INST. MIN. AND TECH., STATE BUR. MINES AND MINERAL RES., CIRC. 78.
4. SANFORD, ALLAN R. AND CASH, DANIEL J., 1964, AN INSTRUMENTAL STUDY OF NEW MEXICO EARTHQUAKES, JULY 1, 1964, THROUGH DEC.31, 1967: N. MEX. INST. MIN. AND TECH., STATE BUR. MINES AND MINERAL RES., CIRC. 102.
5. SANFORD, ALLAN R. ET AL., 1972, SEISMICITY OF THE RIO GRANDE RIFT IN NEW MEXICO: N. MEX. INST. MIN. AND TECH., STATE BUR. MINES AND MINERAL RES., CIRC. 120.

SCALE
40 0 40 FEET

W. A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	SEISMICITY MAP MORENCI TAILINGS DAMS		
PALO ALTO • NEWPORT BEACH • CALIF.		PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. IV-2



KEY

SYMBOL	INTENSITY* M.M	SYMBOL	MAGNITUDE**
○	I-IV	●	2.0-3.9
△	V	▲	4.0-4.9
□	VI	■	5.0-5.9
☐	VII-VIII	⬢	6.0-6.9
⬡	IX-X		

○—6 6 EPICENTERS

*INTENSITY SYMBOLS WITH CENTERED DOT DENOTE INSTRUMENTALLY LOCATED EPICENTERS.

**EARTHQUAKES WITH KNOWN MAGNITUDES WERE INSTRUMENTALLY LOCATED.

NOTE: THIS SEISMICITY MAP INCLUDES ALL KNOWN EARTHQUAKE EPICENTERS BOTH INSTRUMENTALLY AND NON-INSTRUMENTALLY LOCATED IN UTAH (1850-1970), IDAHO (1879-1969), WYOMING (1894-1969), COLORADO (1870-1969) AND EASTERN NEVADA (1915-1969).

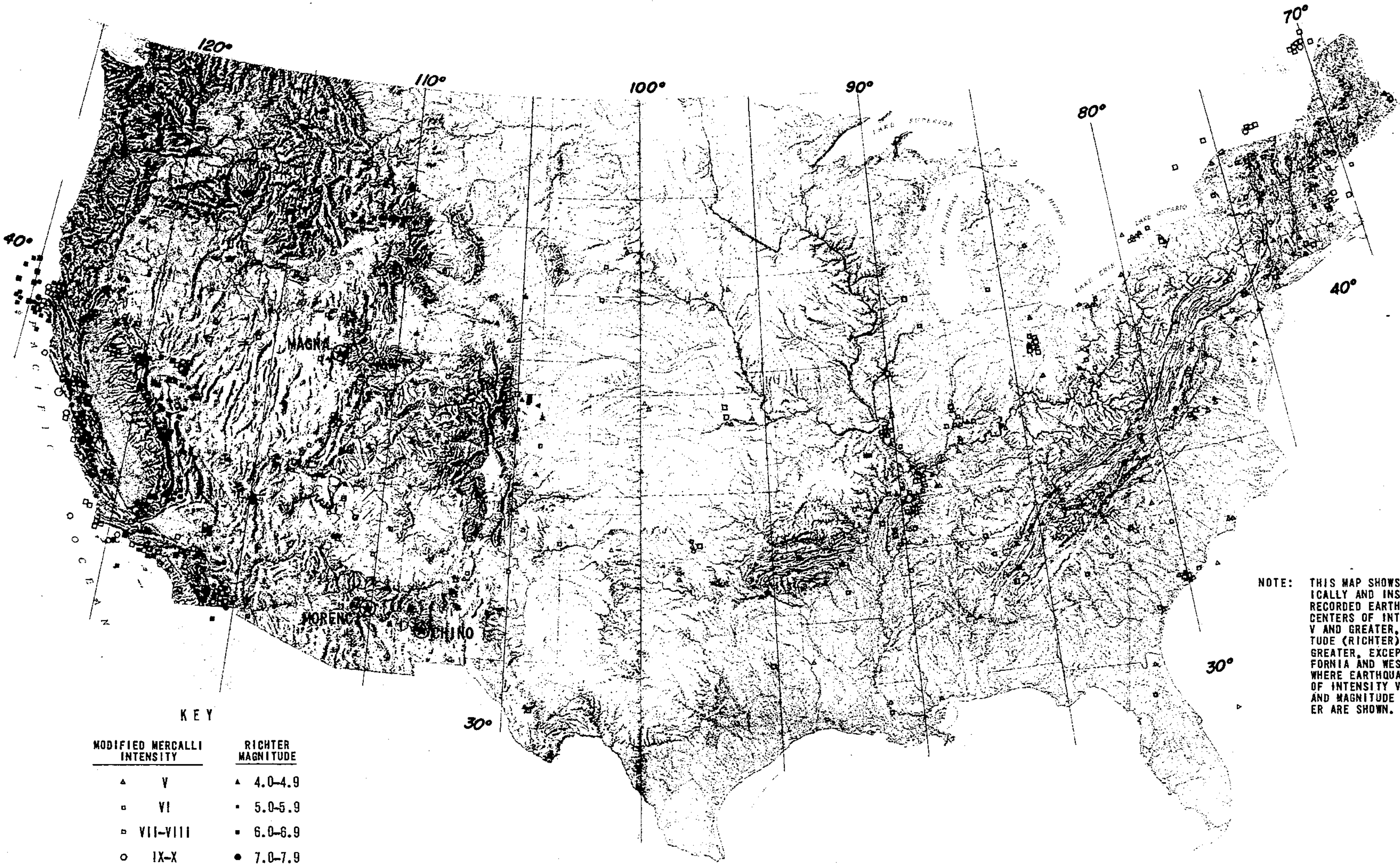
DATA SOURCES

1. COOK, KENNETH L., 1971, EARTHQUAKES ALONG THE WASATCH FRONT, UTAH-THE RECORD AND THE OUTLOOK: FROM ENVIRONMENTAL GEOLOGY OF THE WASATCH FRONT, 1971: UTAH GEOL. ASSOC. PUBL. 1, SALT LAKE CITY, UTAH.
2. HADSELL, F.A., 1968, HISTORY OF EARTHQUAKE ACTIVITY IN COLORADO: COLORADO SCHOOL OF MINES QUART., V. 63, NO. 1, PP. 57-72.
3. HECK, N.H. AND EPPLEY, R.A., 1958, EARTHQUAKE HISTORY OF THE UNITED STATES-PART 1-CONTINENTAL UNITED STATES AND ALASKA (EXCLUSIVE OF CALIFORNIA AND WESTERN NEVADA): U.S. GEOD. SURVEY PUB. NO. 41-2.
4. TOWNLEY, SIDNEY D. AND ALLEN, MAXWELL, M., 1939, DESCRIPTIVE CATALOG OF EARTHQUAKES OF THE PACIFIC COAST OF THE UNITED STATES: BULL. SEISMOL. SOC. AM., VOL. 29, NO. 1.
5. U.S. DEPARTMENT OF COMMERCE, 1923-1969, UNITED STATES EARTHQUAKES, ANNUAL REPORT PUBLICATION, U.S. COAST AND GEODETIC SURVEY.
6. WILLIAMS, J. STEWART AND TAPPER, MARY L., 1953, EARTHQUAKE HISTORY OF UTAH, 1850-1949: BULL. SEISMOL. SOC. AM., VO. 43, NO. 3.

SCALE
40 0 40 MILES

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	SEISMICITY MAP MAGNA TAILINGS DAM		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. IV-3

73



KEY

MODIFIED MERCALLI INTENSITY	RICHTER MAGNITUDE
▲ V	▲ 4.0-4.9
▫ VI	▪ 5.0-5.9
▫ VII-VIII	■ 6.0-6.9
○ IX-X	● 7.0-7.9
○ XI-XII	

NOTE: THIS MAP SHOWS ALL HISTORICALLY AND INSTRUMENTALLY RECORDED EARTHQUAKE EPICENTERS OF INTENSITY (M.M.) V AND GREATER, AND MAGNITUDE (RICHTER) 4.0 AND GREATER, EXCEPT FOR CALIFORNIA AND WESTERN NEVADA WHERE EARTHQUAKE EPICENTERS OF INTENSITY VI AND GREATER AND MAGNITUDE 5.0 AND GREATER ARE SHOWN.

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	SEISMICITY OF THE UNITED STATES		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. IV-4

Precipitation affects tailings dams by eroding the downstream face with running water either from rain or from melting snow. Extreme cold temperatures may freeze the water contained in the tailings and produce instability by heaving or preventing drainage from the downstream face of the structure. When ice contained in a structure melts, it may also produce instability by collapse, erosion, or the initiation of piping.

Deposits blocking drainages may require provisions for spillways to handle flood waters. Factors to carefully evaluate when selecting a design flood for analysis are the flood plain channel characteristics, the extent of development and facilities downstream of the structure, and the consequences of a failure.

The effects of infiltration of tailings water into the natural ground have to be evaluated, since it is possible that undesirable degradation of ground-water quality may occur. The natural chemical quality of existing ground and surface waters should be established prior to any new refuse deposit placement. This will permit a better recognition of any changes in water quality and could be helpful in taking preventive measures.

Deposits that are used to store water have the greatest potential for infiltrating water into the natural ground-water basins. One of the mitigating measures for this infiltration problem would be to provide a relatively impervious blanket over the disposal area before placement of refuse materials. This impervious blanket could possibly be built by placing tailing slimes directly over the surface of the ground, but with proper allowance made for the stability of any retaining structure. A compacted blanket of impervious soil could also be used. More research is needed in this area, to establish the seepage characteristics of such a membrane.

Many existing tailings deposits have features that would make them vulnerable to failure under extreme weather conditions. The major deficiency seems to be the lack of water control or diversion facilities to handle storm runoff in deposits of the cross-valley type.

CHAPTER V

MATERIALS CHARACTERISTICS AND PROPERTIES

CHAPTER V

MATERIALS CHARACTERISTICS AND PROPERTIES

A. GENERAL

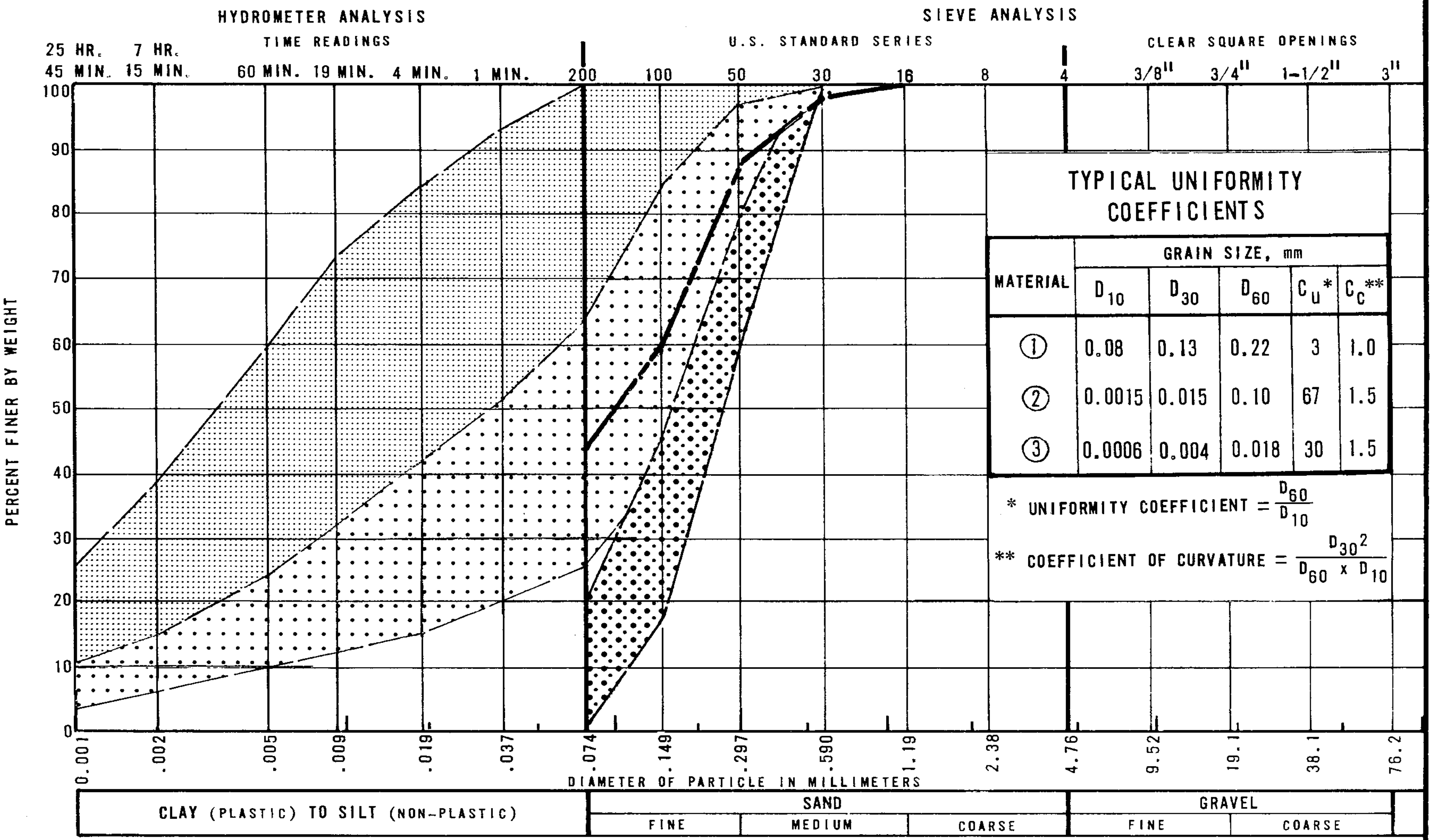
The physical properties presented herein were compiled from laboratory tests performed by W. A. Wahler and Associates in conjunction with the research work under this program and with investigations for other mining companies. Other references were reviewed and, where available, appropriate data have been included.

B. PHYSICAL PROPERTIES OF COPPER TAILINGS

1. Index Properties

a. Grain-Size Distribution - The gradation results for over 200 samples of copper tailings materials are presented on Drawing V-1 in the form of a range of all samples tested. As shown on that drawing, average tailings material as it leaves the mill contains approximately 45 percent by weight of material finer than the No. 200 sieve. Depending on the method of handling, discharge and location within the pond, the final grain-size distribution can vary significantly. If the materials are cycloned, the percentage of fines (minus No. 200 fraction) can be cut approximately in half. Generally, the use of single-stage cycloning on the berm cannot reduce the amount of fines to much less than 10 to 15 percent. Two-stage cycloning, where the underflow (coarse fraction) of the initial cyclone is fed to a second cyclone, is apparently necessary to reduce the fines to less than 5 percent.

The intermediate band of gradation results shown on Drawing No. V-1 is indicative of the average gradation distribution to be expected using peripheral discharge methods. During the course of the present research program it was determined that a very definite classification of the tailings material occurs when the peripheral discharge method is used. A special study, performed at the Morenci site, indicated that the percentage of fines increases at a rate of about 0.1 percent per foot into the pond area such that at a distance of about 500 to 600 feet from the berm (point of discharge) the maximum amount of separation due to natural sedimentation has been accomplished. At the Morenci site, samples were taken at 50-foot intervals away from the berm into the pond area. The gradation results indicated that near the berms the material had between 35 and 40 percent fines or slightly less than the material leaving the tailings thickener. At a distance of about 450 feet from the point of discharge, the portion of fines had increased to about 80 percent. The average gradation of the Magna tailings, obtained from a point about 1.5 miles from the discharge point, had an average of 89 percent fines. Obviously, there are exceptions to the average results discussed above.



TYPICAL UNIFORMITY COEFFICIENTS

MATERIAL	GRAIN SIZE, mm D_{10}	D_{30}	D_{60}	C_u*	C_c**
①	0.08	0.13	0.22	3	1.0
②	0.0015	0.015	0.10	67	1.5
③	0.0006	0.004	0.018	30	1.5

* UNIFORMITY COEFFICIENT $= \frac{D_{60}}{D_{10}}$

** COEFFICIENT OF CURVATURE $= \frac{D_{30}^2}{D_{60} \times D_{10}}$

KEY

- (dashed heavy line) TAILINGS MATERIAL BEFORE ANY PROCESSING OR DISTRIBUTION.
- ① EXPECTED RANGE OF GRADATION FOR COARSE FRACTION AFTER CYCLONING.
- ② TYPICAL RANGE OF GRADATION NEAR EXTERIOR SHELL USING PERIPHERAL DISCHARGE.
- ③ TYPICAL RANGE OF GRADATION OF CYCLONE OVERFLOW OR TAILINGS POND AREA.

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	GRADATION SUMMARY COPPER TAILINGS MATERIAL		
	PALO ALTO • NEWPORT BEACH • CALIF	PROJECT NO 0620	DATE JUNE 1974	DRAWING NO V-1

For example, if a peripheral method of discharge incorporates a lower percent solids of tailings for distribution, say 30-35 percent instead of 45-50 percent, then one would expect a better classification (lower percentage of fines) of the materials near the point of discharge because of the larger ratio of volume of water to volume of solids.

The gradation characteristics discussed above represent current mill processing techniques. Most mining companies indicate, however, that new developments in the flotation cycle of the milling process will require a finer grind of the crushed ore for efficient copper recovery. Although specific gradation results are not yet available for this new practice, it may be stated with some degree of assurance that a change toward a finer grain size of the tailings will adversely influence the engineering properties of density, permeability, and shear strength, especially for those plants currently using peripheral discharge methods.

b. Atterberg Limits - The majority of tailings material is nonplastic. Some of the finer-grained samples tested did exhibit some plasticity; for example, 9 of the 33 samples tested from the Morenci site exhibited silt characteristics with an average Liquid Limit of 24 percent (ranging from 21 to 26 percent), and an average Plastic Limit of 18 percent (ranging from 16 to 19 percent). The Atterberg Limits obtained from the Magna site were substantially higher than those from the Morenci site due to the higher (89 versus 51) percentage of material finer than the No. 200 sieve. For the 26 tests performed for the Magna materials, the average Liquid Limit was 40 percent (ranging from 30 to 56), and the average Plastic Limit was 27 (ranging from 24 to 33).

c. Specific Gravity- Specific gravity results for the copper tailings material have a rather narrow range, varying from 2.64 to 2.78, with an average value of 2.72 for the 55 samples tested. Specific gravity values higher than those quoted above can be expected on samples from certain portions of an open pit where, for example, seams of magnetite or other heavy minerals are encountered. The range in values referenced above is broken down in more detail in Table V-1.

TABLE V-1

SPECIFIC GRAVITY RESULTS
COPPER TAILINGS MATERIAL

Number of Samples	Range of Specific Gravity
6	2.64 - 2.679
25	2.68 - 2.719
20	2.72 - 2.759
4	2.76 - 2.78

Average Specific Gravity Equals 2.72

d. Mineralogical Composition and Soil Structure - Since tailings are essentially crushed rock, their mineralogical composition generally corresponds to that of the parent material. Tailings consist mainly of various mixtures of quartz, feldspars, ferromagnesian minerals, carbonates, some oxides and minor amounts of other minerals. Depending upon factors such as acidity, alkalinity, and quantities of tailings water, weather conditions, age of the deposit, etc., the constituent minerals may be chemically altered and decomposed to clay, kaolin, and other alteration minerals.

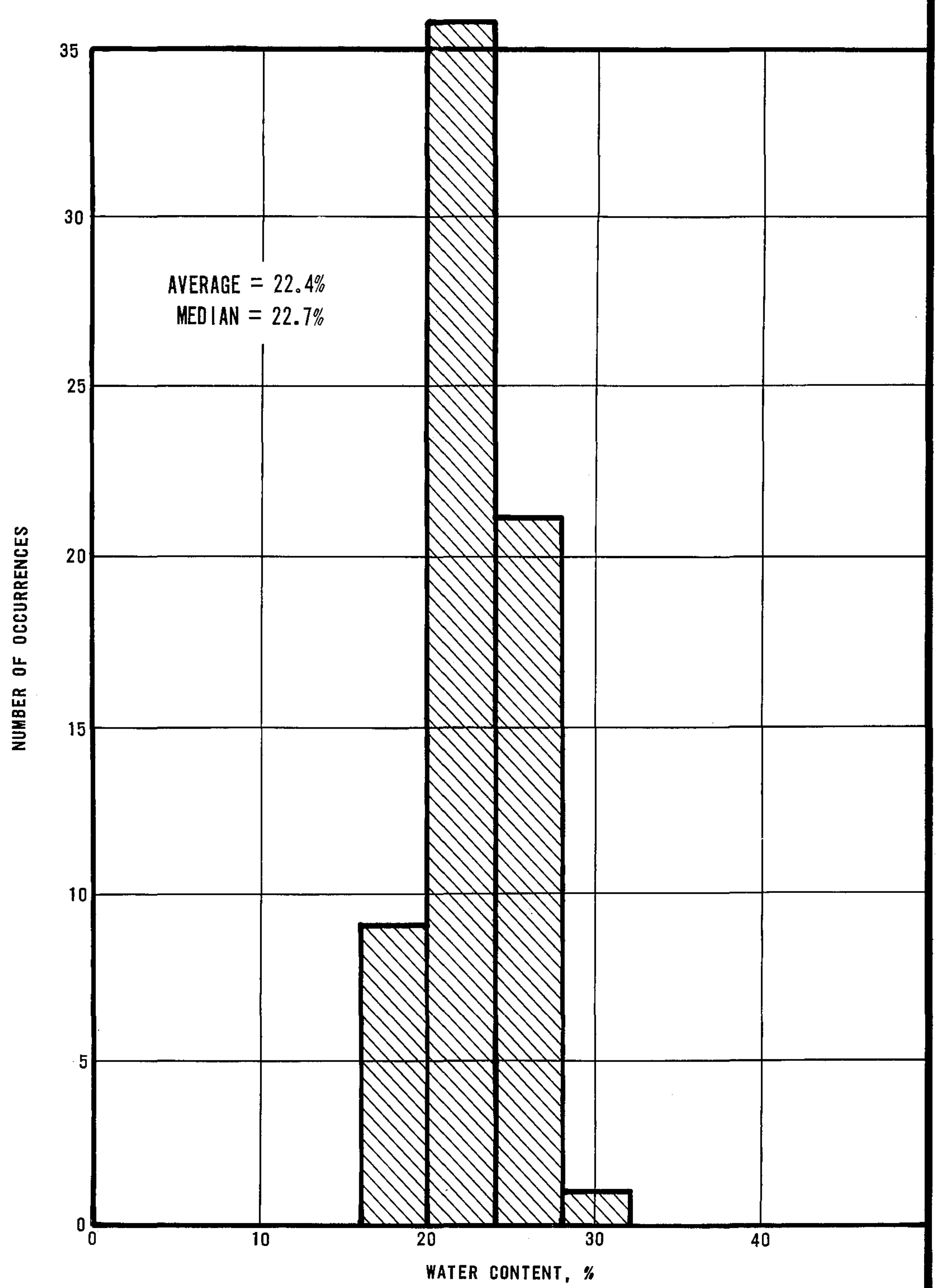
The fact that tailings are the byproduct of crushed rock also provides insight to the resulting soil structure of the material when deposited. Individual particles usually are very angular, thus resulting in the material having a higher shear strength than average soils based on effective grain-to-grain contact when the material is consolidated.

2. Engineering Properties

a. Natural Water Content and Dry Density - The natural water content and dry density of copper tailings material depends directly on the method of disposal used and the location within the tailings pond. Results for in-place water content and dry density tests performed on samples from the Morenci and Magna sites are presented on Drawings V-2 through V-5. These data were obtained from both field density tests and measurements obtained on undisturbed samples in the laboratory.

The in-place densities of a naturally sedimented, fine-grained material like tailings usually exhibit a general increase with depth as a result of consolidation caused by the increasing overburden pressure with depth. Unlike a naturally sedimented process occurring under water, however, the depositional process at most tailings dams is intermittent, which creates density variations within each lift. The reason for the occurrence of these variations is an accelerated densification of the surface and near-surface materials caused by evaporation and drying after a construction cycle has been completed. As water is drawn to the surface during the evaporation process, significant tensile forces are generated within the water menisci of the pore spaces, thus resulting in the densification of the overall mass. Resulting volume changes (increase in density) are greatest near the surface and decrease with depth. The outward, or visible, signs of this form of densification, in the form of tension cracks, were noticed over the entire surface area of nonactive ponds for most sites visited.

The test results for 62 Morenci samples are presented on Drawings V-2 and V-3 in the form of a frequency distribution for water content and dry density, respectively. These results indicate that the average in-place dry density of the tailings material is 101.1 lb/cu ft (pcf) (1.620 gm/cc), and the average water content is 22.4 percent. Similar results obtained from Magna samples, which are presented on Drawings V-4 and V-5,



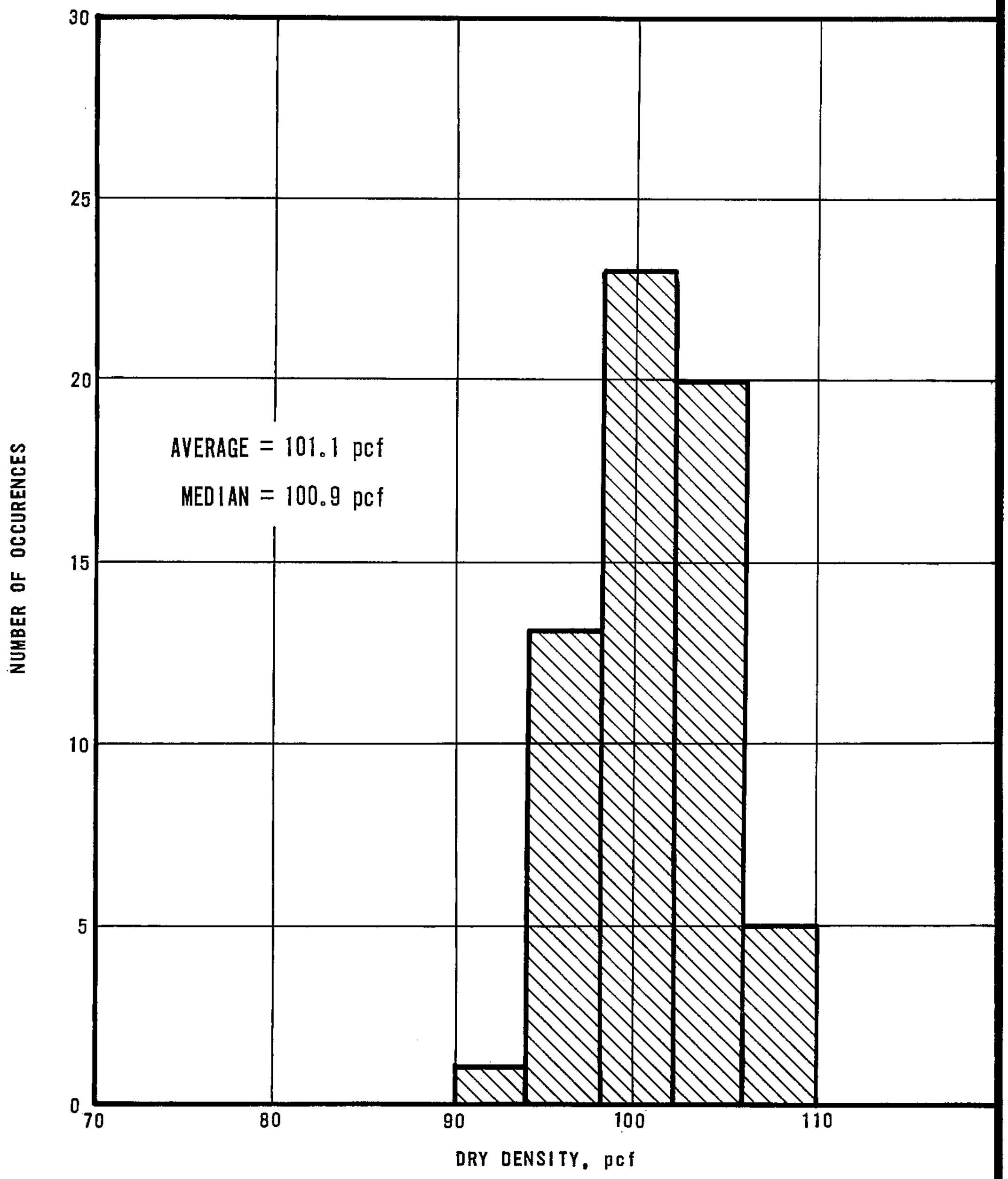
NOTES: (1) THE DATA SHOWN HEREON, WHICH ARE PRESENTED IN ORIGINAL FORM ON TABLE B-1 OF VOLUME 2, REPRESENTS WATER CONTENTS OF SELECTED EMBANKMENT MATERIALS AS DETERMINED FROM UNDISTURBED DRILL HOLE SAMPLES.

(2) A STATISTICAL EVALUATION OF THIS DATA WAS NOT PERFORMED BECAUSE THE SAMPLE SELECTION PROCESS COULD PRECLUDE A RANDOM VARIATION OF THE SAMPLED DATA.

(3) NOT INCLUDED IN THE FREQUENCY DISTRIBUTION ARE THE FIELD DENSITY TEST RESULTS AND SEVERAL OTHER NEAR SURFACE SAMPLES.

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	WATER CONTENT FREQUENCY DISTRIBUTION MORENCI TAILINGS DAM		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO.	DATE	DRAWING NO.
		0620	JUNE 1974	V-2

81



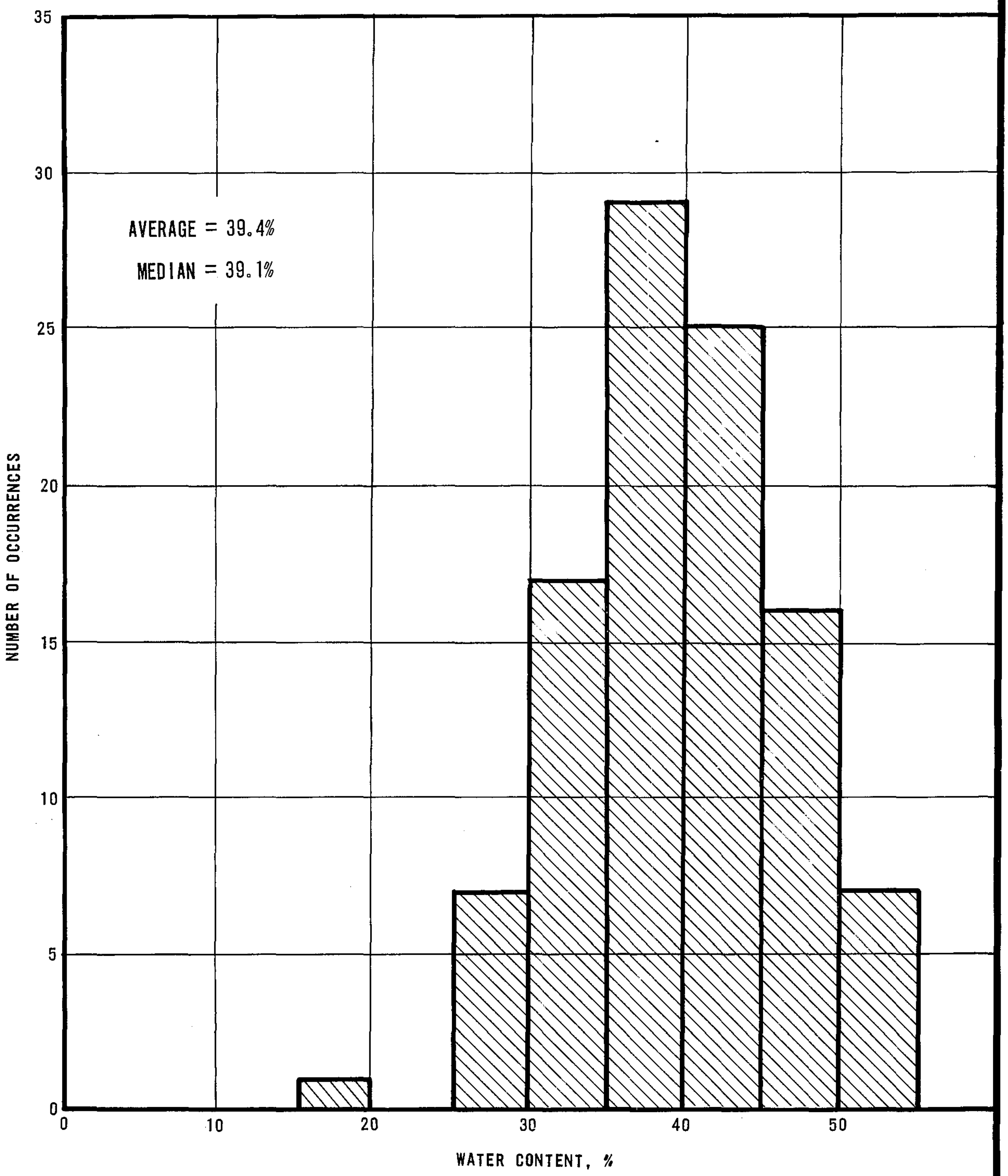
NOTES: (1) THE DATA SHOWN HEREON, WHICH ARE PRESENTED IN ORIGINAL FORM ON TABLE B-1 OF VOLUME 2, REPRESENT DRY DENSITIES OF SELECTED EMBANKMENT MATERIALS AS DETERMINED FROM UNDISTURBED DRILL HOLE SAMPLES.

(2) A STATISTICAL EVALUATION OF THIS DATA WAS NOT PERFORMED BECAUSE THE SAMPLE SELECTION PROCESS COULD PRECLUDE A RANDOM VARIATION OF THE SAMPLED DATA.

(3) NOT INCLUDED IN THE FREQUENCY DISTRIBUTION ARE THE FIELD DENSITY TEST RESULTS.

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	DRY DENSITY FREQUENCY DISTRIBUTION MORENCI TAILINGS DAM		
		PROJECT NO.	DATE	DRAWING NO.
	PALO ALTO • NEWPORT BEACH • CALIF.	0620	JUNE 1974	V-3

82

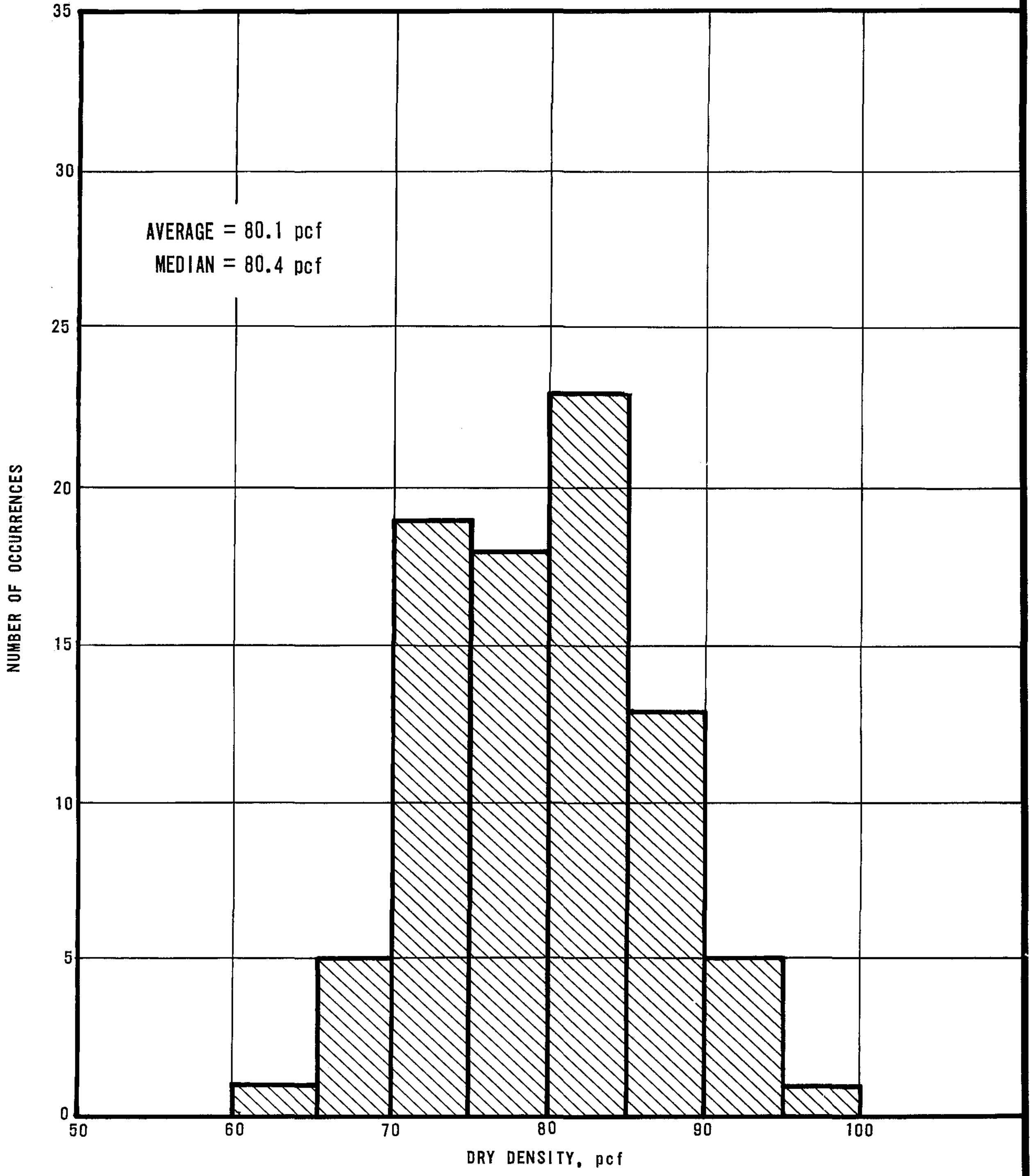


NOTES: (1) THE DATA SHOWN HEREON, WHICH ARE PRESENTED IN ORIGINAL FORM ON TABLE B-1 OF VOLUME 3, REPRESENT DRY DENSITIES OF SELECTED EMBANKMENT MATERIALS AS DETERMINED FROM UNDISTURBED DRILL HOLE SAMPLES.

(2) A STATISTICAL EVALUATION OF THIS DATA WAS NOT PERFORMED BECAUSE THE SAMPLE SELECTION PROCESS COULD PRECLUDE A RANDOM VARIATION OF THE SAMPLE DATA.

(3) NOT INCLUDED IN THE FREQUENCY DISTRIBUTION ARE THE FIELD DENSITY TEST RESULTS.

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	WATER CONTENT FREQUENCY DISTRIBUTION MAGNA TAILINGS DAM		
		PROJECT NO.	DATE	DRAWING NO.
	PALO ALTO • NEWPORT BEACH • CALIF.	0620	JUNE 1974	V-4



NOTES: (1) THE DATA SHOWN HEREON, WHICH ARE PRESENTED IN ORIGINAL FORM ON TABLE B-1 OF VOLUME 3, REPRESENT DRY DENSITIES OF SELECTED EMBANKMENT MATERIALS AS DETERMINED FROM UNDISTURBED DRILL HOLE SAMPLES.

(2) A STATISTICAL EVALUATION OF THIS DATA WAS NOT PERFORMED BECAUSE THE SAMPLE SELECTION PROCESS COULD PRECLUDE A RANDOM VARIATION OF THE SAMPLED DATA.

(3) NOT INCLUDED IN THE FREQUENCY DISTRIBUTION ARE THE FIELD DENSITY TEST RESULTS.

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	DRY DENSITY FREQUENCY DISTRIBUTION MAGNA TAILINGS DAM		
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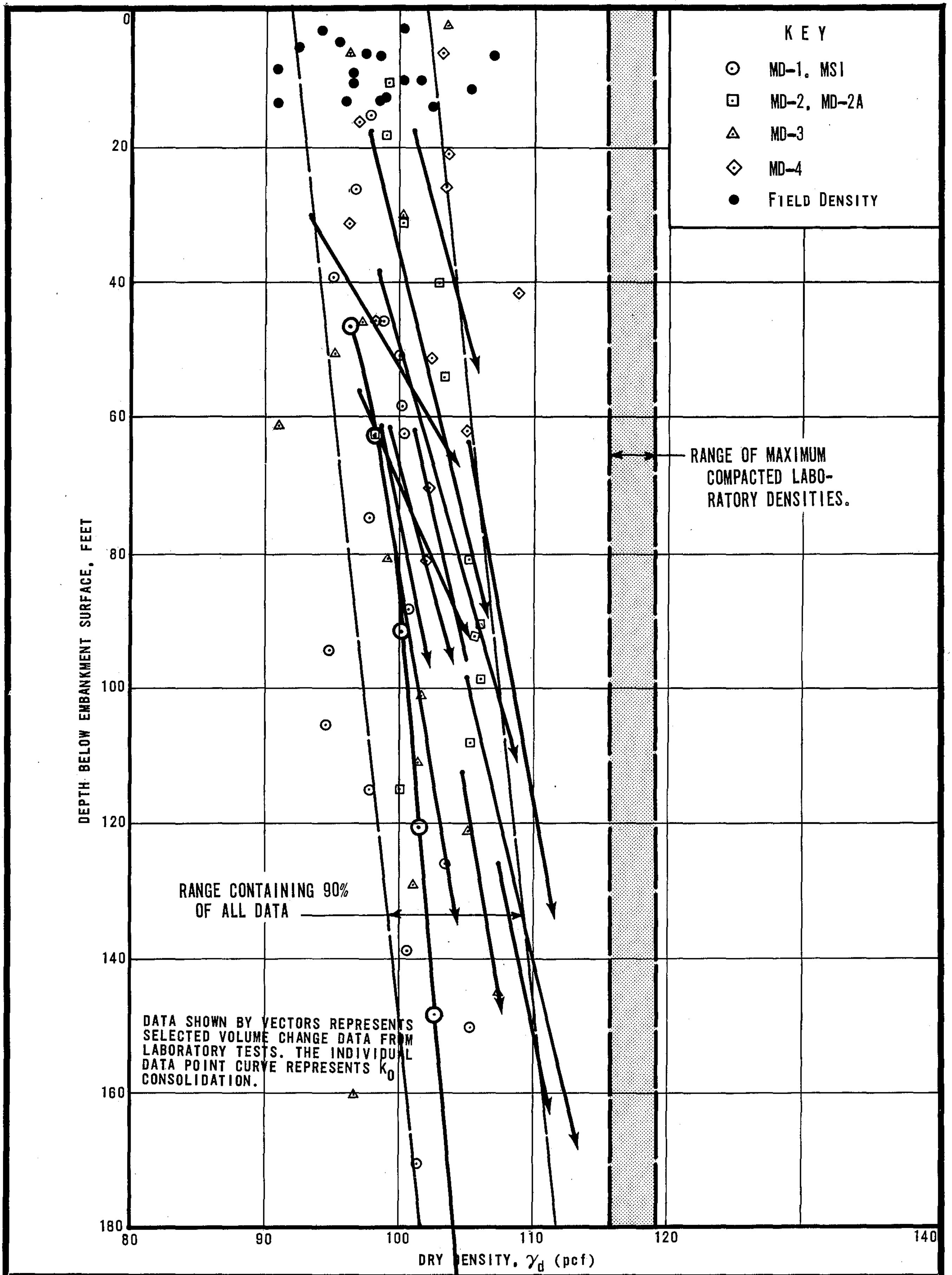
indicate that the average in-place dry density of the tailings material is 80.1 pcf (1.284 gm/cc), and the average water content is 39.4 percent. The results presented above are average values from all samples. The significant difference in in-place dry densities between the two sites is directly a result of the average gradation characteristics at the Magna site being finer grained than at the Morenci site as discussed in the previous section. The average porosity, defined as the ratio of volume of voids to total volume, is equal to 40.4 percent for the Morenci materials and 52.8 percent for the Magna materials.

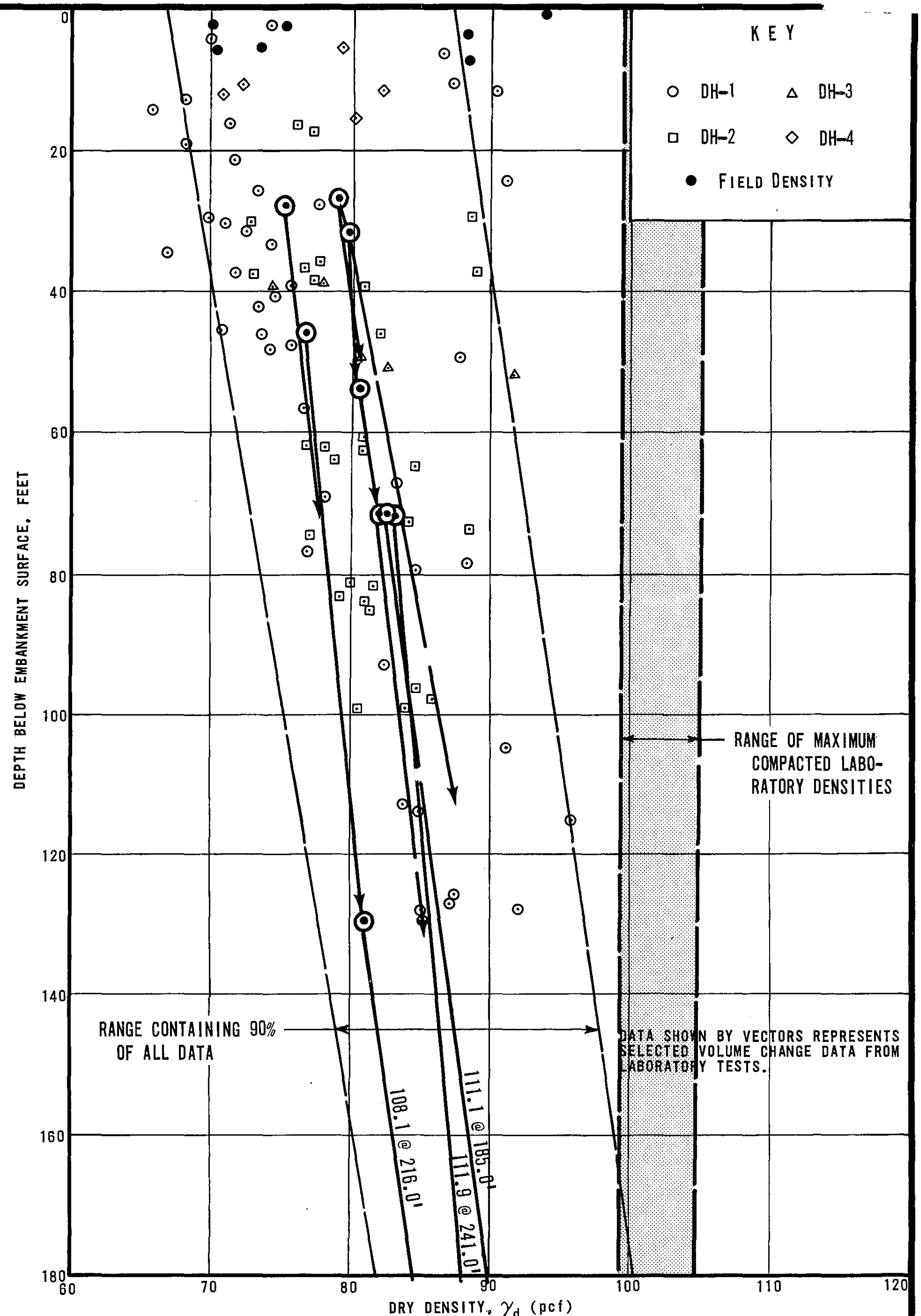
Individual dry density test results, as a function of depth, are presented on Drawings V-6 and V-7 for the Morenci and Magna sites, respectively. As shown on these two drawings, the value of dry density increases at a rate of about 4 to 6 pcf per 100 feet (0.064 to 0.096 gm/cc per 30.5 m) of depth for both sites. Also presented on each drawing are the initial and final dry density results observed from triaxial compression. The vector lines represent the increase in dry density resulting from an applied isotropic or anisotropic consolidation pressure which, for this presentation, has been converted to an equivalent overburden pressure or depth below embankment surface. As shown on the referenced drawings, the indicated 4 to 6 pcf increase in dry density per 100 feet of depth can be observed from the indicated data; however, the test results show that the variability of test data within any depth range is greater than any predictable trend would indicate.

b. Compaction Characteristics - A total of 9 compaction tests were performed on typical tailings material in accordance with ASTM D-1557-70 modified to 20,000 ft-lb/cu.ft. compactive energy. The results, shown on Drawing No. V-8, indicate that the maximum compacted laboratory density for tailings from the Morenci site varied from about 115 to 119 pcf (1.843 to 1.907 gm/cc) whereas the much finer-grained material from Magna varied from 98 to 102 pcf (1.571 to 1.635 gm/cc). As discussed previously in this chapter, the maximum density for any material with more than about 12 percent fines will usually occur using the impact compaction method as opposed to the vibratory method (ASTM D-2049). The reason is that with a higher percentage of fines the water acts as a lubricant resulting in a more compact material. W. A. Wahler and Associates has performed several vibratory density tests on cyclone underflow tailings having less than 10 percent fines and these results indicate a maximum density of 103 to 107 pcf (1.651 to 1.715 gm/cc) is obtainable for tailings material with a similar specific gravity to those of Morenci and Magna. These results are representative for uniformly graded tailings materials with a D_{10} = 0.09 mm, D_{30} = 0.17 mm, and D_{60} = 0.28 mm.

The range in maximum compacted laboratory dry densities referenced above has been plotted on Drawings V-6 and V-7 for comparison with in-place field density results. From these results, the relative compaction (not to be confused with relative density) of the material can be determined by computing the ratio of in-place field dry density to the maximum



W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	DRY DENSITY VARIATION VS. DEPTH MORENCI TAILINGS DAM		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. V-6



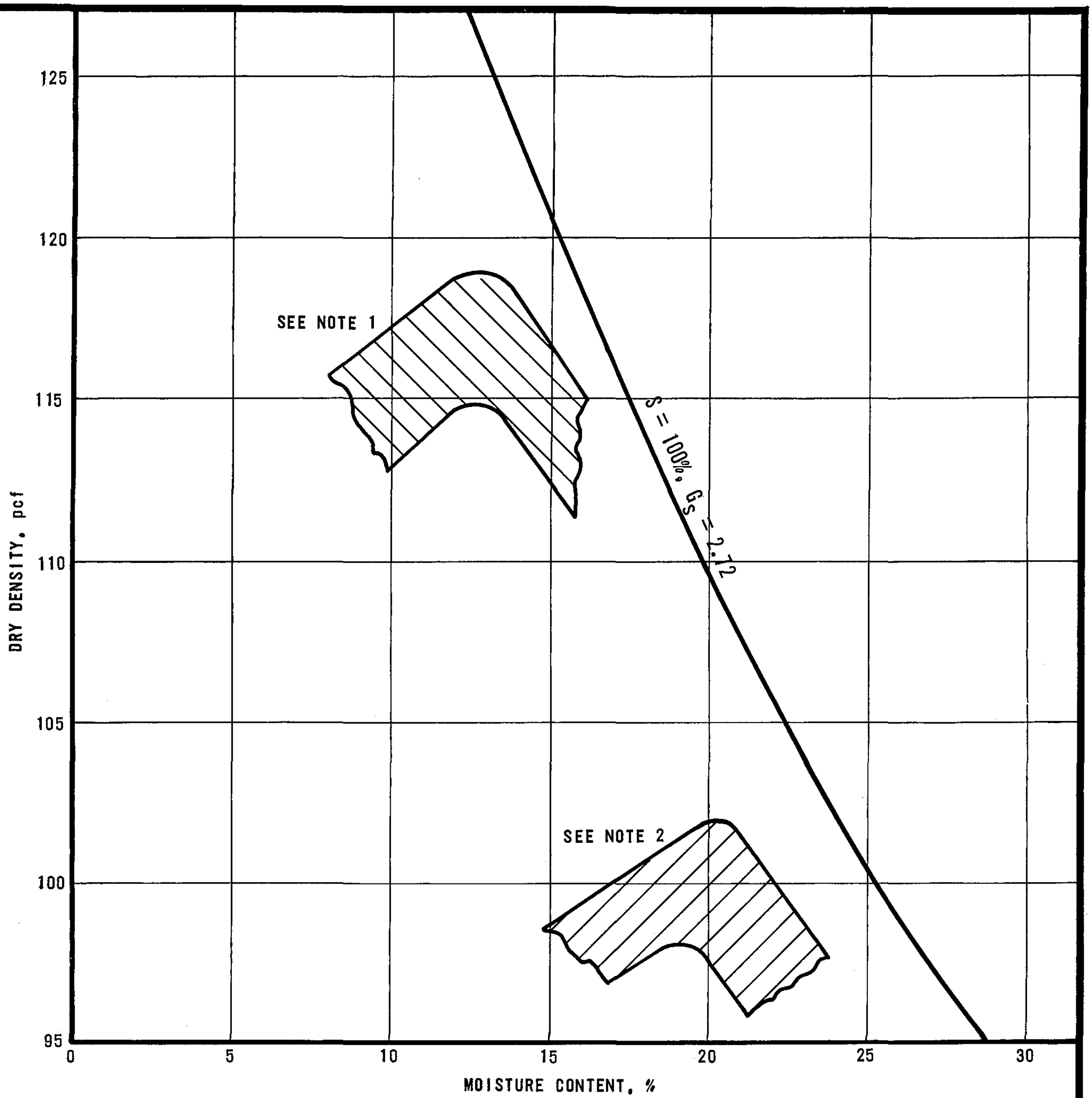
W.A. WAHLER & ASSOCIATES

U.S. BUREAU OF MINES GENERAL REPORT

PALO ALTO • NEWPORT BEACH • CALIF.

DRY DENSITY VARIATION VS. DEPTH
MAGNA TAILINGS DAM

PROJECT NO.	DATE	DRAWING NO.
0620	JUNE 1974	V-7



NOTES:

1. RANGE OF COMPACTION TEST RESULTS FOR 4 TESTS PERFORMED ON TAILINGS FROM MORENCI SITE. THE AVERAGE PERCENT PASSING NO. 200 SIEVE IS EQUAL TO 42 PERCENT.
2. RANGE OF COMPACTION TEST RESULTS FOR 5 TESTS PERFORMED ON TAILINGS FROM MAGNA SITE. THE AVERAGE PERCENT PASSING NO. 200 SIEVE IS EQUAL TO 89 PERCENT.
3. ALL COMPACTION TESTS WERE PERFORMED IN ACCORDANCE WITH ASTM D1557-70 MODIFIED TO 20,000 ft-lb/ft^3 COMPACTIVE ENERGY BY REDUCING THE NUMBER OF LAYERS TO 3 AND THE NUMBER OF BLOWS PER LAYER OF A 10 lb HAMMER TO 15.

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	COPPER TAILINGS COMPACTION CHARACTERISTICS		
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compacted laboratory dry density. The average relative compaction varied from 83 percent near the surface, to 88 percent at a depth of 100 feet for the Morenci site, and from 76 to 82 percent over the same depth range for the Magna site. The low relative compaction values referenced above are considered typical for most sites using peripheral discharge methods.

c. Permeability - The permeability characteristics of copper tailings material presented herein have been evaluated in the laboratory and, therefore, represent values of the coefficient of permeability only in the vertical direction of flow. The coefficient of permeability in the horizontal direction of flow within a tailings dam could be significantly higher than those presented due to density and/or materials variations (lenses) on a limited, but continuous, horizontal plane. The permeability test results for various copper tailings material containing between 3 and 90 percent fines are shown on Drawing No. V-9 in the form of coefficient of permeability vs dry density. As shown on Drawing No. V-9, the coefficient of permeability exhibits a range of values between 1×10^{-6} cm/sec (1 ft/yr) and 5×10^{-3} cm/sec (5200 ft/yr) depending on the amount of fines contained in the tailings. Also shown on Drawing No. V-9 are test results from undisturbed samples from both the Magna and Morenci sites. These results appear consistent with the laboratory fabricated samples when considering the "average" amount of fines contained in the field samples (e.g. 50 percent for Morenci samples and 90 percent for Magna samples).

Because the coefficient of permeability, or more precisely the difference in permeability for the various materials involved, has a direct influence on the location of the phreatic surface within a dam, it is important to note that the coefficient of permeability for the Morenci and Magna materials, which cover an average range of gradation for sites using single or multiple point peripheral discharge methods, did not show an appreciable difference. The common assumption that permeability of materials using peripheral discharge methods increases towards the exterior face of the dam was not clearly demonstrated for those samples tested. In fact, the research results indicate that cycloning is necessary in order to significantly increase the permeability characteristics of tailings materials. Controlling the location of the phreatic surface within a tailings dam built by peripheral discharge methods, therefore, would seem to be completely dependent on the location of the free water surface in the pond and the efficiency of the decant system in removing free water from a ponded area. Also, if the pond area is allowed to desiccate, a perched or trapped water surface may develop.

d. Compressibility - The consolidation characteristics of the tailings material were evaluated from laboratory tests and a field monitoring program. Consolidation data for saturated, isotropically consolidated triaxial tests, as well as one saturated, anisotropically consolidated triaxial sample, are presented on Drawing V-10 in the form of volume change versus effective major principal stress. The average consolidation parameters determined from these test results are summarized in Table V-2.

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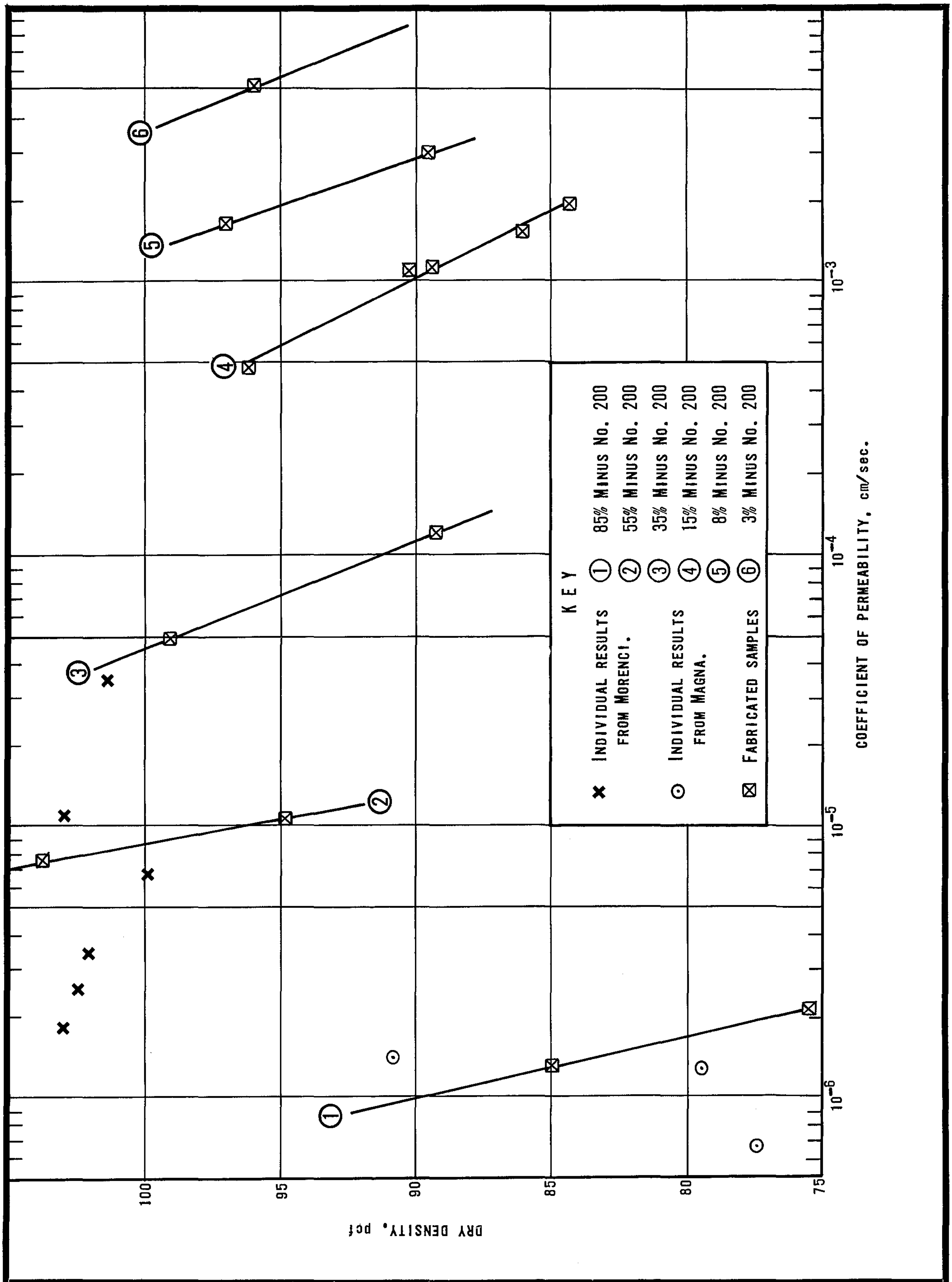

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	PERMEABILITY VS. DRY DENSITY COPPER TAILINGS MATERIAL		
		PROJECT NO.	DATE	DRAWING NO.
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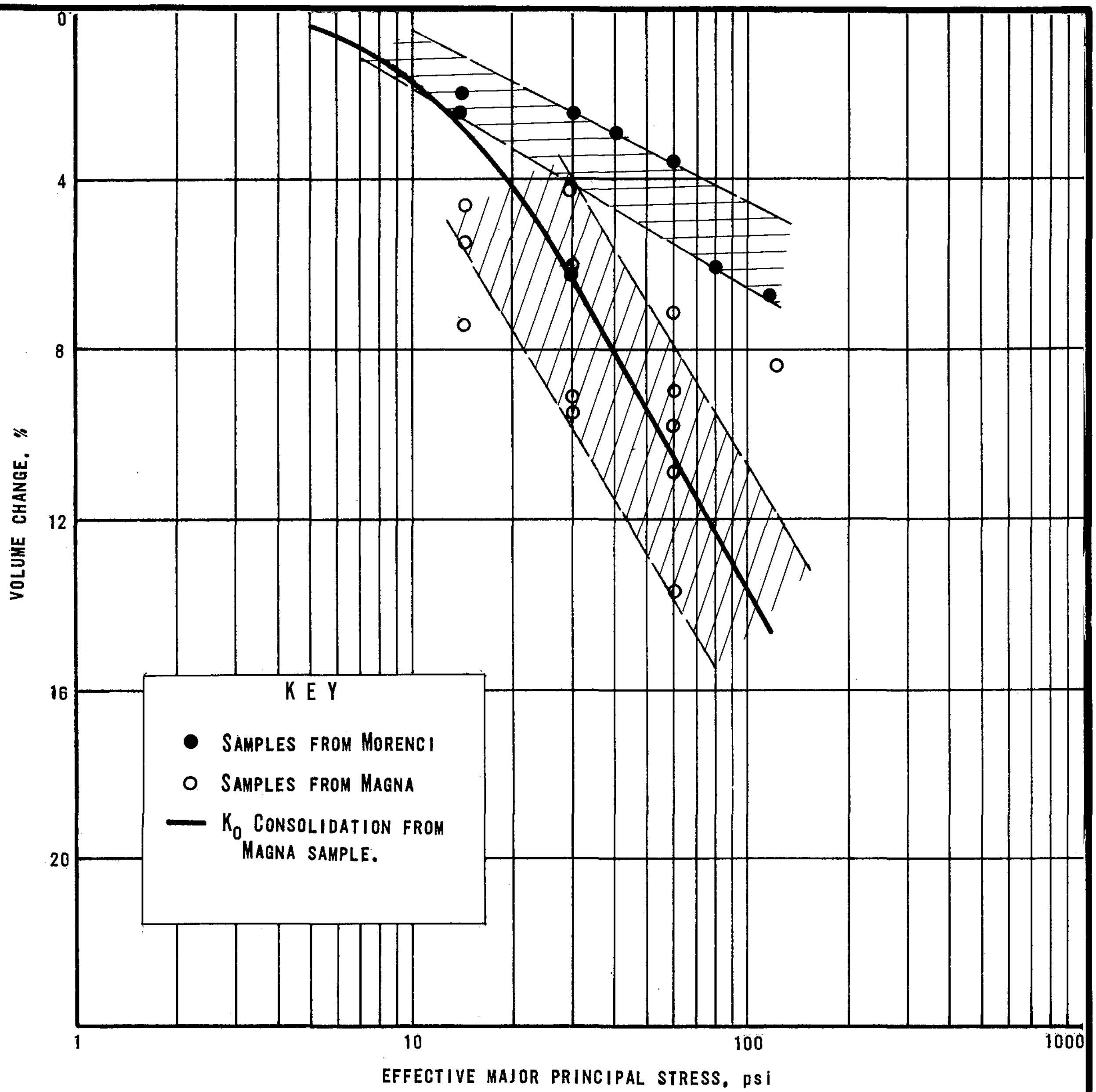


AVERAGE VALUES	MAGNA SITE	MORENCI SITE
Coefficient of Compressibility (a_v)	8.5×10^{-6} psf^{-1}	2.0×10^{-5} psf^{-1}
Compression Index (C_c)	0.28	0.09
Coefficient of Consolidation (c_v)	13.7 ft^2/day	34.2 ft^2/day

W. A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	CONSOLIDATION CHARACTERISTICS OF COPPER TAILINGS		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. V-10

TABLE V-2

AVERAGE CONSOLIDATION PARAMETERS

Parameter	Magna	Morenci
Coefficient of Compressibility (a_v)	8.5×10^{-6} ft²/lb (1.7×10^{-2} cm²/kg)	2.0×10^{-5} ft²/lb (4.1×10^{-2} cm²/kg)
Compression Index (C_c)	0.28	0.09
Coefficient of Consolidation (c_v)	13.7 ft²/day (0.15 cm²/sec)	34.2 ft²/day (0.37 cm²/sec)

The triaxial cell may be used to study the buildup of pore pressure due to a stress change under undrained conditions, and the subsequent rate of dissipation of pore pressure when drainage is permitted from one end of the sample only. For purposes of settlement analyses, the necessary data about compressibility and rate of consolidation are usually obtained from the volume changes in the odometer test. However, under certain conditions, the direct measurement of pore pressure change is to be preferred, especially when the data is to be applied to an estimate of stability or dissipation characteristics of the pore pressure. Pore pressure dissipation tests were performed on undisturbed samples obtained from the Morenci site to aid in the interpretation of the field settlement data. A detailed discussion of the field data is presented in the investigation report for the Morenci tailings dam in Volume 2 of this report. A summary of the observed external and internal movements is presented below.

- The consolidation characteristics of tailings material follow a very predictable trend and generally were found to be quite uniform across the entire face of the dam.

- It took 162 days to fill dam 2W at the Morenci site with about 10 feet (3.05 m) of tailings during which time movements of about 3.6 inches (9.1 cm) vertically, and 3.0 inches (7.6 cm) horizontally were observed on the exterior face of the dam, 14 feet (4.27 m) below the active crest.

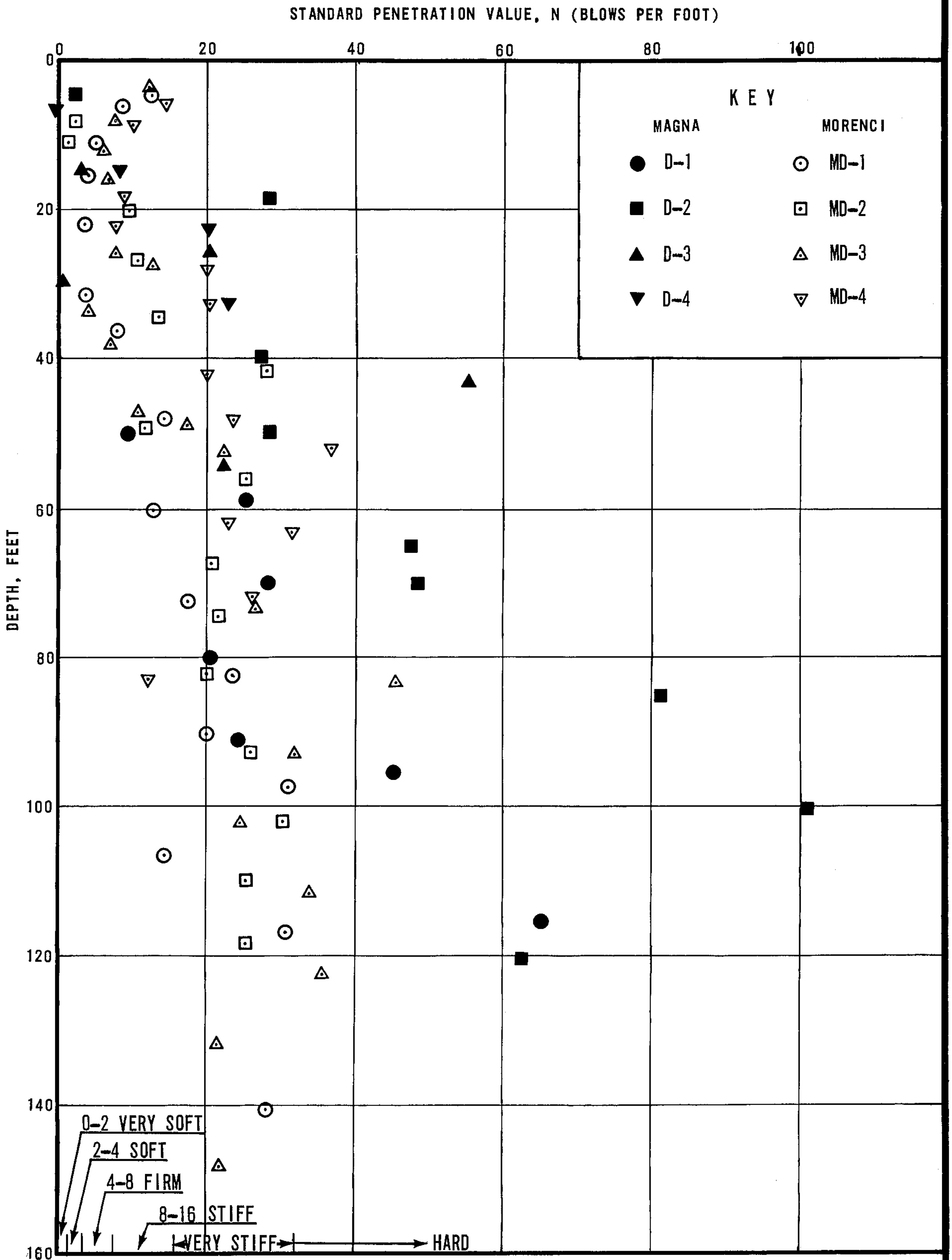
- The embankment continued to deform for about 80 to 90 days after filling of the pond had ceased, during which time an additional movement of 3.6 inches (9.1 cm) vertically and 2.4 inches (6.1 cm) horizontally was observed.

- During the 10 months that survey data were obtained at Dam 2W, total movements of approximately 5.4 inches (13.7 cm) horizontally and 8.4 inches (21.3 cm) vertically were observed.

- Internal movements, which were also monitored during the filling cycle of Dam 2W, confirmed the 5.4 inches (13.7 cm) of total horizontal movement at the surface obtained by the surface survey. The total internal horizontal movement increased to a maximum value of 8 inches (20.3 cm) at a depth of 40 feet (12.2 meters) below ground surface (54 feet below crest) and then decreased linearly to zero at a depth of 210 feet (64.0 meters) below ground surface, the assumed point of fixity for the Slope Indicator casing.

In conclusion, the field and laboratory data regarding the deformation or possibly shear strain characteristics of tailings indicate that significant movements occur within a tailings dam during construction in a uniform and apparently predictable fashion. Additional research is needed, as discussed in Chapter IX herein, using nonlinear finite element techniques to both verify the predictability of embankment movements, as well as assess the significance of these movements to overall stability of the dam.

e. Shear Strength - The shear strength characteristics of the tailings material were evaluated qualitatively by the use of both static and dynamic penetration tests and quantitatively by performing 74 field vane shear tests at the Magna site, and 33 laboratory triaxial tests on undisturbed tube samples from both the Magna and Morenci sites. The Dutch Cone penetration results, discussed in detail in Chapter VI, indicated significantly more variation in penetration resistance than the standard penetration test (SPT) results. The SPT values for both Morenci and Magna are presented on Drawing V-11 in the form of blow counts per foot (N) versus depth. The results from Morenci indicate a range in values of 1 to 47 blows per foot with a noticeable trend for increasing penetration resistance versus depth, similar to the trend for increasing density versus depth discussed previously. Within the upper 40 feet of the embankment, the results indicated that 70 percent of all tests were below 10 blows per foot, thus indicating a loose to very loose consistency when considering the material to be a silty sand. The remaining 30 percent of the test results within the upper 40 feet (12.2 m) of the embankment, indicated a consistency of the tailings material between 10 and 30 blows per foot, or a medium dense consistency. Below a depth of 40 feet, where all materials may be considered to be a sandy silt, 75 percent of all tests were between 10 and 30 blows per foot, indicating a stiff to very stiff consistency and 25 percent were between 30 and 50 blows per foot, indicating a very stiff to hard consistency. There were no test results lower than 10 blows per foot below 40 feet depth. Also, the results presented above were actual values from the field; no correction due to depth of hole or location of water table has been applied. Standard penetration test results obtained from 26 tests performed at the Magna

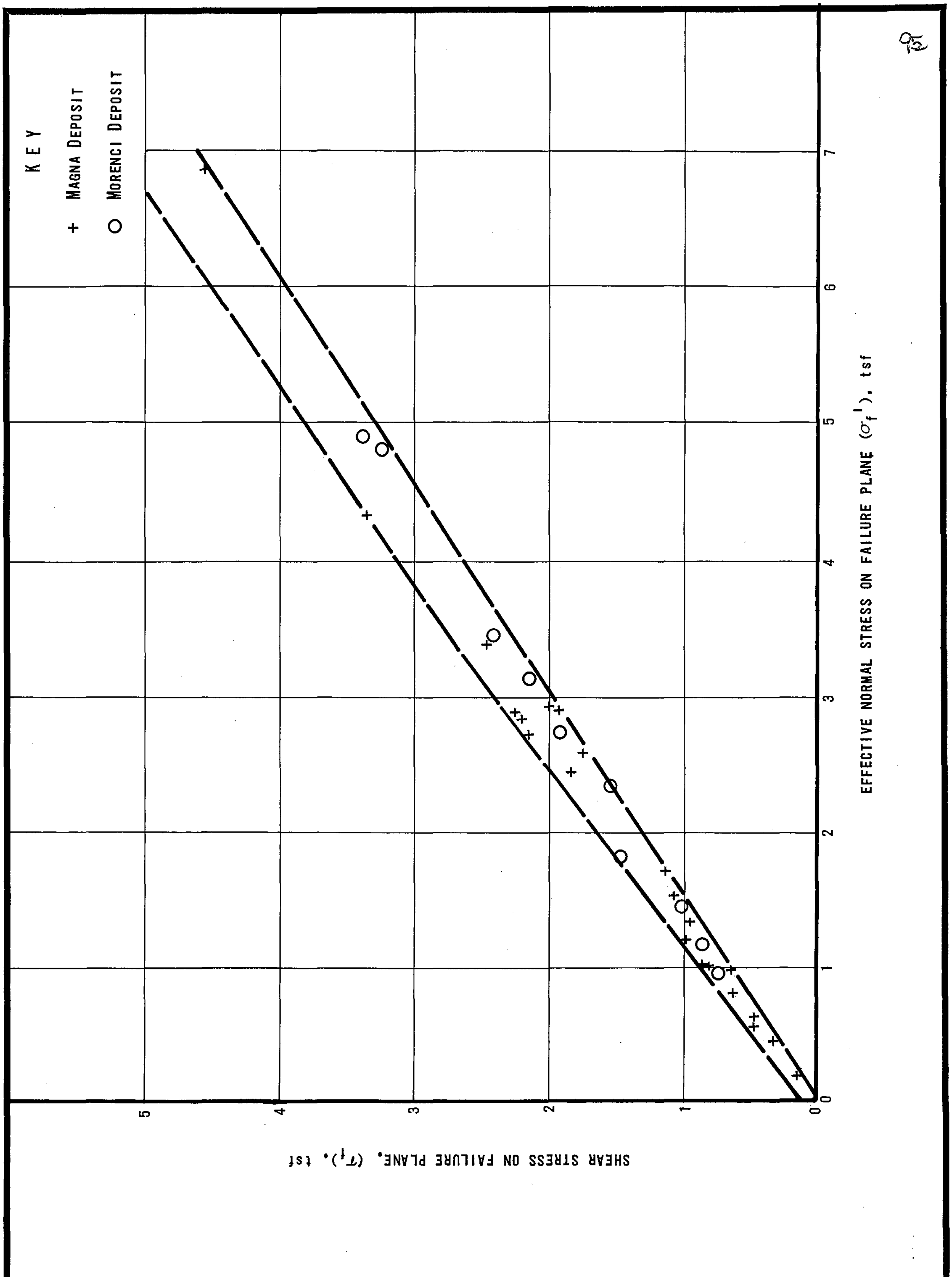


W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	STANDARD PENETRATION VALUE VERSUS DEPTH COPPER TAILINGS MATERIAL		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. V-11

site indicated a range in values of less than 1 to 102 blows per foot, with a similar trend for increasing penetration of resistance versus depth to that described above for the Morenci site. Test results between a depth of 0 to 20 feet (6.1 m), indicate a blow count of less than 10 or a very soft to firm consistency, most likely resulting from the low confining pressures and the low intrinsic strength. Between a depth of 20 to 60 feet (6.1 to 18.3 m), the majority of all test results are between 20 to 30 blows per foot, indicating a very stiff consistency. Below a depth of 60 feet, 8 of the 11 tests were higher than 40 blows per foot indicating a hard consistency.

Laboratory triaxial test results are presented on Drawing V-12 in the form of effective normal stress on the failure plane (σ'_f) versus shear stress on the failure plane (τ_f) at the point of failure, defined herein as the point of maximum obliquity $(\sigma'_1/\sigma'_3)_{max}$. These results, determined from samples obtained at both the Morenci and Magna site, indicate a value of internal friction angle, based on effective stress, equal to 33 - 37 degrees with an indicated cohesion intercept of less than 0.1 ton per square foot (tsf). It is interesting to point out that the dry density of the consolidated samples used for the triaxial tests varied from 77.3 to 111.9 pcf (1.24 to 1.79 gm/cc) and yet the shear strength results indicate remarkable uniformity. The uniformly high effective stress shear strength for copper tailings material can be attributed to material uniformity, similarity in parent rock types, consistency in production methods, and the angularity of the fines. Shear strength results based on total stresses are presented on Drawing V-13 in the form of average total stress $\left(\frac{\sigma_1 + \sigma_3}{2}\right)$ versus maximum shear stress $\left(\frac{\sigma_1 - \sigma_3}{2}\right)$ computed at either the point of maximum deviator stress or 10 percent axial strain, whichever occurred first during the triaxial test. The shear strength results based on total stresses indicate a broader range than those based on effective stress. These results indicate a value of the total stress friction angle equal to 14 - 17 degrees and a cohesion based on total stress equal to 0 - 1.04 tsf (1.01 kg/cm^2).

In addition to the laboratory test results discussed above, the undrained shear strength of copper tailings was determined by using a portable vane shear device. The undrained shear strength results, summarized on Drawing V-14, indicate a general increase in shear strength with depth. The ratio of undrained strength (s_u) to the effective overburden pressure (p_o) varies from 0.7 to 2.0. Individual values of the undrained shear strength varied from approximately 0.05 to 1.3 tsf (0.05 - 1.26 kg/cm^2). The undrained shear strength results discussed above, obtained at the Magna site, are thought to be typical of the shear strength characteristics of the very fine-grained copper tailings which, for most sites using a peripheral discharge method, would be typical of the pond area well back from the crest. Although the shear strength data presented on Drawing V-14 indicate a scatter at any given depth, the individual data from a given vane probe show a fairly consistent and somewhat linear



W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	SHEAR STRENGTH CHARACTERISTICS OF COPPER TAILINGS MATERIAL BASED ON EFFECTIVE STRESS		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO.	DATE	DRAWING NO.
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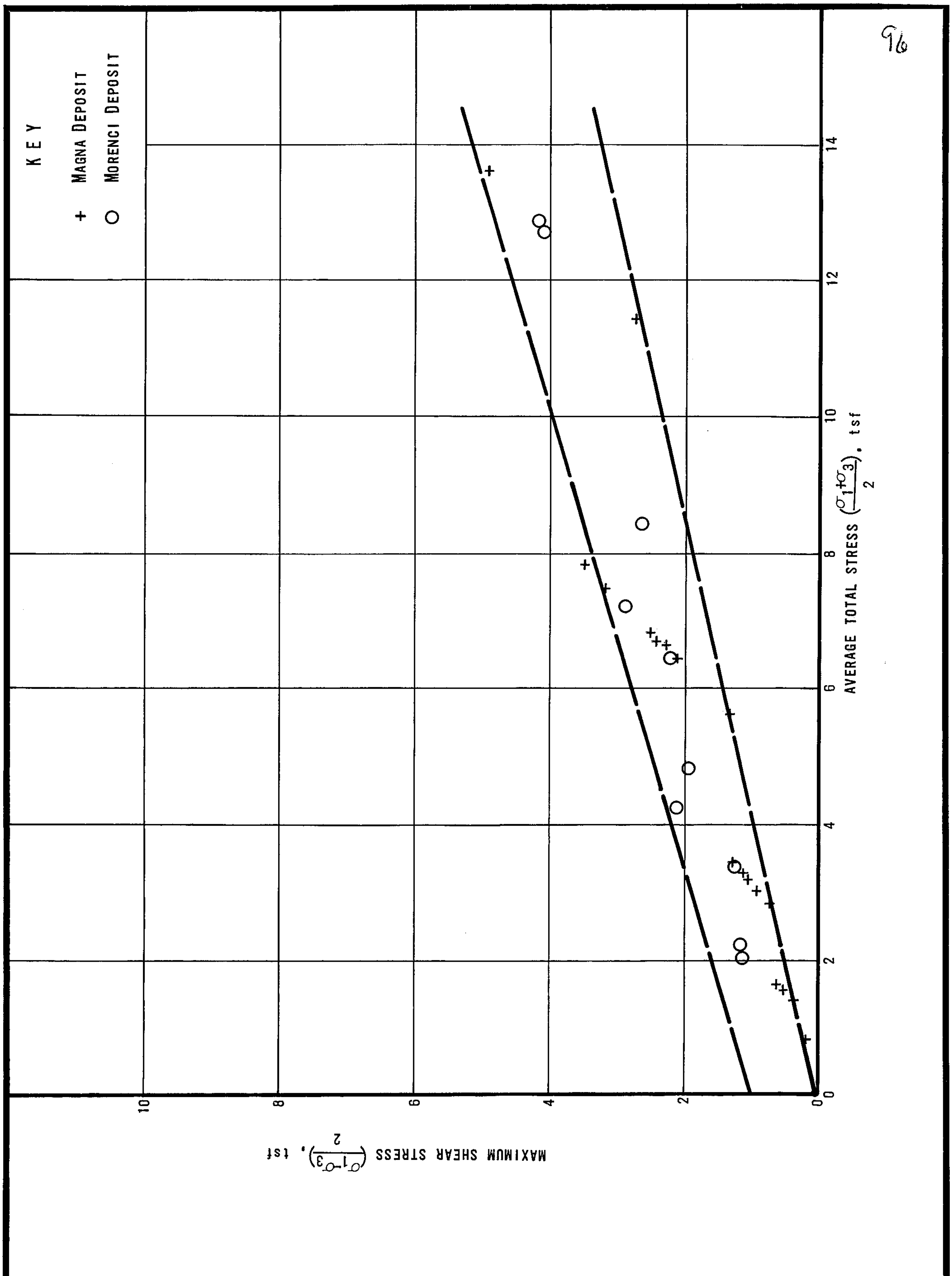

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	SHEAR STRENGTH BASED ON TOTAL STRESS COPPER TAILINGS MATERIAL		
		PROJECT NO.	DATE	DRAWING NO.
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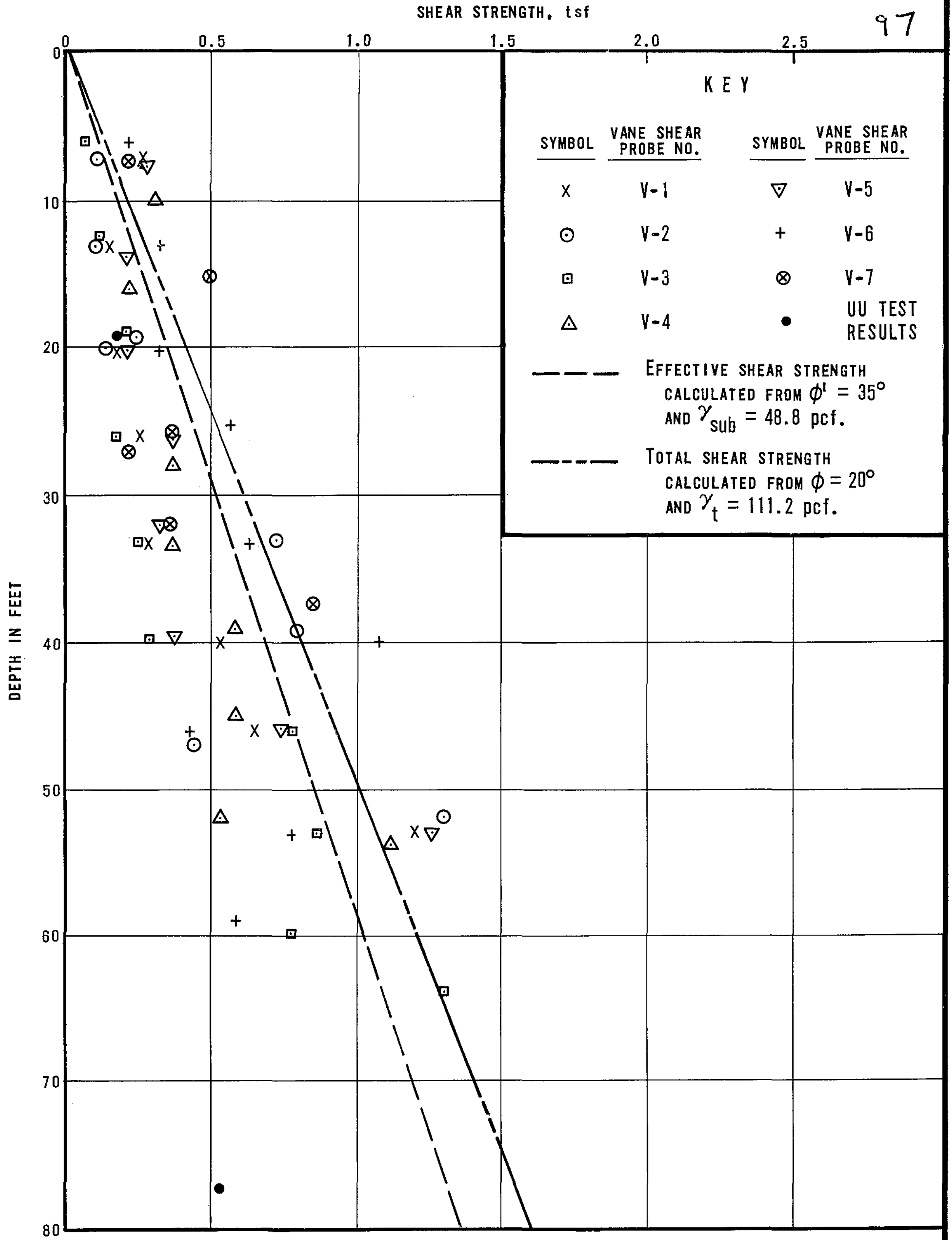


W. A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	VANE SHEAR TEST RESULTS MAGNA TAILINGS DAM		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. V-14

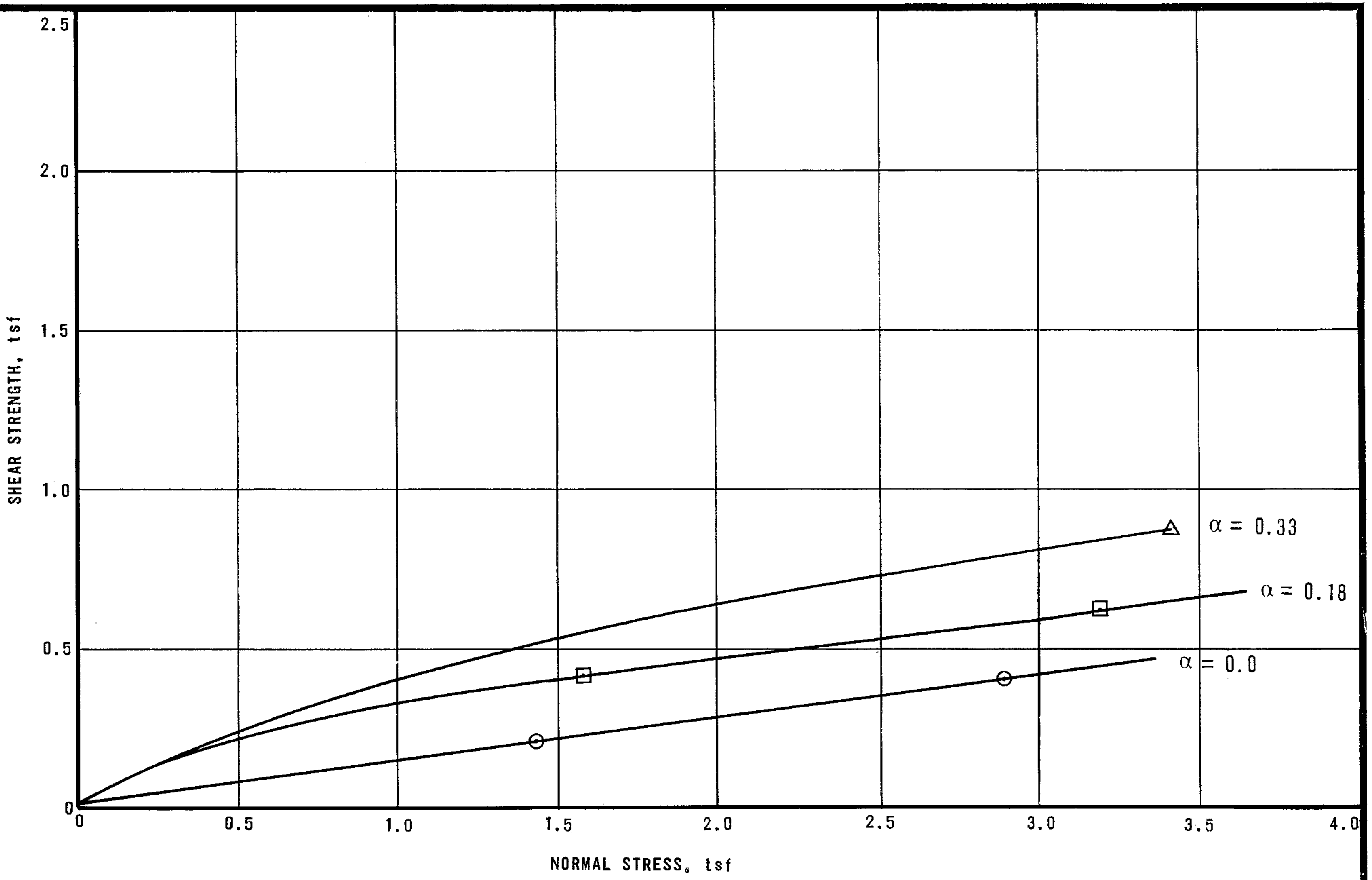
increase of strength with depth. The validity of the vane shear strength results may be suspect in certain portions of the pond area because of partial relief of pore pressure induced by the shear strain during the test. This is especially true in some "coarse" silts; however, the average coefficient of permeability of 10^{-6} cm/sec (1 ft/yr) for the tailings in the Magna pond area would indicate the materials to be sufficiently impervious to preclude drainage during the progress of the vane shear test.

Also shown on Drawing No. V-14 for correlative purposes, is the increase in shear strength with depth using the average effective or total stress parameters as determined in the laboratory by consolidated-undrained triaxial shear tests. As shown on Drawing No. V-14, the in-situ undrained shear strength (vane shear) results generally indicate somewhat weaker strength than average results from the laboratory. The most plausible reason for this is that the upper portions of pond material are not yet fully consolidated. This concept is more fully developed in Volume 3 of this report.

The shear strength of copper tailings under dynamic loading conditions was determined only for samples from the Magna site. These results, which are summarized on Drawings V-15 and V-16, indicate the materials are susceptible to a liquefaction mode of failure. Although the results obtained for the Magna tailings cannot be extrapolated to other sites because of the high percentage of fines, dynamic triaxial tests performed by W. A. Wahler and Associates for other tailings material indicate that tailings existing at a dry density representing a relative compaction less than about 90 percent, based on ASTM Test Designation D1557-70, modified to 20,000 ft-lb/ft^3 as a compaction standard, regardless of the method of discharge, will usually exhibit low resistance to liquefaction when saturated. Obviously, the severity of this deficiency in resisting dynamic load application is dependent on the seismicity of the site, conditions within a deposit, and specific test results. The expected performance of tailings material under earthquake loading is an area of needed future research as discussed in Chapter IX of this report.

C. PHYSICAL PROPERTIES OF LEACH DUMP MATERIALS

Because special emphasis was placed on tailings dam stability during the current research program, only one leach dump was investigated in detail. While it was not possible to draw general conclusions regarding the physical properties of leach dump materials from just one investigation, it is possible to delineate their important physical properties characteristics to aid in the planning of other similar investigations. Detailed field and laboratory test results for the Kennecott Leach Dump at Hurley, New Mexico, are presented in Volume 4 of this report.



NOTES:
1. THE SHEAR STRENGTH DATA PRESENTED HEREON ARE BASED ON INITIAL LIQUEFACTION IN 10.3 SIGNIFICANT CYCLES.
2. THE SHEAR STRENGTH DATA FOR $\alpha = 0.0$ WAS REDUCED FROM LABORATORY RESULTS USING $C_r = 0.65$. OTHER VALUES OF α WERE INTERPRETED USING $C_r = 1.0$.
3. THE VALUE OF ALPHA (α) IS DEFINED AS THE RATIO OF SHEAR STRESS TO NORMAL STRESS ACTING ON THE FAILURE PLANE UNDER STATIC LOADING CONDITIONS.

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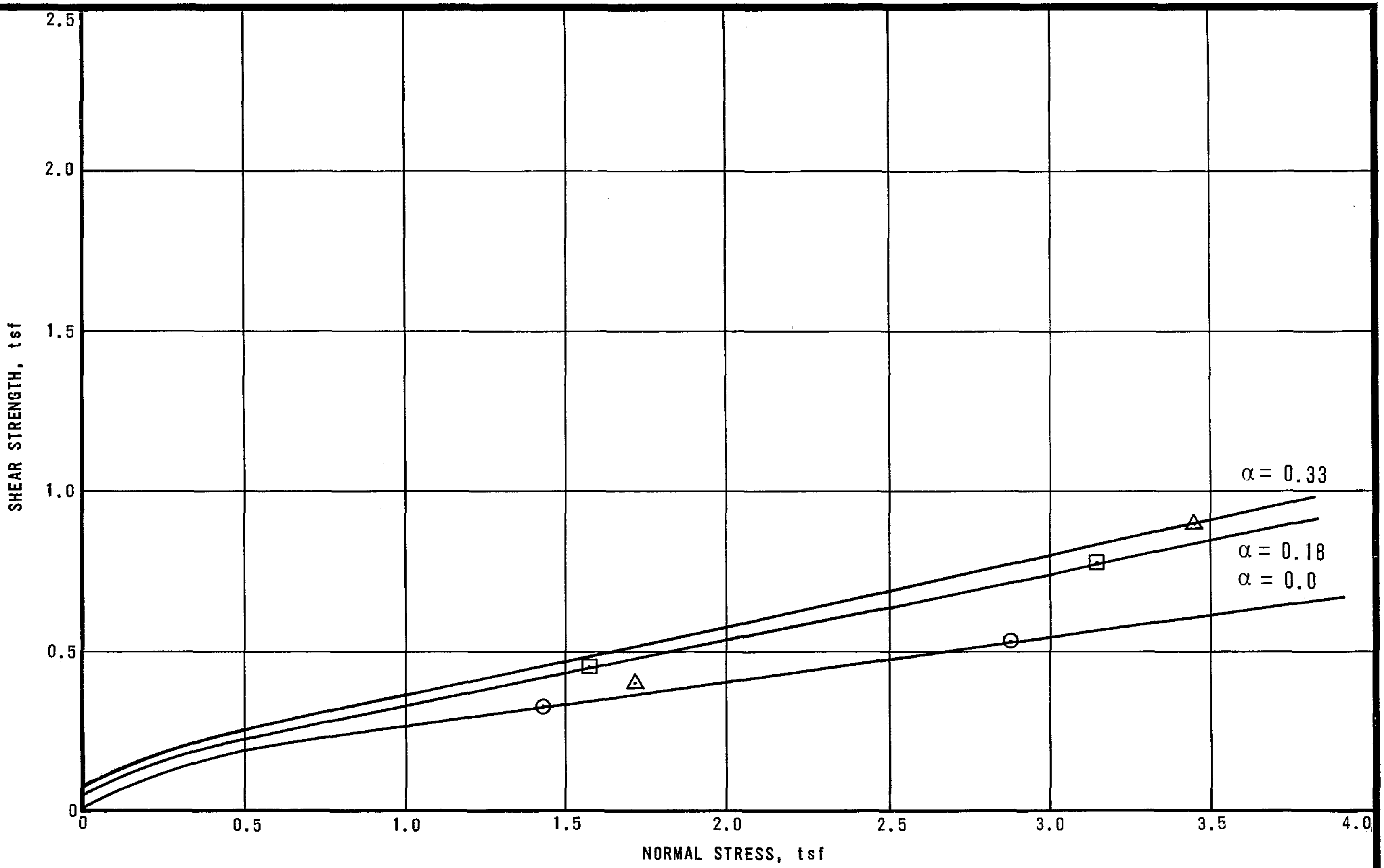
W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	DYNAMIC SHEAR STRENGTH BASED ON INITIAL LIQUEFACTION MAGNA TAILINGS DAM		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. V-15



NOTES: 1. THE SHEAR STRENGTH DATA PRESENTED HEREON ARE BASED ON 10 PERCENT STRAIN IN 10.3 SIGNIFICANT CYCLES.
2. THE SHEAR STRENGTH DATA FOR $\alpha = 0.0$ WAS REDUCED FROM LABORATORY RESULTS USING $C_r = 0.65$. OTHER VALUES OF α WERE INTERPRETED USING $C_r = 1.0$.
3. THE VALUE OF ALPHA (α) IS DEFINED AS THE RATIO OF SHEAR STRESS TO NORMAL STRESS ACTING ON THE FAILURE PLANE UNDER STATIC LOADING CONDITIONS.

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	DYNAMIC SHEAR STRENGTH BASED ON 10% STRAIN MAGNA TAILINGS DAM		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. V-16

1. Index Properties

a. Grain-Size Distribution - The major difficulty associated with any leaching dump, from a standpoint of field and laboratory testing, is the extremely coarse-grained nature of much of the material in question. Gradation results for 10 field density samples are shown on Drawing V-17. As shown on the referenced drawing, the average gradation results indicate the dump materials are composed of 50 percent by weight coarser than the No. 4 (4.8 mm) sieve. Because the selection process in locating a field density test will generally favor a finer-grained area, it is estimated from the referenced results, plus a visual inspection of the materials penetrated by the drill holes, that the dump material is composed of approximately 60 percent gravel, 20 percent sand and 20 percent silts and clays.

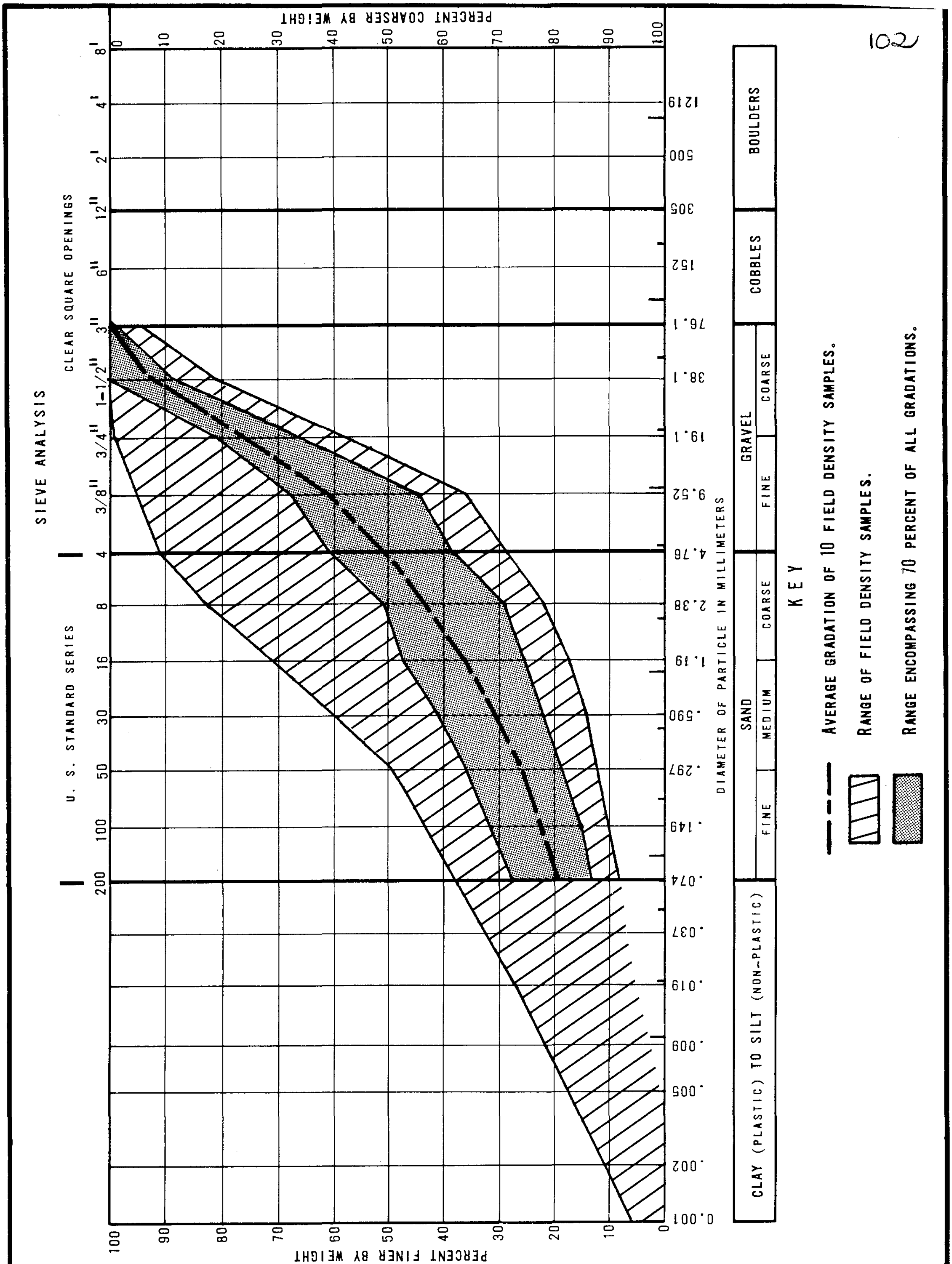
b. Atterberg Limits - Although the dump materials contain only about 20 percent fines, this percentage of fines can significantly influence other engineering properties such as permeability and shear strength. The 10 field density samples obtained at the Chino site exhibited clayey silt characteristics with an average liquid limit of 28 percent, varying from 22 to 33 percent, and an average plastic limit of 23 percent, varying from 19 to 28 percent.

c. Specific Gravity - Specific gravity results for the leach dump materials were found to vary from 2.63 to 2.75, with the coarser (plus 3/4 inch) particles exhibiting the lower range of values. The average specific gravity for 11 samples of minus No. 4 material was 2.69, whereas the value of the plus 3/4 inch material was 2.63 based on saturated surface dry methods.

2. Engineering Properties

a. Natural Water Content and Dry Densities - Because of the coarse-grained nature of the leach dump material, it was necessary to use 4- or 6-foot diameter density rings in order to obtain valid dry density data. This method of density testing is far more costly and time-consuming than the simple sand cone method. A total of 10 field density tests was performed in 5 bulldozed trenches at the Chino site at depths varying from 3.7 to 9.5 feet below ground surface. The in-place dry density of the total sample varied from 80.2 to 117.2 pcf (1.28 to 1.87 gm/cc) with 6 of the 10 tests having values less than 100 pcf (1.60 gm/cc).

b. Compaction Characteristics - A total of 7 compaction tests was performed on the leach dump material using only the minus 3/4 inch material in accordance with ASTM D1557-70 Compaction Standards, modified to 20,000 ft-lbs/cu.ft. compactive energy. The results, presented on Drawing V-18, indicate a range of maximum compacted dry density of 119.5 to 129.0 pcf (1.91 to 2.06 gm/cc). We conclude, however, that compaction tests on leached dump material should be performed on the total sample or at least



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W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	GRADATION SUMMARY LEACH DUMP MATERIALS

PALO ALTO ● NEWPORT BEACH ● CALIF.

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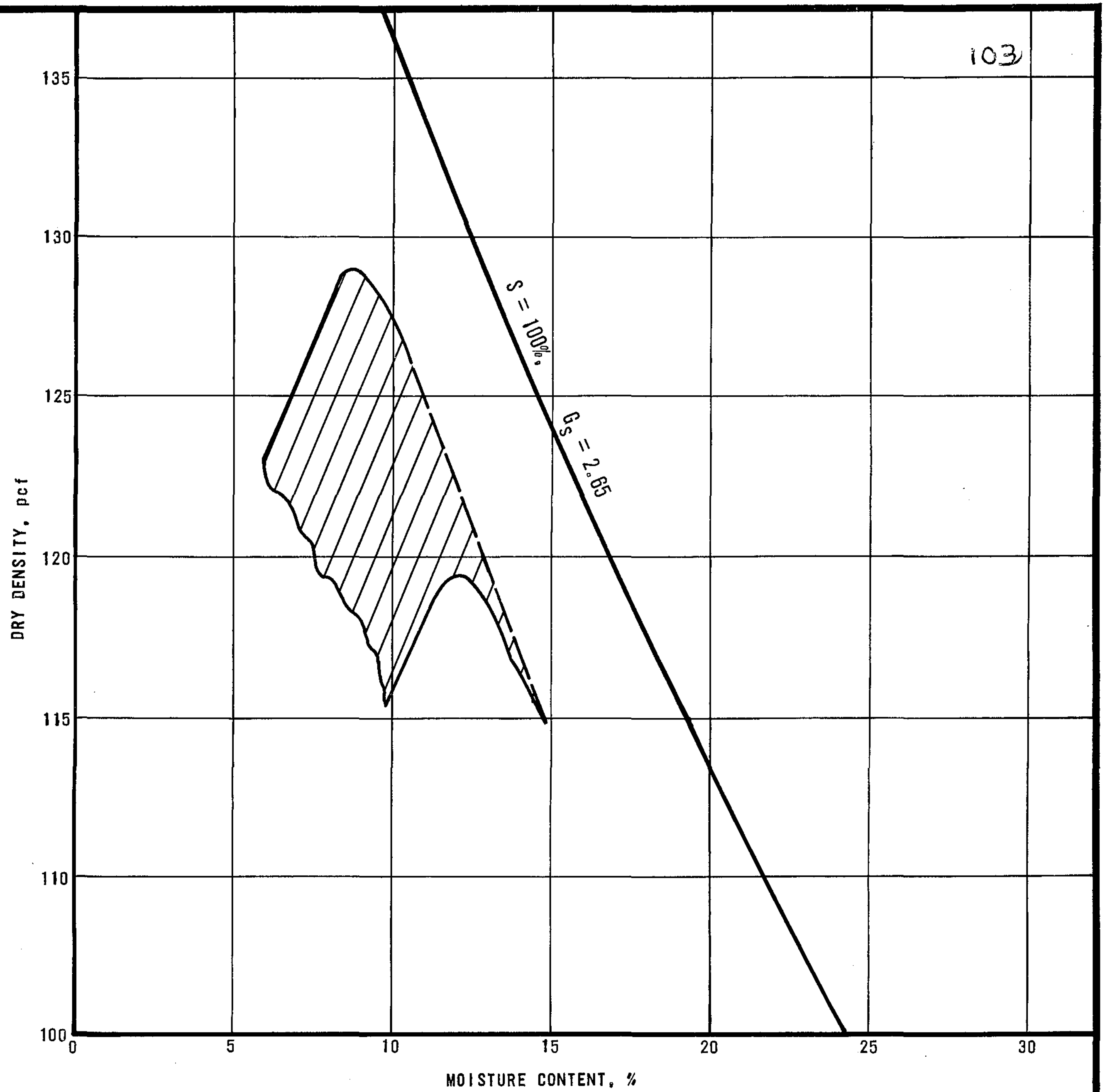
0620	JUNE 1974	V-17



NOTES: 1. RANGE OF COMPACTION TEST RESULTS FOR 7 SAMPLES FROM THE CHINO LEACH DUMP.

2. ALL SAMPLES WERE SCALPED ON THE 3/4 INCH SIEVE PRIOR TO TESTING.

3. ALL COMPACTION TESTS WERE PERFORMED IN ACCORDANCE WITH ASTM D1557-70 MODIFIED TO 20,000 ft-lb/ft^3 COMPACTIVE ENERGY BY REDUCING THE NUMBER OF LAYERS TO 3 AND THE NUMBER OF BLOWS PER LAYER OF A 10 lb HAMMER TO 15.

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	COMPACTION CHARACTERISTICS LEACH DUMP MATERIALS		
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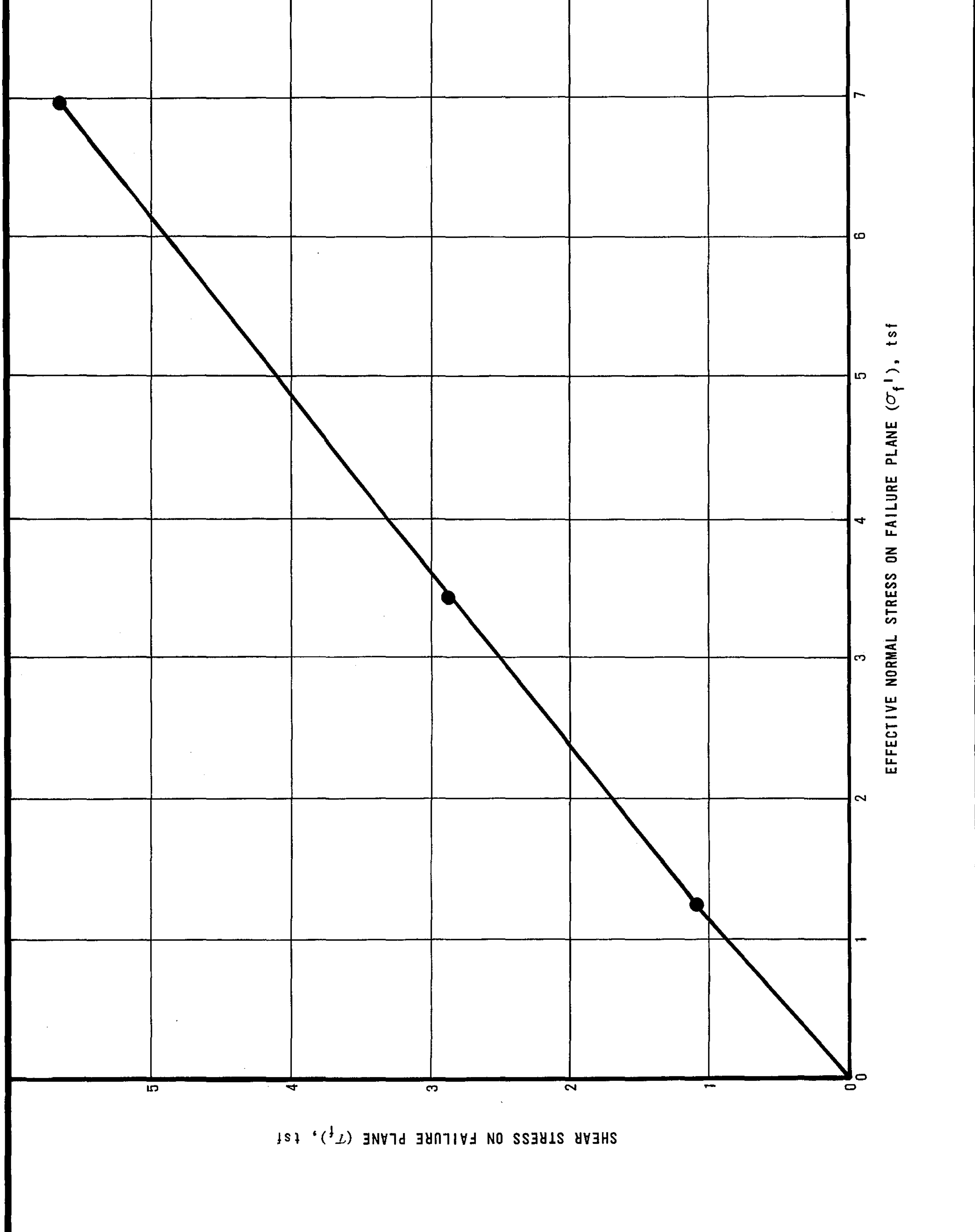
include material up to 3-inch maximum particle size. This would require the use of 12 or 18-inch diameter compaction molds but would allow a direct comparison of field density and laboratory test results. A comparison of the field density results with laboratory compaction results for only the minus 3/4 inch portion of the total sample (using a rock correction) indicate that the relative compaction varied from about 61 to 87 percent. These results are not unrealistic considering the method of dump placement and the amount of "compaction" received by each area of the dump.

c. Permeability - Only one sample of leach dump material was tested for its permeability characteristics. This was accomplished on a sample fabricated in the laboratory to the average gradation and dry density determined from the field density test results. The value obtained was 1.3×10^{-3}cm/sec (1,300 ft/yr); there is little doubt, however, that the permeability of the actual leach dump material varies dramatically from the value obtained. For example, the coarser gravels and cobbles near the base of each lift are probably at least one order of magnitude higher (more permeable) than the average value, and the finer-grained top portion of each lift, or in other areas of high weathering, is probably less permeable by at least two orders of magnitude from the average value. This points out a very important fact regarding the engineering properties of leach dump materials; that is, there is little doubt, after reviewing the construction methods and leaching practices, that the significant engineering properties of shear strength, compressibility and, more importantly, permeability, cannot be represented for analytical purposes by average values.

d. Compressibility - The compressibility characteristics of the leach dump materials were not studied in detail. Results from one isotropically consolidated triaxial sample indicated a volume change of approximately 8 percent with an applied consolidation pressure equal to approximately 60 feet (18.3 m) of overburden. This value, which is roughly double that of a typical earth or rockfill dam, is considered possible due to the relatively low in-place dry densities of the leach dump material.

e. Shear Strength - The shear strength characteristics of the dump material were evaluated by isotropically consolidated undrained triaxial compression tests performed on laboratory fabricated samples. The samples were fabricated to an average dry density of 109 pcf (1.74 gm/cc), the average value of the near-surface density test results. The maximum particle size of the material received in the laboratory was approximately 5 inches (12.7 cm); however, the samples used for triaxial testing were scalped on the 1-1/2-inch sieve in order to limit the specimen diameter to 6 inches (15.2 cm), or four times the maximum particle size. The procedure used in scalping the material larger than the 1/2 inch sieve was to replace an equivalent amount of material between the 3/4 inch and 1-1/2-inch size to force the gradation of the tested sample below the 3/4 inch size to match the grading of the as-received sample. Approximately 25 percent of the original sample was larger than the 3/4 inch size, which means that the tested samples had identical grading characteristics of the finer 75 percent of the original material.

The internal friction angle for the fabricated leach dump material was found to be 39 degrees based on effective stresses (Drawing V-19), and 19 degrees based upon total stresses (Drawing V-20) with no apparent cohesion. For similar reasons stated above under the discussion of permeability, however, it is not possible, in our opinion, to accurately define shear strength characteristics for leach dump materials by a single or unique value. The strongest materials in the dump, in terms of shear strength, are probably represented by the well-graded gravels and coarser materials that collect near the bottom of each lift, whereas the weakest materials would be found in weathered zones that have higher contents of clay or fine-grained materials.



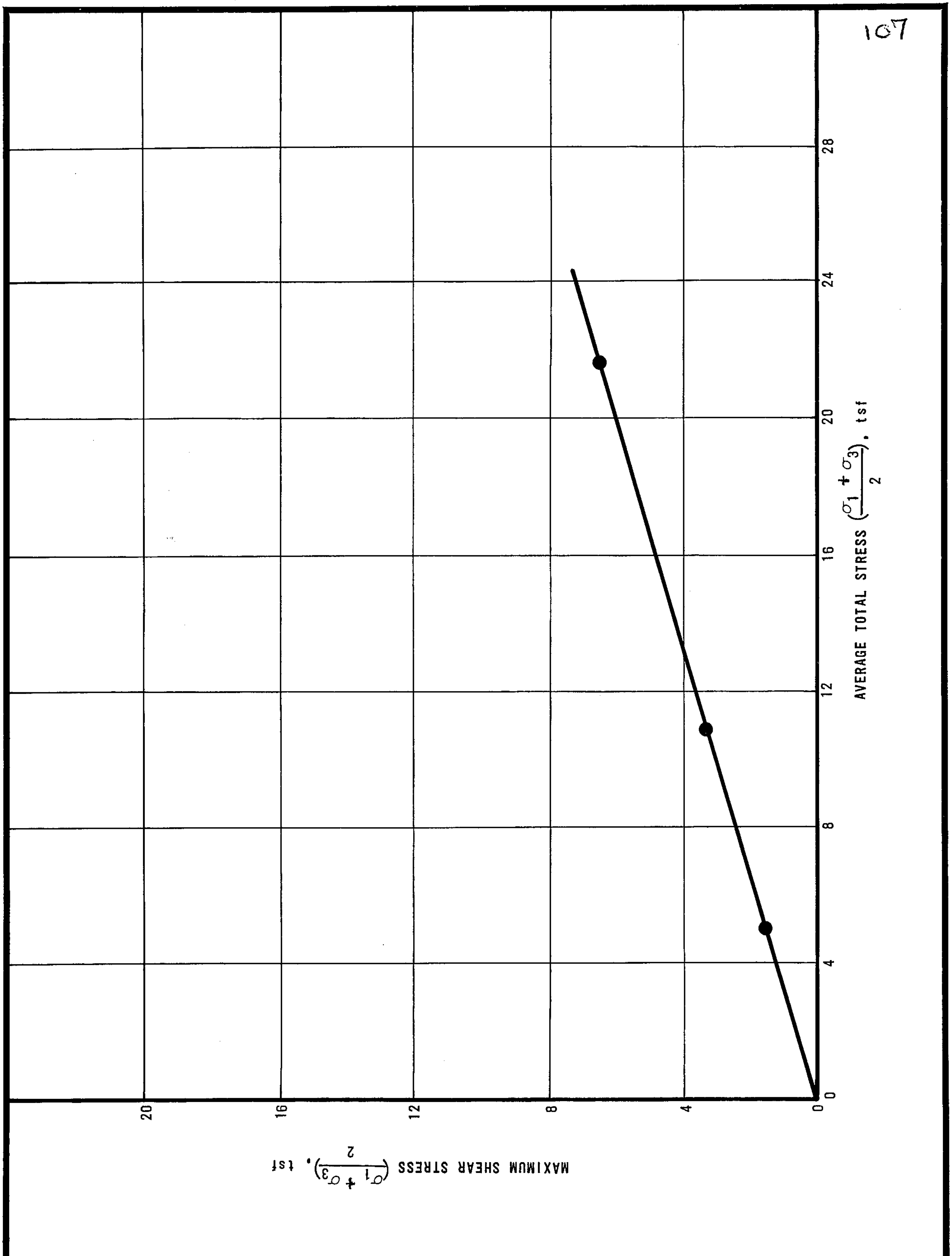
W.A. WAHLER & ASSOCIATES

U.S. BUREAU OF MINES
GENERAL REPORT

PALO ALTO • NEWPORT BEACH • CALIF.

EFFECTIVE STRESS SHEAR STRENGTH RESULTS
LEACH DUMP MATERIALS (CHINO)

PROJECT NO.	DATE	DRAWING NO.
0620	JUNE 1974	V-19



W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	TOTAL STRESS SHEAR STRENGTH RESULTS LEACH DUMP MATERIALS (CHINO)		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. V-20

CHAPTER VI

EVALUATION OF INVESTIGATIONAL TECHNIQUES

GENERAL

FIELD PROGRAM

LABORATORY PROGRAM

CHAPTER VI

EVALUATION OF INVESTIGATIONAL TECHNIQUES

A. GENERAL

One of the major efforts associated with this research program was an evaluation of various types of exploration equipment, field investigative techniques, geotechnical instruments, and laboratory testing procedures. This chapter describes the equipment and techniques generally used for the detailed investigations, and presents our conclusions regarding the most applicable equipment and techniques to be used in the future for similar investigations.

B. FIELD PROGRAM

The field program was divided into two main phases. One phase consisted of the detailed exploration of the Magna, Morenci, and Chino deposits, and the other consisted of the reconnaissance-level investigation of 15 other tailings disposal sites throughout the United States.

For the detailed work at the three mentioned sites, the field exploration consisted of geologic mapping, drilling and sampling of exploration holes, excavating test pits and installing piezometers and survey monuments. Furthermore, Slope Indicator casing was installed and Dutch Cone penetration tests were performed at the Magna and Morenci sites. At the Magna deposit, vane shear tests and a shear-wave velocity seismic survey were performed; in addition, sampling of fine-grained tailings was performed there with a Swedish Foil sampler.

1. Geologic Mapping

In order to provide a background for the engineering analyses of the structures and assess the influence of local and regional geological characteristics on them, the geology of each site was investigated and maps representing the geology of the site area and the regional geology were prepared. These maps served also as a basis to evaluate the seismicity in relation to probable fault movements.

2. Drill Holes

Exploration holes were drilled in the three investigated sites in order to log and sample the materials constituting the deposits. Where possible, the holes were located on one line along the maximum section of the structure. Only one section of each deposit was chosen as representative of the whole structure because the purpose of this investigation program was not to assess the characteristics of the deposits in detail, but rather to consider them as a whole.

The drilling was contracted with three different contractors and was performed with four different drill rigs. At Magna, two Sprague & Henwood skid-mounted rigs were used; a CL-40 and a CL-42. Both are hydraulically fed, Diesel-engine powered, rotary drill rigs, which differ only in capacity. The CL-42 is more powerful and was also used to push the Swedish Foil sampler into the tailings for slimes sampling. At Morenci, a Failing 1500, truck-mounted, hydraulically fed, gasoline-engine powered, rotary drill rig was used. At the Chino leaching dump, the drilling was performed with a Becker Hammer drill, which is a Diesel-powered pile hammer with air circulation and an attachment for rotary drilling.

The drilling in the tailings dam at Magna and Morenci was done with mud circulation to keep the holes open. Sampling was done in the holes mainly using thin-walled Shelby tubes. The recovery of samples with these tubes was generally good, except when sampling very wet tailings, which had a soupy consistency and fell out of the tube. An Osterberg piston sampler was tried at Morenci, but since it did not improve sample recovery and was less easy to operate than simply pushing Shelby tubes, it was not tried again. Some problems were encountered at Morenci keeping the hole from squeezing together at depth. By mixing thick mud, it was possible to achieve a maximum depth of about 225 feet. A particular problem occurred when the drill hole had to be flushed clean to install piezometers. Casing would, of course, alleviate these problems but would be very expensive. The simple approach of working fast was the most expedient solution.

A Swedish Foil sampler was used in one hole at the Magna deposit to recover fine-grained tailings or slimes. Several difficulties were experienced with its use, the main one being that the cutting edge of the sampler was unable to penetrate thin layers of dense material. Although recovery of wet, very loose tailings was good, the use of the Swedish Foil sampler was discontinued at a depth of 43.8 feet (13.4 meters) due to the slow rate of advance caused by the existence of dense layers in the deposit, and sampling in that hole was continued by pushing Shelby tubes.

The sampling in drill holes was done according to the following general sequence:

1. Push 2-foot (0.61 meter) long, 3-inch (7.62 cm) O.D. steel Shelby tube and retrieve.

2. Push another similar Shelby tube and retrieve.

3. Make standard penetration test in hole after Shelby samples. Retrieve spoon and examine sample.

4. Drill and clean hole to next predetermined depth.

5. Repeat procedure.

A few 3-foot (0.91 meter) long, thin-walled tubes were pushed with the Osterberg sampler at Morenci, and the sequence of operation was the same as above.

The tube samples were sealed with molten paraffin poured over the sample at both ends of the tube. Once the paraffin hardened, plastic caps were placed on each end of the tube and sealed with plastic electrician adhesive tape to prevent loss of moisture. Each tube was marked indicating hole number, sample number, depth interval, and date, and was placed in a wooden box. Sawdust placed in the box around the tube protected the sample from vibrations and shocks during transportation. Most of the samples were sent by commercial truck to the WAWA soil mechanics laboratory in Palo Alto where they were tested, while some were left at the site for field laboratory testing.

A Model 250 Becker Hammer drill was used to advance the exploration hole at the Chino leaching dump. The Becker hammer method of drilling consists of driving a double-walled pipe with a Diesel-operated pile hammer while air, under pressure, is forced down the annulus of the pipe. The material that is cut by the drill bit is transported by air upward through the inside of the pipe. The drill cuttings are recovered by diverting them through a spout in the drill head and through a flexible rubber hose into a cyclone where they are slowed down and dropped into a container for sample recovery. Material recovery is generally very good with the Becker hammer drill and material changes can be pinpointed very closely. Conventional rotary drilling equipment would not be very productive for the investigation of leach dumps because of the coarse-grained nature of the materials.

3. Piezometer Installation

At Magna and Morenci, the bentonite mud used for drilling the exploration holes was flushed out by continuous circulation of fresh water in order to install open well piezometers in the holes. At Chino, the holes were drilled dry and were clean for piezometer installation so that no water flushing was necessary. The piezometers that were installed were manufactured by W. A. Wahler and Associates and consist of an 18-inch (45.7 cm) long, 1-1/2-inch (3.81 cm) diameter Schedule 40 PVC pipe with a 3/4-inch (1.90 cm) diameter PVC pipe inside with a porous fiberglass filling the annular space between both pipes. The exterior pipe is slotted for a length of 16 inches (40.6 cm). The bottom end of the piezometer is sealed with a plastic plug and the top is fitted with a 3/4-inch (1.90 cm) diameter open coupling for receiving the unslotted riser pipe.

After cleaning the hole, the piezometer was attached to sufficient riser pipe and lowered to a predetermined depth. Clean sand and pea gravel was poured into the hole to provide a 3-foot long (0.91 meter) filter above and below the tip location. Finer sand was then poured over the filter to provide a 5-foot (1.52 meter) long cover over which a 2- to 3-foot

(0.61 to 0.91 meter) thick bentonite plug was poured. The remainder of each hole was filled with drill cuttings except in those holes having more than one piezometer, in which case the same procedure described was used for each piezometer tip installation. The riser pipe was cut to leave a 2- to 3-foot (0.61 to 0.91 meter) length above natural ground and was marked with identifying numbers for future reference.

Piezometers of the type installed in the investigated tailings dams are an economical way of monitoring water levels within the deposits. The water level within the riser pipe of each piezometer will generally stabilize within a few days or a few weeks, depending upon the permeability of the materials.

Piezometers can be installed at various depths within each deposit to obtain water level data of perched or free water surfaces, depending upon the configuration and deposition history characteristics of the particular deposit. Water levels obtained from piezometers provide data to estimate saturation levels and to correctly assess the stability of the dam.

4. Test Pits

Trenches were dug in all sites for the purposes of performing in-place density tests, obtaining bulk samples, and logging the exposed trench walls and excavated materials. The trenches were located as close as practical to drill hole locations in order to make correlations with results of tests performed on drill hole samples. Equipment used for excavation purposes consisted of backhoes equipped with 2-foot (0.61 meter) wide buckets and, at Magna, a front-end loader. The trenches were about 20 to 25 feet (6.1 to 7.6 meters) long, as wide as the bucket and up to 14 feet (4.27 meters) deep. Three density tests were taken in each trench on level pads that were hand excavated. The field density test holes were dug an average depth of one foot (0.30 meter) (measured normal) into the soil from the sloping surface that remained after excavation. This minimized disturbances from excavation.

A backhoe was also used to excavate 2-foot (0.61 meter) deep trenches in the dry pond area of Dam 4W at Morenci. Trenches for bulk samples were dug at approximately 50-foot (15.2-meter) intervals starting about 110 feet (33.5 meters) from the upstream side of the crest to a maximum distance of 460 feet (140.2 meters) into the pond area.

Test pits provide a means to obtain samples, perform density tests, and log the excavated materials; also, they give access to a visual observation of the structure of the deposit, such as stratification, grain size, and moisture conditions. The pits are a fast and economical investigation tool, but care has to be taken when entering one for testing or observation because of the danger of collapse of the pit walls. Pit walls are generally very unstable in the near surface tailings material. The fines content and moisture enhance the stability of the walls to some degree; however, narrow, deep trenches should be avoided whenever possible. In any event, pit walls must be supported while occupied by investigating personnel and the trenches backfilled immediately after completion of the tests to avoid accidents.

5. Surface Movement Monuments

In order to determine any movements that may occur on the surface of the deposits, associated with consolidation, settlement, or sliding, surface monuments were installed at various locations on each deposit. Periodic surveys of these markers were arranged with the mining company survey crews at Magna and Morenci, and with a private surveying firm at Chino.

The monuments at Morenci were installed on the main access road for Dam 2W and on the upper bench of Dam 1W. At Magna, they were placed close to drill holes on the upper, middle, and lower access roads, and at Chino they were placed along the maximum section of the deposit.

Surface monuments are easily installed, economical, and can provide an early warning to more serious movements if surveyed on a regular and continuing basis. Because of the immense size of some deposits, careful consideration should be given to the number and location of surface monuments to provide the most meaningful data. Generally, monuments can be easily installed on the side of access roads or benches. It is important that the installation of surface monuments provide a secure, stable survey point that will have a long life.

The prime objective of a well-designed group of surface monuments is to provide a history of both vertical and horizontal movements of a given deposit. In order to monitor horizontal movement, it is generally necessary to tie the monuments to stable abutment monuments on both sides of the dam. The requirements and ability for doing so will vary from site to site.

The time interval between surveys should be established for each site depending on the history of indicated movements, frequency of loading changes, and the number of surface monuments. For those deposits that are receiving tailings continuously, surveys may be planned on a regular basis, say quarterly or semiannually. If, however, a deposit receives tailings for a prescribed period of time each year, the surveys should be planned before, during, and after each load cycle. Regardless of the frequency adopted, it is important that after each set of readings is obtained, the data be reduced and analyzed. If it is determined that unusual movements have occurred or historic trends have been altered, then the frequency of readings should be increased and a determination made regarding the influence of the observed movements on overall stability of the structure.

6. Slope Indicator Casing

Slope Indicator casing was installed in order to detect movements expected to occur within the deposits at Magna and Morenci. At Morenci, 220 feet

(67.0 meters) of this casing were installed in a previously drilled hole approximately 10 feet (3.0 meters) below the existing crest of Dam 2W. At Magna, casing was installed in two holes adjacent to exploratory drill holes located near the crest of the dam and on the middle access road, respectively. Both strings of casing terminate in natural ground underlying the tailings deposit.

Although originally designed to monitor incipient slope failures, the Slope Indicator, or a similar type of instrument, can provide valuable information on the magnitude and direction of internal movements occurring within any dam. Installation in an existing dam requires a drilled hole and is moderately expensive, the average cost including drilling equipment running between $6.00 - $10.00 per foot (0.30 meter) of installation, depending on the depth of hole. Readings should be scheduled in accordance with the same philosophy discussed above for surface monuments. Historically, the time required for data collection and reduction had been high; however, new instrument models and data reduction techniques are available that no longer make these original drawbacks a prime consideration.

7. Dutch Cone Penetration Tests

Static penetration tests were performed at Magna and Morenci using a truck-mounted Dutch Cone penetrometer. The test procedure consisted of hydraulically advancing a special cone with a sealed vertical slip coupling which permits separating the two components of total penetration resistance: skin friction along the rod surface and friction resistance at the cone. Measurements of both local rod friction and cone resistance were taken every 8 inches (20 cm).

Test results were calculated as the field work progressed and a soil profile was interpreted from the data. These data were correlated with those obtained from drill hole sample testing, standard penetration tests and with results from the vane shear tests.

The Dutch Cone penetrometer, which is relatively new to the field of geotechnical engineering in the United States, having been introduced by Schmertmann[1] in 1965, shows great promise as a means of in-situ testing of tailings material. A recent publication by Sanglerat[2] presents a complete discussion on the use of penetrometers and interpretation of test results.

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[1]Schmertmann, J. H., "Static Cone Penetrometers for Soil Exploration," ASCE Civil Engineering, June 1967, pp. 71-73.

[2]Sanglerat, G., "The Penetrometer and Soil Exploration," Elsevier Publishing Company, Amsterdam, 1972.

The Dutch Cone penetration results obtained at both the Morenci and Magna sites indicated a far greater degree of scatter in penetration resistance versus depth than did the standard penetration results. Both results showed an increase in resistance at greater depths; however, the Dutch Cone results, because of the close spacing of tests, indicated that extremely low resistance occurred intermittently throughout the entire depth of penetration. Also of interest was the rapidity with which the point resistance could build up to a value in excess of 60 ton/ft^2 (kg/cm^2) and then drop to a value less than 10 ton/ft^2 (kg/cm^2) within a vertical distance of less than 2 feet (0.61 meter). The reason for such a drastic change in penetration resistance may be associated with variations in gradation, density, or possibly due to a chemical alteration of thin lenses within the tailings. As discussed in Chapter IX of this report, before the Dutch Cone penetrometer can become a viable method of field exploration for tailings dam evaluation, a significant amount of laboratory and field research must be completed.

8. Vane Shear and Penetration Tests

Portable equipment to perform static penetration tests and vane shear tests was used at the Magna site. The equipment used was manufactured by Jonell-Nilsson of Sweden.

The test procedure consisted of mechanically advancing a slip-joint cone similar to the Dutch Cone and continuously recording total and tip penetration resistance on an automatic paper recorder. In-situ shear strengths were determined using the same portable equipment by removing the penetrometer tip and replacing it with a 4.7-inch (12 cm) long by 2.4-inch (6 cm) in diameter vane. The vane was advanced mechanically and shear tests obtained about every 6.6 feet (2 meters). The test results were automatically recorded on a wax-coated circular disc.

The vane shear test is extremely valuable in obtaining in-situ undrained shear strength for soils where undisturbed samples are difficult to obtain or the materials exhibit a high degree of sensitivity. The use of the vane shear instrument for tailings dam investigations, however, is somewhat limited because of the materials characteristics. In order to obtain a true undrained shear strength, the materials should be: 1) sufficiently impervious to prevent any drainage (dissipation of shear strain induced pore pressure) during the progress of the test. These requirements would seem to limit the use of the vane shear equipment to the slimes area or those deposits composed of fine-grained material.

9. Seismic Survey

A special seismic refraction survey was conducted at the Magna site to determine shear wave velocities and calculate shear moduli of the embankment materials. Four seismic lines were run close to each one of the drill holes in order to correlate, as closely as possible, the data developed through the seismic survey with the data obtained from penetration tests, density tests, and the soil parameters of the undisturbed samples taken in each drill hole.

The method used for the survey consisted of the following: a 4-inch by 12-inch (10.2 x 30.5 cm), 8-foot (2.4 meter) long wood plank was placed flat on the ground and the front wheels of a car were driven onto it. Each end of the plank was then hit with a horizontal swing of a 20-pound (9.1 kg) sledge hammer in order to produce mainly shear waves. The soil vibrations caused by this impact were recorded on a 12-channel seismograph. The energy was picked up by 6 horizontally and 6 vertically oriented and paired geophones which had been placed in the soil along a 100-foot (30.5 meters) long line at 20-foot (6.1 meter) intervals; this line extended normal to the plank's long axis. In two places, there was no access for a vehicle and in order to produce the shear waves, the wood plank was placed into a 2- to 3-foot (0.61 to 0.91 meter) deep trench with a vertical wall; the plank was placed against the vertical wall and hit with a horizontal swing of the sledge hammer. This procedure was then repeated in a trench dug next to the first one but oriented at 180 degrees to repeat the test in the opposite direction and cancel out any noise or other disturbances. The plank was also hit vertically at each shot point in order to develop P, or compressional waves. The resulting seismographs were recorded on Polaroid film and a report presenting the findings of the survey was incorporated in the report on the investigation at Magna.

The seismic method used at the Magna site to determine the velocity of the shear waves was very successful. It was fast, relatively easy and safe since no explosives were used as the source of energy. Site accessibility can be a problem if the soils are too soft for a vehicle to drive on them and provide the weight necessary to hold in place the wood plank used to transmit the impact energy of the sledge hammer blow. The method used for two of the seismic lines at Magna overcame this restriction by placing the wood plank in an excavated trench. Another problem of this method can be the noise background on the geophones produced by the impact of sand grains which are lifted and transported by strong winds. Since the energy levels produced by the hammer impact in the loose and soft tailings materials are low, the noise interference can show a stronger signal than the arriving wave and overshadow the latter. This problem can be overcome by performing the test during calm weather or by burying the geophones in the ground to avoid direct exposure to sand grain impacts and wind. The seismograms obtained at the Magna site were recorded on Polaroid film and were very clear; consequently, the interpretation of the shear wave arrival times was not difficult. The method is considered appropriate and useful to obtain data necessary for input to a dynamic analysis of soil behavior.

C. LABORATORY PROGRAM

The laboratory testing procedures used throughout the research effort were those conventionally used in the field of soil mechanics and thoroughly described in Appendix A. No unusual problems associated with the tailings materials were encountered except for the extremely loose condition of some samples. Several samples from Morenci and Magna actually liquefied either during the extruding process or after the sample was extruded. This phenomenon was more prevalent when trying to extrude the sample in a vertical rather than horizontal direction. It was necessary, especially for triaxial sample preparation, to work very quickly once the sample was extruded. The sensitivity of the tailings further emphasizes the need for improvements of in-situ testing techniques.

A special study was performed to determine whether the tailings material were susceptible to disturbance during sample shipment. During the drilling at the Magna site, several dual samples (two 2-1/2-foot long samples taken within 5 feet) were obtained. One of the samples was left at the site while the other one was shipped to the main WAWA laboratory. After sealing, labeling, and boxing the samples as previously described, a sufficient number (usually 20 to 25) of boxes was assembled, stacked, and banded onto a pallet for shipping. This procedure precluded the possibility of handling each sample during the loading and unloading process.

Comparative triaxial tests were performed on the dual samples, one series being performed on-site in the portable WAWA laboratory and the other at the main WAWA laboratory in Palo Alto, California. The results of the comparative tests, presented in detail in Appendix of Volume 3, indicated no appreciable difference in the density, modulus, or shear strength between those samples tested on-site and those shipped to the laboratory.

CHAPTER VII

INTERIM GENERALIZED INVESTIGATIONAL, ANALYTICAL, AND INSPECTION PROCEDURES

GENERAL

SITE INVESTIGATION AND EXPLORATION

DISPOSAL FACILITY ANALYSIS AND DESIGN

EMBANKMENT CONSTRUCTION INSPECTION

EMBANKMENT SURVEILLANCE AND INSTRUMENTATION

CHAPTER VII

INTERIM GENERALIZED INVESTIGATIONAL, ANALYTICAL, AND INSPECTION PROCEDURES

A. GENERAL

As a result of the worldwide demand for increased production of primary refined copper, the copper industry and its related suppliers have responded with more efficient means of handling and processing ever-increasing tonnages of ore. In 1968, for example, the United States copper industry produced 1.54 million short-tons of copper, which generated approximately 308 million tons of tailings. The forecasted demand for the year 2000 is 6.4 million short-tons of copper to be produced in the United States, which will generate almost 1.3 billion tons of tailings. In other words, between 1974 and 2000 enough tailings will be generated to fill a 100-square-mile area to an average depth of 170 feet. Needless to say, the expected increases in tailings production will produce a heavy demand on existing tailings dams and will, in our opinion, require the design of new dams substantially higher than the existing structures. For example, W. A. Wahler and Associates is currently performing the final design for a tailings dam complex which will have one structure in excess of 450 feet (137 m) high, requiring a 75-foot-high (22.8 m) starter dam. In summary, over the next two decades we foresee the construction of new tailings dams or the continued expansion of existing dams that will rival the world's largest earth and rockfill structures.

New Federal and State legislation will undoubtedly be promulgated in the near future regarding the metals and nonmetals industry, specifically with regard to the hazards associated with tailings dams. This new legislation will require regulations and enforcement by MESA and others. Hopefully, sufficient research will be completed before the enactment of new legislation to provide the jurisdictional agencies with the necessary geotechnical engineering understanding of the investigational, analytical, and inspection procedures associated with tailings dams to effectively enforce any new laws.

A need exists, however, for interim procedures prior to the completion of needed future research and the development of all of the technology required to establish standards. This chapter is devoted to providing those procedures and guidelines that W. A. Wahler and Associates considers meaningful and practical at this time. It must be pointed out that the procedures proposed herein are based solely on our current understanding of the geotechnical engineering problems associated with tailings dams. This understanding reflects the individual experience-background of the engineers and geologists working for W. A. Wahler and Associates as a result of having investigated, designed, and/or supervised during construction, over 150 refuse, earth, or rockfill dams throughout the United States, South and Central America. We do not consider these procedures to be final, because, as pointed out in our discussion of needed future research, a fundamental understanding of the problems associated with tailings dams stability, including field investigational techniques and analytical procedures, requires more research work. We strongly recommend, therefore, that USBM/MESA establish a commitment to completing the necessary research in a timely fashion so as to be prepared to implement their responsibilities in the best interest of the public and the mining industry with as complete an understanding as possible of the fundamental geotechnical engineering problems associated with tailings disposal.

B. SITE INVESTIGATION AND EXPLORATION

1. Existing Facilities

The primary purpose of a site investigation for an existing disposal facility is to evaluate the potential hazard which continued existence or use imposes. A site investigation can be broken into two phases: 1) a site reconnaissance followed by, 2) detailed exploration. The study may end with the first phase if evaluation of results indicate further study is unnecessary.

a. Site Reconnaissance - The site reconnaissance phase of an investigation of an existing disposal site is conducted to evaluate the hazard potential and to formulate a detailed investigation if it is justified. Site reconnaissance or inspections can be made for various other reasons including determination of conformance with regulations or in response to complaints of "interested" citizens.

The techniques employed are strictly observational, with use of available reports, maps, and photos. With each inspection of a site, additional photos should be taken to build a pictorial record which will be extremely valuable to subsequent evaluations. The key to reconnaissance-level studies is the experience of the investigator. He must be able to recognize indicators of instability, interpret their significance, and to consider environmental effects. The primary indicators of hazardous or potentially unstable conditions can be listed. However, it must be kept in mind that each site is unique and in a detailed sense, specific indicators may be unique to a site. The most important factors involved in stability are:

- the types of materials being disposed and foundation conditions;
- the manner in which the materials were deposited;
- the slopes and condition of the embankment and/or foundation; and
- the occurrence, state, and control of water (and other fluids) associated with the deposit.

Under these general factors, many specific indicators can be listed, such as cracking, seeps, piping, slumping, slip-outs, mass creep, erosion, natural slope instability, sinkholes, etc.

The significance of the above indicators often cannot be fully evaluated until they are placed in perspective by locating them on maps and photos. When the instability indicators are incorporated on a topographic map with site geology and refuse materials types, an interpretation can be made. Construction of cross sections is not only useful to illustrate conditions, but is also a powerful interpretation tool. Construction of sections through critical areas with a given set of surface indicators forces a logical conclusion or series of conclusions to be drawn. In the case of a complex site, this procedure may raise serious questions which will lead to a more intensive investigation, most probably involving subsurface exploration techniques.

Another useful indicator is the overall appearance of a disposal site. A complex series of irregular deposits that appear to be disorganized is immediately suspect of being potentially hazardous. In contrast, the better the appearance of the site and the overall operation, most probably the less potentially hazardous the facility in general. Of course, cosmetic appearance must be distinguished from actual stability. However, it is much easier to evaluate an orderly site as opposed to a disorderly site, which often requires investigation just to identify the elements of the deposit.

b. Detailed Exploration - There are many exploration tools available to accomplish site investigations. New, more effective tools and variations of old tools are constantly being developed. Some of the more exotic tools and techniques are beyond the scope of this discussion; some of the tools available today may be too expensive in relation to their value. One of the prime responsibilities of the site investigator is to choose the most effective and economical tools available, that is, to obtain the most information for the exploration budget. Some of the more commonly used exploration tools and techniques are described below. Emphasis is placed on methods that are most useful for tailings deposits.

(1) Mapping--Topographical and Geological - If the complexity of the site or degree of hazard warrants, a detailed topographical map should be prepared at an appropriate scale and contour interval. In most areas, a USGS quadrangle sheet is available which is usually needed in order to define the degree of hazard. Sometimes, depending upon the extensiveness of the investigation, a quadrangle sheet at either the original scale or an enlarged scale may suffice. More detailed topographic maps are usually prepared by standard photogrammatic methods but selected profiles may be adequate where time and money are not available for more complete mapping.

For even the most limited investigation, at least a reconnaissance geologic map should be prepared. The trained engineering geologist can develop a reconnaissance geologic map of most sites in a few hours. The extent of the tailings deposit, variations in the deposit, signs of instability, and the materials upon which the deposit is in contact are delineated on the reconnaissance map. Often, the reconnaissance geologic map will provide information to help evaluate the degree of hazard and the amount of additional exploration required.

A detailed geologic map is prepared when the degree of hazard is great or the site is highly complex, and a detailed investigation is required. However, to prepare a detailed geologic map, a large-scale topographic map is required. Detailed geologic cross sections may provide clues as to the rates of deposition of tailings in the deposit, changes made in the kinds of materials deposited, and information on the foundation materials beneath and adjacent to the deposit. Signs of instability should be noted, such as cracks in the deposit, slumps, springs, and seeps, and lack of vegetation. The geologic map, combined with geologic sections, becomes an essential tool for planning the remaining exploration program.

(2) Trenches and Test Pits - Trenches and test pits provide an economical means of observing materials in the subsurface, of obtaining samples of the materials, and of performing in-place tests. Trenches are usually made by a bulldozer or backhoe, but can be dug by hand. The main disadvantage of trenches and test pits is they have a depth limitation, and can be dangerous until properly shored. Trenches or test pits are often placed in strategic topographic locations or across cracks or slumps to determine the nature of the feature. Shallow excavations may provide sufficient information for analysis, or may be the first stage in a field investigation to help plan additional exploration.

(3) Drilling - To obtain deeper information, some form of drilling is required. A three-dimensional picture is obtained, samples at depth can be secured, down-hole tests can be performed, water levels can be determined, and instrumentation, such as piezometers, can be installed. A large number of drilling systems are available but if all the above purposes are to be achieved, a flexible system is required. Other factors will influence the type of drilling used such as accessibility, steep slopes, and bearing capability to support equipment.

Problems are often encountered, especially in copper tailings, because the materials are loose and soft, and the undisturbed samples which are required for analysis are difficult to obtain. The standard rotary method, which was used at both the Morenci and Magna sites with a lightweight rig and having standard penetration testing capability, has proven to be satisfactory, but casing may be required the full depth of drill holes.

Another drill system applicable to tailings exploration is the hollow stem auger. The advantages of this system are that it is equally fast in medium- and fine-grained soils, and piezometers are easy to install through the hollow drill pipe. The disadvantages include the limited ability to penetrate gravel sizes greater than 3 to 4 inches in diameter, drive or push samples are limited to the inside diameter of the drill pipe, and the retrieval of good, undisturbed samples in areas of saturated tailings is difficult.

The Swedish Foil Sampler was tried at the Magna site and did not prove at all successful. Costs for the equipment are substantially higher than for conventional equipment and relatively thin beds of sandy material were difficult to penetrate.

(4) Geophysical Surveys - Seismic refraction surveys can be used to supplement and extrapolate drill hole data and to determine dynamic properties of embankment materials. The primary use would be to determine the location, extent and thickness of various types of materials including those of the foundation. Often, subsurface features such as faults can be identified and delineated. Surface resistivity surveys may also be useful to define the saturated zone of the embankment. A large number of down-the-hole geophysical tools are available today, including electrical and radioactive properties surveys, to assist in defining physical properties of embankment and foundation materials.

c. Logging and Sampling - Any field investigation program is most effective if all field information is thoroughly catalogued by trained and experienced field personnel, and a permanent record of all data is developed. The experienced observer should be present at the site during all the field activities, so that "fugitive data" is also preserved. Field personnel making an appearance only after exploration is completed to log samples and exposures can result in a serious loss of information or misinterpretation and the "fugitive data" that is available only as the exploration progresses is totally lost.

A field program that is inflexibly preconceived in the office risks missing key data that are needed to make correct interpretations. Therefore, the field program should be developed and modified as exploration data becomes available. The field observer must have the experience to be able to make field judgments as field conditions dictate to choose appropriate techniques and the location and proper extent of each exploration element.

Similar experience and judgment is required to choose appropriate sampling techniques and locations for disturbed and undisturbed samples. Materials with unusual characteristics, such as fine-grained soft tailings, will challenge the most experienced observer to obtain and preserve usable undisturbed samples.

Samples are taken for a large variety of specific purposes, all of which are intended to develop an understanding of the physical properties of the materials being explored. Disturbed samples can range in size from a handful of material for a visual record to several tons of material for performing large-scale laboratory testing. Undisturbed sampling is accomplished to preserve in-place properties of the material so that in-place characteristics can be simulated in the laboratory. Undisturbed samples are usually taken in metal tubes by pushing, driving, or carving around in-place soils. Undisturbed samples are sometimes taken by carving samples of one cubic foot or larger and placing them in sealed boxes to preserve in-place characteristics.

Methods of packaging, sealing, shipping, and overall care of samples must be carefully considered in the light of the laboratory testing program that is contemplated. Often in-place moisture contents and densities are critical to laboratory determinations; therefore, proper and thorough sealing of samples is required.

d. Field Testing - Most exploration programs include some field tests and an extensive program may include highly sophisticated and unusual tests. Field tests are performed to correlate with more extensive laboratory results or because the properties of materials cannot be adequately determined in the laboratory.

Many field tests are conducted in a drill hole in conjunction with a drilling program. Such tests include standard penetration tests (SPT), water tests to determine permeability, and others. Special testing equipment, such as the Dutch Cone Penetrometer and vane shear device can be located adjacent to drill holes in order to correlate field results with laboratory results for a given material type. Many of these tests are performed for qualitative or correlation purposes, rather than for precise numerical data and are usually supplemented with later laboratory tests.

If required, field moisture, gradation, and density tests can be performed in the field by moving the appropriate equipment into the field. In many cases, density test data, which is required for stability analysis, is best developed in the field and supplemented later in the laboratory. Standard sand-cone methods are used in relatively fine-grained soils (sands, silts, and clays); large rings up to 6 feet (1.8 m) in diameter, using water-displacement method for volume determination, may be required in coarser materials. Field density tests are usually limited, however, to near-surface materials, although deeper tests can be performed in test pits or shafts.

Standard penetration tests and Dutch Cone tests, along with variations of these tests, are all performed to determine the relative firmness of material, which is an indication of strength. Since the SPT test can be easily accomplished as the drilling progresses, this test is commonly used on many projects. The number of blows per foot can be plotted graphically to show the qualitative variation of density of materials with depth. A sample is recovered during the SPT either to provide a visual log or for laboratory testing. Dutch Cone and vane shear test results are quantitative in nature and more reliable than SPT data.

e. Types of Instrumentation - Instrumentation, if properly used, installed, and monitored should provide indications of an impending problem so that routine or emergency remedial measures could be taken to mitigate the potential hazard effectively and economically.

The requirements for instrumentation depend upon the information wanted. The most essential information needed to evaluate the performance of mine waste embankments includes:

- horizontal and vertical movements,
- neutral (pore-water) stresses,
- a continuous record of seepage losses through the embankment, the foundation, and the abutments, and
- measurement of the in-place properties of the embankment and its foundations.

For the respective items above, satisfactory data can usually be obtained by:

- the use of surface monuments on the crest and embankment slopes,
- the use of piezometers,
- a simple seepage-collection system and measuring device,
- observation and testing during construction.

(1) Surface and Internal Measurements - If carried out with the necessary degree of precision, surface measurements will provide information as to the direction and rate of movement of the embankment surface after its completion. The most difficult problem is often the establishment of a reference base line on firm ground located outside the area of movement. Since the distance to "fixed" reference points may be considerable, normal survey errors may often exceed tolerable movement limits.

Whenever possible, movement monuments should be set on a direct line of sight between stable bench marks. As movement develops, the offset of these monuments from the line of sight must be measured with precision. Where the line of monuments is curved, precise computations of movement are made more difficult but are still capable of accomplishment.

Surface points may be steel rods either driven into the embankment surface or set in concrete for greater stability. Often the points are set in lines, and elevations and relative horizontal positions are determined from a stationary control point off the embankment. Second order surveying techniques and accuracy are usually satisfactory for this type of control system. Time intervals for control may vary from daily measurements to annual measurements, depending upon the degree of potential hazard or the historical record desired.

Devices for measurement of elevation changes at depth can also be installed in an embankment as the embankment is raised. There are usually telescoping pipes where elevations can be periodically measured at varying depths. The use of this type of control point makes it possible to isolate settlement within various depth intervals of an embankment.

Another type of installation that is used to measure movement in an embankment is the slope indicator device. In this application, a tube is surveyed at regular depth intervals and the position of the tube in space is determined. After a number of measurements, a history is developed. It is important to realize that movement of an embankment does not necessarily indicate instability. A large embankment is dynamic and will consolidate and have other movements which, to a degree, are natural. A history of measurements will, however, provide the basis for determining whether movements are normal or abnormal.

(2) Piezometers - Piezometers are used to measure the hydrostatic pressure or head (elevation to which water will rise in a standpipe) of water contained within the void spaces between soil particles. It is well acknowledged in soil engineering that a knowledge of the magnitude of these stresses and their variations is essential to understanding the performance of any dam. The important factors influencing the selection of a piezometer system include reliability and durability, time lag and sensitivity, and maintenance and ease of monitoring. Table VII-1 is a summary listing of relative comments based on past experience, use, and instrument design.

Open Standpipe - This type of piezometer varies mainly in the diameter of the standpipe and the type and volume of the collecting chamber. The simplest type is merely a cased or open observation well in which the elevation to which the water rises is measured directly by means of a small probe. In this case, the static head is the average head which exists within the depth of the inflow part of the well below the water table. This measured head may be higher or lower than the free water table and, in the case of moderately impervious soils, may be subject to a large time lag.

Hydraulic Type - The hydraulic type piezometer consists of a collection chamber connected directly to a pressure gage near the downstream face of the dam. The pressure gage and its

TABLE VII-1

TYPES OF PIEZOMETERS

TYPE	SYSTEM	ADVANTAGES	LIMITATIONS	RELATIVE COST BASIS
OPEN STANDPIPE	CASAGRANDE (1948) BJERRUM (1961) TERRAMETRICS WAHLER	(1) No gauge house required (2) No deairing required after installation. (3) No freezing problem unless artesian conditions cause water level to stand near or above ground level. (4) Bjerrum tip can be pushed into soft clay formations. (5) Bjerrum suited for use in natural ground.	(1) Requires vertical standpipe which is a nuisance to construction equipment on embankment. Bore hole installation is common. (2) Very large lag time in impermeable soils. (3) Suitable only for saturated soils with fairly high permeability. (4) Volume of water required to enter stone to record a given pressure change may tend to plug stone. (5) Air dissolved or entrappen in pore fluid escapes and does not give a true measure of the pressure at the point of intake.	\$30 \$35 \$15 \$20
HYDRAULIC (CLOSED SYSTEM)	U.S. BUREAU OF RECLAMATION BISHOP WAHLER	(1) Remote readout (2) Fairly small time lag if "saturated" bourdon gauges used for reading pressures. (3) Suited for installation in earth embankments, and foundation and abutments. (4) Fast reading on bourdon gauge.	(1) Tips should not be more than 24 feet below the gauge elevation in the terminal house unless ground water level is high, then tips can be lower. (2) Install tubing below frost zone and protect gauge lines in Terminal house. If freezing could be possible, antifreeze may be used.	\$20 --- \$20
AIR (DIAPHRAGM)	SLOPE INDICATOR TERRATEC EARL HALL WARLAM GLOETZL	(1) Relatively small lag time (2) Deairing not required (3) No freezing problem (4) Install the tip in a bore hole of any reasonable depth. (5) Best suited for use in tailings dams and foundations.	(1) Limited experience with some types for proven long term accuracy. (2) Distance of leads to readout is limited and tubes must be buried. (3) Inaccurate or erratic readings when air surrounds the tip. (4) Valves may malfunction when foreign matter gets into tip.	\$100 \$135 ---- \$190 \$180
ELECTRIC	MAIHAK CARLSON	SAME AS AIR	(1) Limited experience with some types for proven long term accuracy. (2) Sometimes erratic readings. Not well suited for dam embankments.	\$275 \$180

housing should generally be at an elevation lower than the piezometer tip. These installations require long tubing lines, rather expensive and complex gage houses, and the use of careful techniques during installation and operation.

Air (Diaphragm) or Pneumatic Type - The pneumatic type piezometer consists of a sealed tip containing a pressure-sensitive valve. The valve opens or closes the connection between two tubes which lead to the surface, or the embankment face, at any convenient location and elevation. In the Warlam piezometer, flow of air through the outlet tube occurs as soon as the inlet tube pressure equals that of the pore water pressure. In the Gloetzl piezometer, hydraulic fluid is used instead of gas, the basic principle being the same. This type of piezometer is probably the best for use in tailings dams.

Electrical Piezometers - Electrical piezometers consist of a tip having a diaphragm that is deflected by the pore pressure against one face. The deflection of the diaphragm is proportional to the pressure, and is measured by means of various electrical transducers. Such devices have negligible time lag and are extremely sensitive. Thus, they are suitable for installation in quite impervious and highly plastic clayey materials. Because of severe environmental problems and long-term stability, the use of electrical piezometers is not generally recommended for installations in embankments where reliable readings are required over an extended period of time.

2. Proposed Facilities

The main purpose of investigating proposed disposal sites is to avoid stability difficulties with the deposit at a future date. This is a planning function and supports feasibility evaluations and design, rather than providing a hazard evaluation. Any large disposal facility should have an investigation consistent with the scope of future planned use of the site. As with investigations for existing facilities, the investigation can be done in two phases: 1) a reconnaissance phase, and 2) a detailed exploration phase.

a. Site Reconnaissance - For proposed sites, this level of study is made, utilizing available data, to compare alternative sites, evaluate environmental effects, and formulate a detailed exploration program, if preliminary evaluation warrants it. Again, the techniques used are observational, supplemented by research and use of available data. Most alternative sites cannot be eliminated by observation alone, but often the most advantageous available site can be readily selected on the basis of observation. Again, experience of the investigator is of extreme importance for proper site selection. The preliminary observations usually need to be backed up by detailed exploration which should be planned during the reconnaissance stage.

b. Detailed Exploration - The same tools used during detailed exploration for existing sites are available for exploration of proposed facilities. Because of a shift in emphasis from hazard evaluation to site feasibility, specific equipment and methods would be different. Presentation of data would also have a change in emphasis, because data developed to establish the feasibility of a site can be used during construction. Certainly, detailed exploration before construction is the key to environmental planning, because the philosophy should be geared toward performing all the steps leading to final site abandonment. The steps involved, then, are planning, design, construction, operation, and abandonment. Exploration that is conducted with these steps in mind assumes greater value than exploration to only accomplish a single purpose.

(1) Mapping--Topographic and Geological - Although topographic mapping is highly desirable when appraising an existing site, it normally is required for a planned facility of any scope. A suitably detailed topographic map is needed to locate and document all drilling, trenching, and other exploration work, and is also essential for preparation of cross sections that will depict subsurface exploration and subsurface conditions. Finally, the topographic map is essential to show the planned facilities.

A geologic map to appropriate detail is prepared on the topographic map. The geologic features should be shown with completed exploration and proposed project features where possible to show interrelationships. For planned disposal facilities, the map should emphasize geologic features that would affect the design and construction of the facility, such as soil depth, rock types and physical characteristics, bedding structure, ground-water indicators such as springs, and any other features that could physically affect the planned facility.

(2) Trenches and Test Pits - In many cases, shallow trenches or test pits can be excavated through soil overburden to expose underlying geologic units, and provide sufficient information for design. Trenching is fast and economical and provides maximum information for the expenditures involved. Trenches can be placed at strategic locations and in-place testing of foundation materials can easily be performed in trenches. Calculations of overburden stripping are best made from trench exploration information. Of course, trenches have depth limitations; test pits can be carried to considerable depths with shoring, but this procedure becomes expensive, and drilling may be necessary for obtaining information at depth. Trenches often are the first stage in a field exploration program and provide a good basis for planning additional exploration.

(3) Drilling - For proposed facilities, drilling offers the same benefits as for existing facilities; however, in many cases, the type of equipment used would differ. For sites that are generally

underlain by rock at shallow depths, rotary drills using coring devices are the most common type equipment. Light rotary coring rigs are most adapted to sites with steep slopes that are underlain by shallow rock. The Becker hammer drill system is valuable for drilling at sites with deep alluvium, but cannot be used in hard rock. Sites with deep soils are explored to the best advantage with soil sampling rotary rigs. Hollow-stem auger rigs are well suited for deep soil situations.

(4) Geophysical Surveys - Geophysical prospecting, particularly seismic refraction, is an excellent tool where a site has considerable soil cover over hard rock. Seismic refraction surveys are useful and inexpensive in extending subsurface information outward from drill holes across a site. Discontinuities, such as faults, often can be found using seismic refraction or resistivity surveys.

c. Logging and Sampling - Procedures for logging exploration and sampling materials are the same as for existing and proposed facilities.

For proposed facilities, the program needs to be carefully staged so that location of planned facilities can be modified, if necessary, as foundation exploration proceeds. Close coordination between field and design functions is essential. The exploration program should be geared so that design changes can be made or, in the case of very unusual field conditions discovered during exploration, a particular site can be eliminated from further consideration.

d. Field Testing - Field testing has been discussed under "Existing Facilities." For new facilities the same methods and procedures apply. In general, field testing for proposed facilities would be oriented more to foundation conditions and, in some cases, borrow materials. Tests of in-place rock conditions for large complex projects might be contemplated. For a large borrow operation, field gradation and density testing should be considered as a supplement to a laboratory testing program.

C. DISPOSAL FACILITY ANALYSIS AND DESIGN

This general section describes the basic concepts of analysis and design as they are understood in civil and other engineering disciplines, and as they may be applied to tailings disposal facilities.

1. Distinction Between Analysis and Design

In many branches of the engineering disciplines, analysis is basically an examination of structures or components thereof to assess whether they can safely and economically serve the intended purpose; that is, whether they meet generally accepted "standard" criteria. Standard criteria are normally related to allowable materials stress, deflection or settlement, and economy. Often components of a structure and even an entire structure will have to be analyzed for revised loading conditions as a result of human demands or nature itself. For example, an existing bridge may be considered for use by heavier trucks, an airport runway may be contemplated to serve larger aircraft, and an embankment may be considered for enlargement. In the first case, the engineer will evaluate the new stress levels in existing girders and other members; in the case of the runway, the existing pavement thickness will have to be analyzed for adequacy under heavier loads. Stability analyses would be performed to evaluate the modified embankment.

Engineers have seen very rapid technical advances in the geotechnical field of engineering over the last few decades. Karl Terzaghi was probably the first to formalize the basic theory of soil mechanics in the mid-1920s. On the basis of his work and that of others, engineers have gradually developed a better understanding of the behavior of earthen structures. Today, after significant additional contributions by many researchers and practicing engineers, the geotechnical engineer is in a position to perform sophisticated analyses and can rely on the results obtained with a reasonably high degree of confidence. In view of the above, it would be natural to find variations in the safety of earth structures, depending on the time during which they were built and the degree of available technology which was applied to their design and construction. Of course, other factors such as environmental and economic considerations have played and do play important roles. Existing earthen facilities have various shapes and are subjected to varying loads. Load conditions are functions of, for example, the type of structure, the position of the phreatic surface, and the inclination of embankment slopes. The configurations of existing tailings dams or leach dumps are, as in the cases of the bridge girders and runway pavement, definable. Analyses can be performed on the specifically shaped facility under given load conditions to give an indication of its overall safety. If the factor of safety is below a set standard, then the analysis has indicated that design and some type of remedial work should be initiated.

The engineer's experience and ingenuity play important roles in the design of effective remedial measures, as well as in the planning and design of new facilities. Following the basic planning process, the various components of a structure are dimensioned. The planning and dimensioning process is commonly known as design.

2. Engineering Analysis as a Design Tool

The foregoing section defined analysis as it relates to existing structures. Analytical techniques are used in the design process in a similar manner. The procedure is basically a "trial and correction" or iterative process. The dimensions of a structural component, such as a drain in a dam, or slope of an embankment, are first chosen based on the experience of the engineer with materials properties, seepage forces, etc. Load conditions are imposed and the safety factor evaluated by appropriate analyses. If unsatisfactory conditions are indicated for the selected embankment shape and boundary conditions, drain configurations may be modified or the slope may be flattened, or both, and the analyses repeated. This process is continued until the optimum conditions have been found.

3. Analytical Procedures

Section B of this chapter describes investigative techniques that can be used for evaluating subsurface conditions in foundations and existing dumps and impoundments, including extraction of disturbed and undisturbed samples. Appendix A outlines test methods and the manner in which materials properties can be determined. With the data from field investigations and testing at hand, appropriate analyses can be performed to evaluate whether design standards and criteria are met, giving due consideration to the factors described in the foregoing section of this chapter.

In performing stability analyses, the characteristics of the foundation and the embankment materials have to be considered together--that is, stability analyses cannot be performed on the embankment without considering foundation conditions and vice-versa, if meaningful results are to be obtained. Analysis procedures described herein apply to existing, as well as proposed, tailings dams or leach dumps. Dumps may or may not be subjected to seepage forces; if not, relatively straightforward stability analysis may suffice. However, where water is present, as revealed by inspection and/or explorations and direct observations, seepage forces will have to be included in the stability analyses in a manner similar to that for an impoundment facility. Where the foundations consist of alluvial and other soil type materials, settlement studies will be required.

Generally, there are four types of stability analysis methods; these are the infinite slope, the widely used slip-circle analysis, the noncircular arc (wedge) method, and the finite element method. The noncircular arc method is not widely used unless there is a definable weak plane upon which failure could occur. The slip-circle analysis method may have several versions. All of these methods can be used either for static conditions or with pseudo-static earthquake forces included. A complete documentation of the stability methods used during this research, in addition to a list of published references on the type of stability analysis, is contained in Volumes 2, 3, and 4 of this report.

A few organizations are presently equipped to perform the static and dynamic finite element methods of analysis. Presently, the finite element method of analysis has not been programmed explicitly to take seepage forces into account; however, these can be included by specifying certain boundary conditions. However, studies are in progress at the present time to include seepage forces in a more refined manner. This program may be completed in the near future. Several ways of including seepage forces in the slip-circle analysis are possible. Most of these methods utilize flow nets as a basic initial step.

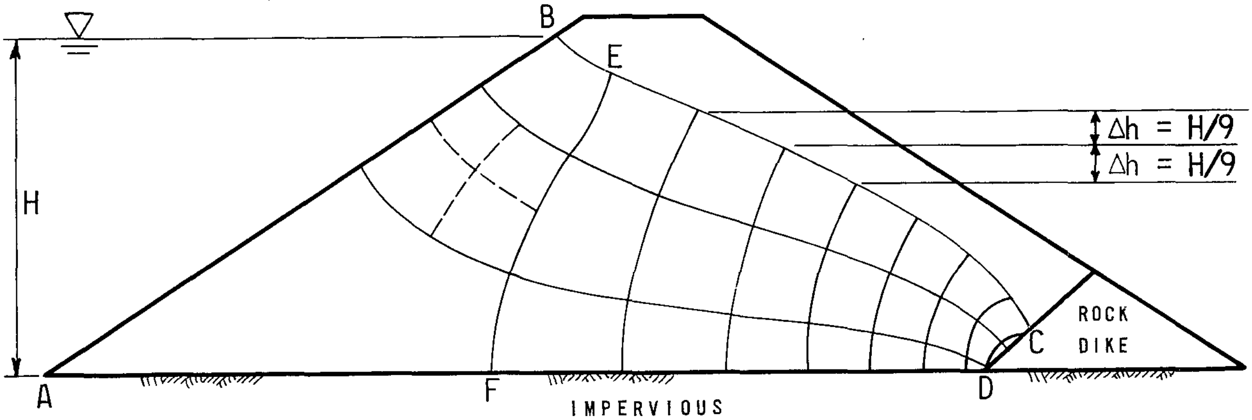
The finite element method of analysis lends itself only to electronic computer solutions because of the complexity of the equation system that needs to be solved. Slip-circle and wedge analyses can be performed with or without computers. However, solutions by computers are more effective as less time is required for the computations themselves, and a greater combination of potential influencing factors can be considered. Numerous computer programs for slip-circle analyses have been prepared and can be developed with little effort.

The following summarizes the various available methods of stability analysis and discusses their usage and limitations. The discussions presented herein are intended to make the reader aware of the various concepts and to introduce him to the basic theories and failure modes in a general sense. In-depth studies of the various methods, along with sound engineering judgment are mandatory for problem solutions. Detailed procedures for applying the methods and procedures discussed are contained in many publications on soil mechanics and earth dam design.

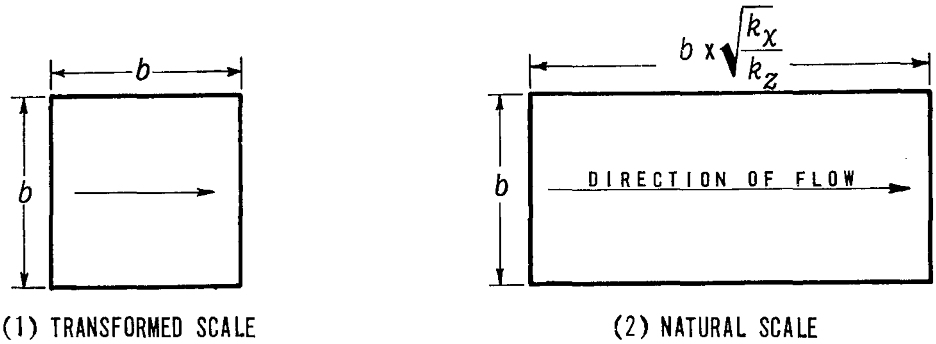
a. Seepage - Probably the most reliable way of evaluating seepage forces is the graphical representation of flow through soil, which is known as the flow net. From this, information may be obtained on seepage forces acting on a free body and on the possibility of danger of a "quick" or liquefaction condition at points where seepage water comes to the ground surface. Seepage quantities can also be computed by use of accurate flow nets.

The path along which a particle of water follows in its course of seepage through a soil mass is called a flow line. Line BC on Drawing VII-1a represents a flow line for the assumed conditions of homogeneous soil and isotropic flow. Along each flow line there must be a point where the water has dissipated a given specific portion of its potential energy. A line connecting all such points of equal total head is referred to as an equipotential line, which should intersect the flow line at an angle of 90 degrees. EF in Drawing VII-1a is such a line. The line AB is the upstream equipotential and forms one boundary condition. Other boundary conditions on Drawing VII-1a are the impervious foundation, the top flow line, and the downstream equipotential line.

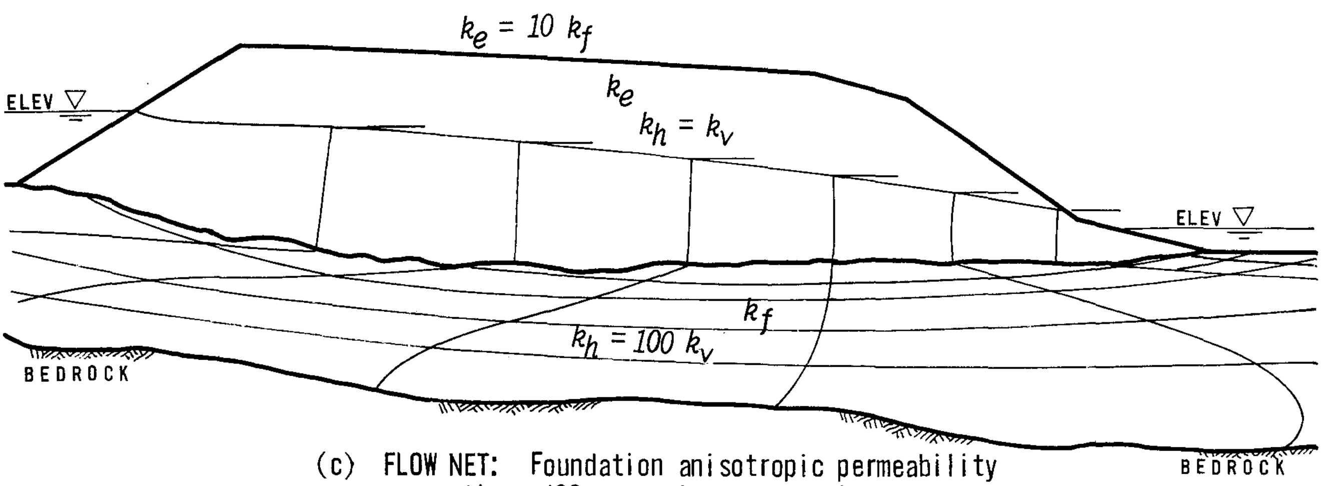
Drawing VII-1a shows a flow net in a homogeneous embankment, which is the least complex kind to present graphically. In cases where the permeabilities in the horizontal and vertical directions within a mass are different (anisotropic), the graphical model of the cross section will have to be transformed in order to draw the flow net using the right angle criterion for the intersection of flow and equipotential lines. Where the horizontal coefficient of permeability (k_x) is greater than that of the vertical (k_z), the natural horizontal scale will have to be reduced by a factor equal to $\sqrt{\frac{k_x}{k_z}}$; this is illustrated on Drawing VII-1b.



(a) Homogeneous embankment



(b) Diagram used for the derivation of the expression for effective permeability



(c) FLOW NET: Foundation anisotropic permeability ratio = 100; normal reservoir level

W. A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	FLOW NETS		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO 0620	DATE 4	DRAWING NO VII-1

Increased complexities in the graphical presentation arise where the horizontal and vertical permeabilities are different and the foundation and an embankment are of different characteristics, or where more than two material types are present. Kealy and Busch[1] have developed a computer program to analyze complex seepage problems. A more complex flow net, drawn to true scale, is shown on Drawing VII-1c, which W. A. Wahler and Associates prepared and presented in a report entitled "Analysis of Coal Refuse Dam Failure, Middle Fork, Buffalo Creek, Saunders, West Virginia." The engineer's experience and judgment become invaluable factors in analyzing seepage forces under such conditions.

b. Infinite Slope Analysis - The infinite slope method is a very simple method of analysis and may be used for analyzing the potential for near-surface type failures in refuse deposits and embankments composed of cohesionless, as well as fine-grained cohesive materials. In embankments with variable material and strength, the results of the analyses will only give a rough idea of the stability conditions of the exterior slopes.

As in all other stability analysis methods, the engineer is interested in determining whether the factor of safety meets acceptable standards. The factor of safety is defined as FS = S/T on the potential failure plane (see Drawing VII-2) where S represents shear strength and T represents the shear stress. As shown on the referenced drawing, it is possible to derive general formulas for materials with both cohesion and friction, to be applied to many combinations of slope inclination, ground-water level, earthquake, and soil properties.

Although the infinite slope method of analysis represents only an approximation of the near-surface stability, any value of factor of safety below 1.1 or 1.2 may indicate the possibility of either progressive failure or major failure if the stress conditions were varied only slightly from those assumed.

c. Slip-Circle Analyses - The stability condition of slopes with limited height can be evaluated by the circular arc method and modifications thereof. Three approximate failure modes are shown on Drawings VII-3a, VII-3b, and VII-3c. Drawing VII-3b shows a common circular failure surface; the other two are compound surfaces, one made up of several straight lines and the second of a combination of straight lines and arcs.

The circular arc method of analysis appears to have been used first by K. E. Petterson in 1915 or 1916 during the study of the quay wall in Goeteborg, Sweden. Therefrom comes the term Swedish Method. Subsequently, an elaborate study was carried out on embankment failures along Swedish railroads by the Swedish Geotechnical Commission under the leadership of W. Fellenius. These studies indicated that the failure surfaces generally did not deviate greatly in shape from the circular cylinder. In its original form, the method is applicable only to homogeneous, isotropic finite slopes.

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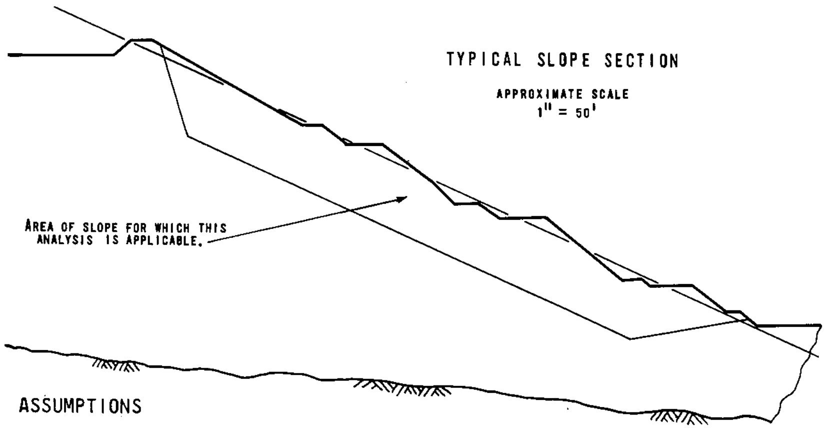
[1]"Determining Seepage Characteristics of Mill Tailings Dams by the Finite Element Method," by C. Dan Kealy and R. A. Busch, Report of Investigations 7477, Bureau of Mines, January 1971.

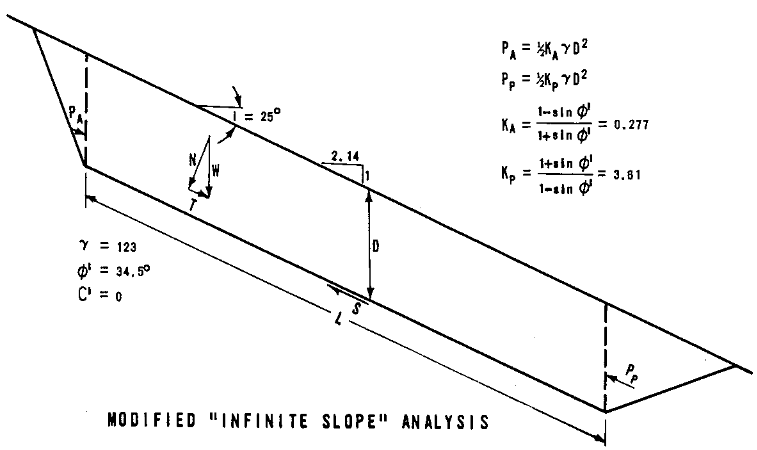
TYPICAL SLOPE SECTION

APPROXIMATE SCALE
1" = 50'



ASSUMPTIONS

1. Shear strength parameters $\phi' = 34.5^\circ$, $C' = 0$ based on undisturbed embankment samples. Cementation produced by chemical alteration could increase the shear strength near the outer edges of the slope thereby significantly influencing the infinite slope stability results.
2. The phreatic surface is located below the deepest assumed failure surface, hence no pore pressures were considered in this analysis.
3. This analysis has been performed for average slope conditions. Locally oversteepened slope portions would exhibit lower results than presented hereon.



MODIFIED "INFINITE SLOPE" ANALYSIS

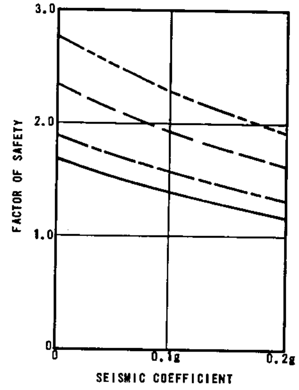
$P_A = \frac{1}{2}K_A \gamma D^2$

$P_P = \frac{1}{2}K_P \gamma D^2$

$K_A = \frac{1-\sin\phi'}{1+\sin\phi'} = 0.277$

$K_P = \frac{1+\sin\phi'}{1-\sin\phi'} = 3.61$

FACTOR OF SAFETY VS SEISMIC COEFFICIENT



KEY

	D/L
———	0.05
— — —	0.10
—— ——	0.20
- - - -	0.30

STRENGTH:

$S = N \tan\phi' + P_P - P_A$

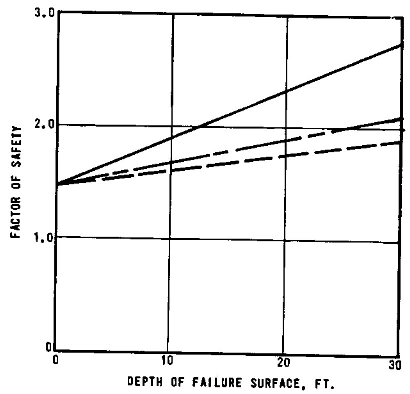
$N = \gamma DL \cos^2 i$

STRESS:

$T = \gamma DL \cos i (\sin i + K \cos i)$

WHERE K = SEISMIC COEFFICIENT ASSUMED TO ACT IN A HORIZONTAL DIRECTION.

FACTOR OF SAFETY VS DEPTH OF FAILURE SURFACE



KEY

——— LENGTH OF FAILURE SURFACE = 100 FEET
— — — LENGTH OF FAILURE SURFACE = 200 FEET
- - - - LENGTH OF FAILURE SURFACE = 300 FEET

FACTOR OF SAFETY:

$$FS = \frac{\text{STRENGTH}}{\text{STRESS}} = \frac{S}{T}$$

$$= \frac{\gamma DL \cos^2 i \tan\phi' + \frac{1}{2}(3.61-0.277)\gamma D^2}{\gamma DL \cos i (\sin i + K \cos i)}$$

$$= \frac{\cos i}{\sin i + K \cos i}\tan\phi' + \frac{1.666}{\cos i (\sin i + K \cos i)} \cdot D/L$$

FOR SEISMIC COEFFICIENT K = 0

$FS = 1.47 + 4.36\ D/L$

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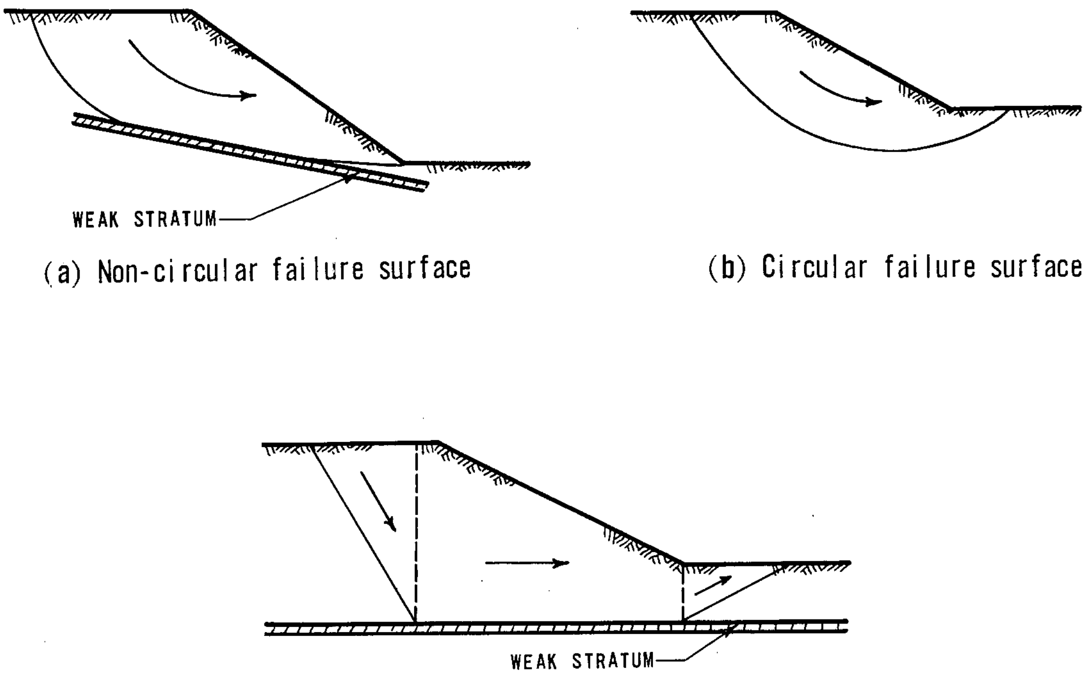
W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	TYPICAL STABILITY ANALYSIS RESULTS INFINITE SLOPE METHOD		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. VII-2



(a) Non-circular failure surface

(b) Circular failure surface

(c) Sliding block failure

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	FAILURE - LIMITED HEIGHT SLOPES		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO. 0620	DATE JUNE 1974	DRAWING NO. VII-3

In this method and other circular methods discussed subsequently, failure surfaces may be assumed with specific centers and radii and the computations performed for this condition. This is carried on until the critical circle has been found. Computer programs are available for automatic search for the critical surface.

The Swedish slip-circle method in its original form may have little applicability in the analyses of existing dumps and impoundment facilities because of their heterogeneous nature. For such facilities, improved circular methods, known as the Method of Slices, Bishop's method, and the simplified version of the Bishop's method developed by Janbu et.al., (1956) can be used to obtain more reliable results. These are better since they lend themselves to taking into account strength variability in the material mass. Wedge analysis and noncircular methods (Morgenstern-Price) may, in some instances, also be used on such facilities. The result of field explorations may give the best indication of the pertinent analysis method or methods. The improved Swedish method can be used in the design of new facilities as well.

The general formula for factor of safety for circular arc analysis is

$$F = \frac{C' + \bar{\sigma} \tan \phi'}{T}$$

where:

C' = Available cohesion

$\bar{\sigma}$ = Effective intergranular pressure

ϕ' = Internal friction angle based on effective stress

T = Induced shear stresses

The effective intergranular pressure at a specific point on the failure surface is dependent on the total overburden and pore water pressure, and the shear stress will be a function of slope inclination, materials unit weights, seepage forces, and earthquake loading.

Typical stability analyses results are generally presented in the form of showing the critical arc or band of arcs on the cross section being analysed. If the analyses have also considered pseudo-static earthquake loading conditions, it is convenient to show the reduction in critical factor of safety vs seismic factor. A typical stability analysis is shown on Drawing VII-4.

d. Finite Element Analysis - In the process of determining the stability of any slope by any of the conventional methods discussed above, it is assumed that the material in question mobilizes its shearing resistance uniformly over the entire length of arc. This may not always be correct, especially where an embankment may contain several different soil types, each with different stress-strain characteristics. The assumption of uniform mobilization of shearing resistance is not required when using the recently developed finite element method of analysis. The reasons are

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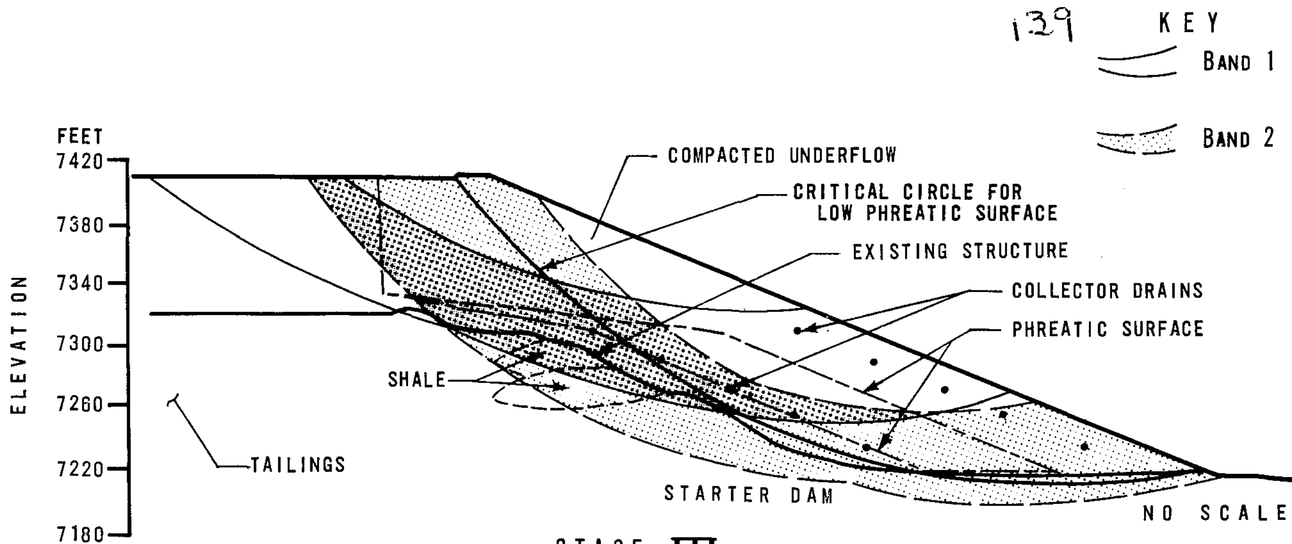
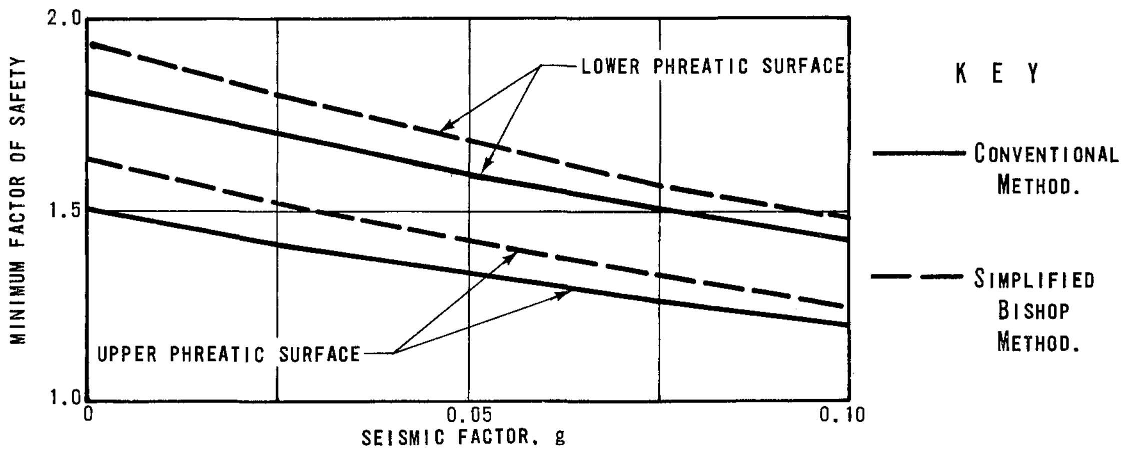


STAGE III



NOTES:

1. PORE PRESSURES WERE COMPUTED ASSUMING VERTICAL EQUIPOTENTIAL LINES.
2. NUMEROUS TRIAL FAILURE ARCS WERE ANALIZED FOR EACH BAND SHOWN ABOVE. ONLY THE FACTOR OF SAFETY FOR THE CRITICAL CIRCLE IS SHOWN FOR EACH PHREATIC SURFACE.
3. THE RANGE OF FACTORS OF SAFETY BY THE CONVENTIONAL METHOD OF ANALYSIS FOR THE LOWER PHREATIC SURFACE UNDER STATIC CONDITIONS IS:

   BAND 1: 1.89–2.67

   BAND 2: 1.81–2.12

W.A. WAHLER & ASSOCIATES	U.S. BUREAU OF MINES GENERAL REPORT	TYPICAL STABILITY ANALYSIS RESULTS CIRCULAR ARC METHOD		
	PALO ALTO • NEWPORT BEACH • CALIF.	PROJECT NO 0620	DATE JUNE 1974	DRAWING NO. VII-4

rather simple. The basic concept of the finite element technique is that a continuous structure may be represented as an assemblage of elements interconnected at a finite number of nodal points. The elements may be triangles, groups of triangles or rectangles for two-dimensional plane strain or plane stress analysis. Within each element, displacements are assumed to vary in such a way that compatibility within the element and along its boundary is maintained.

The input data required for each element for nonearthquake conditions consists of the unit weight, Young's modulus in compression and tension, and Poisson's ratio or, using the more recently developed 1972 nonlinear computer program, the unit weight and several parameters to define the nonlinear characteristics of the materials. Because each element in the assemblage may have a different modulus value from its neighbors, the method is well-suited to problems involving heterogeneity. The computer program solves the set of simultaneous equations defined by the stiffness matrix for each element consistent with the number of degrees of freedom inherent in the structure, as represented by the finite element matrix and any external boundary conditions. It then determines the displacement of each nodal point and for each element, the horizontal and vertical stresses, the major and minor principal stresses, the horizontal and maximum shear stresses, and the angle of orientation from the horizontal for that plane on which the major and minor principal stresses are acting. A recent publication by Corp[2] provides a very interesting correlation of stability analysis results by the finite element and conventional methods of analysis.

The above paragraphs describe the static finite element analysis which solves for displacements and stress conditions in an embankment under static loading conditions. Another computer program is available for assessment of the dynamic stability of an embankment under earthquake conditions. This analysis yields complete time histories of the shear strain in all elements, and factors of safety against the development of liquefaction or some assumed failure strain as shown on Drawing VII-5.

Use of the finite element analysis would normally be considered unnecessarily sophisticated for tailings dam unless the impoundment posed a serious hazard or the construction methods, materials utilization or embankment configuration deviated substantially from normal practice.

e. Settlement Analysis - Cracks which may develop in water-retaining earth and tailings embankments due to differential settlement are one form of distress that can lead to rapid and often total collapse. Numerous examples of such failures are cited in earth dam literature. Cracking allows water to penetrate under full hydrostatic head into the embankment,

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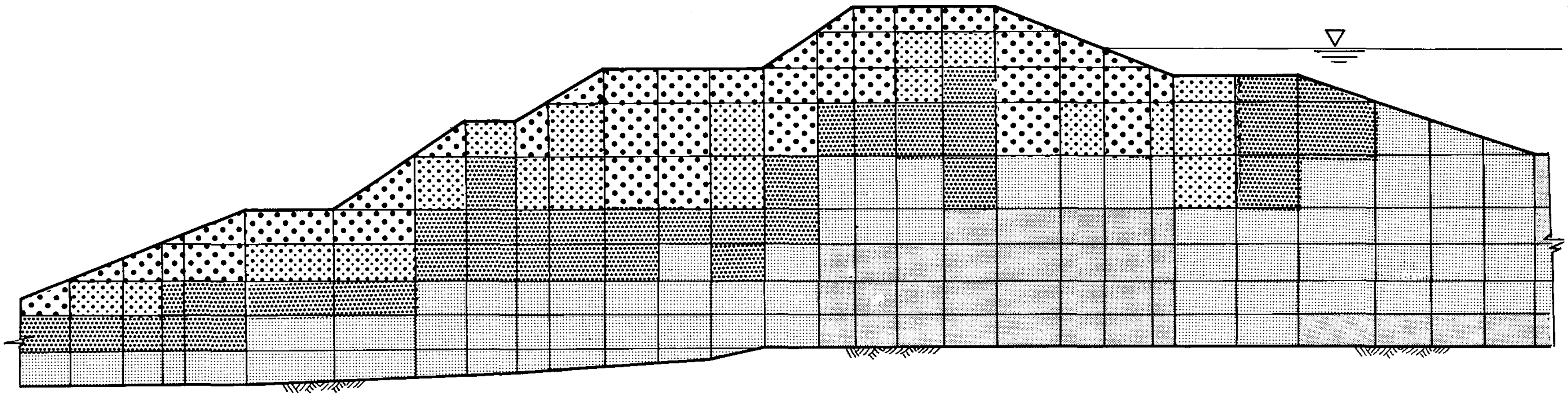
[2] "A Finite Element Model for Stability Analysis of Mine Waste Embankments Subjected to Seepage," by Ernest L. Corp, Ph.D. Thesis, University of Idaho, June 1974.



SECTION LINE XXXII

KEY

PATTERN	FACTOR OF SAFETY
(dense large dots)	LESS THAN 0.8
(fine dots)	0.8 – 1.0
(dense fine dots)	1.0 – 1.1
(fine stipple)	1.1 – 1.5
(light stipple)	GREATER THAN 1.5

NOTES:

(1) THE FACTORS OF SAFETY SHOWN REPRESENT THE RATIOS OF AVAILABLE DYNAMIC SHEAR STRENGTH TO TOTAL SHEAR STRESS AND DO NOT REFLECT THE TIME HISTORY OF VARIATION WHICH ACTUALLY OCCURS.

(2) THE SHEAR STRESS ACTING ON EACH ELEMENT IS ASSUMED TO BE THE ABSOLUTE SUMMATION OF THE HORIZONTAL SHEAR STRESS FROM THE STATIC FINITE ELEMENT ANALYSIS WITH FULL RESERVOIR LOADING CONDITIONS AND 0.65 TIMES THE MAXIMUM PEAK SHEAR STRESS FROM THE DYNAMIC FINITE ELEMENT ANALYSIS.

(3) THE SHEAR STRENGTHS USED FOR THIS ANALYSIS WERE THE APPROPRIATE DYNAMIC STRENGTHS DETERMINED FROM THE LABORATORY TESTING WITH DUE REGARD TO THE INITIAL STATE OF STRESS ACTING WITHIN EACH ELEMENT PRIOR TO THE APPLICATION OF THE DESIGN EARTHQUAKE.

(4) THE FACTORS OF SAFETY FOR THE DOWNSTREAM PORTION OF THE EMBANKMENT, ABOVE THE ASSUMED PHREATIC SURFACE WERE EVALUATED USING THE TOTALLY SATURATED DYNAMIC STRENGTH CHARACTERISTICS OF THE ROCKFILL. PRELIMINARY DYNAMIC TEST RESULTS USING PARTIALLY SATURATED SAMPLES OF THE ROCKFILL INDICATE A POSSIBLE 10 TO 30 PERCENT INCREASE IN DYNAMIC STRENGTH. THE RESULTS FOR THE PARTIALLY SATURATED PORTION OF THE DOWNSTREAM SHELL, THEREFORE, ARE CONSIDERED CONSERVATIVE, AND SHOULD BE RE-EVALUATED ON THE BASIS OF THE RESULTS OF ADDITIONAL TESTING DURING FINAL DESIGN FOR REMEDIAL WORK.

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W. A. WAHLER & ASSOCIATES

U.S. BUREAU OF MINES
GENERAL REPORT

PALO ALTO • NEWPORT BEACH • CALIF.

FINITE ELEMENT MODEL
WITH RESULTS OF ANALYSIS

PROJECT NO	DATE	DRAWING NO
0620	JUNE 1974	VII-5

causing radical changes in the state of stress within the structure. Even when mass instability does not result, internal erosion may soon open clear channels through which embankment materials are carried away, or severe undercutting due to excessive seepage may cause successive slope failures.

If the design is based on settlement calculations, all predictions of the rate and magnitude of settlement and change in pore water pressures should be checked by field instrumentation installed beneath and within the dam. The predictions based on laboratory data can be modified by the actual measurements to provide reasonably accurate long-term estimates. Differential settlement may also cause damage to pipe drains and decant lines located within or beneath the dam. Therefore, the installation of pipes should be avoided at locations where settlement of the foundation is expected.

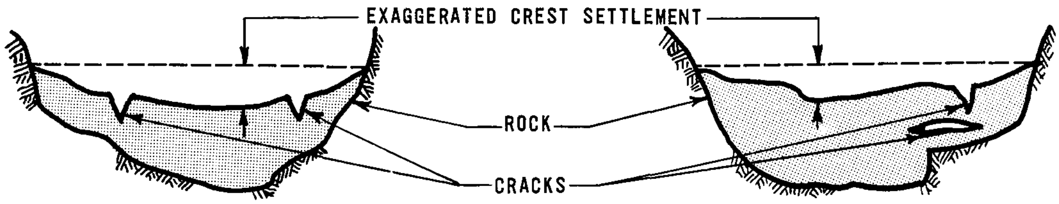
Settlements which would originate within the dam can be reduced by adequate compaction. Where settlements are expected within the foundation due to compressible soils, the decision must be made to either remove these materials or design to tolerate the anticipated settlements. In any case, all organic soils should be removed from the foundation area.

Typical modes of cracking of embankments due to differential settlements from various causes are illustrated on Drawing VII-6.

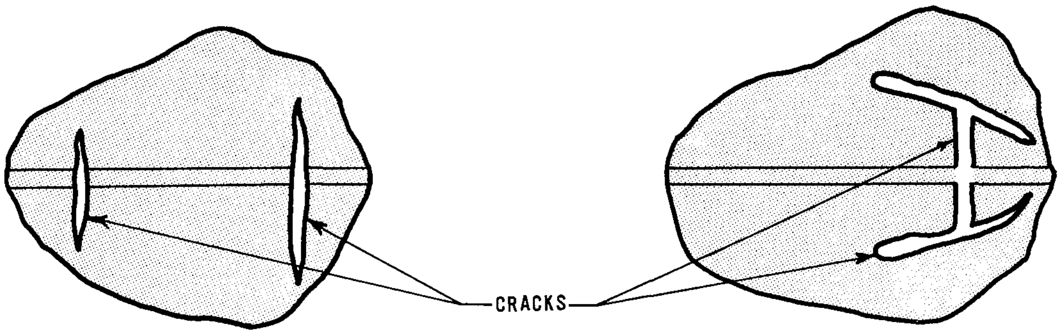
D. EMBANKMENT CONSTRUCTION INSPECTION

1. General

There are several areas associated with the construction inspection of tailings dams that set them apart from conventional earth dam structures. First and foremost, the construction of most tailings dams in the Southwest is continuous and ongoing and may last from 5 to 40 years. For example, Dam 1 at the Phelps Dodge Morenci site in Arizona, was started in 1944 and, most probably, will still be in construction through 1985. Secondly, the principal objectives of inspection for earthwork construction are to observe the construction methods and, coupled with field testing, verify that the structure is completed in accordance with the design assumptions and requirements set forth in the plans and specifications. These objectives are not practical when applied to current disposal methods being used in the copper tailings industry. Plans and specifications are virtually non-existent for existing tailings dams and earthmoving equipment is used only when dikes must be raised. It is important, therefore, to differentiate between the requirements of construction inspection for existing and future tailings dams. For existing structures, all future inspections of the site should be directed toward evaluating whether or not the structure creates a potential hazard. To facilitate this recognition, we have included in Appendix C, of this volume, a hazard recognition summary which presents all of the salient points needed by an inspector for site inspection. With regard to the construction of future tailings dams, we assume that although

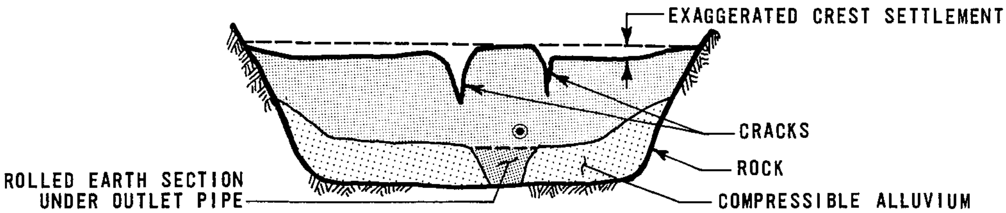


LONGITUDINAL SECTIONS

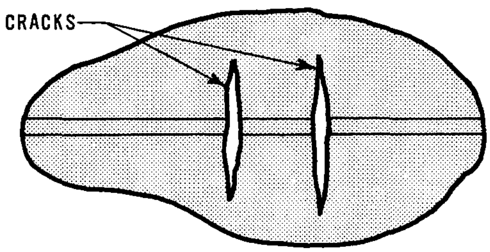


PLAN VIEWS

(a) Loose refuse impoundment facility on irregular foundation



LONGITUDINAL SECTION



PLAN VIEW

(b) Compacted refuse impoundment facility on variable foundation

USBM/MESA or the governing State agency may not be directly involved with the day-to-day construction inspection, they will participate in a regular inspection program at key points during the construction, as well as receive final documentation at the end of construction. The remaining section of this chapter, therefore, presents the objectives and techniques of construction inspection.

The site inspector's responsibilities are necessarily variable in scope. The inspector must be completely familiar with the construction documents before commencement of the work. He should have a close relationship to the project designers and notify the designer of any discrepancies observed, and request clarification for all items not fully understood. The inspector must organize and maintain a system of construction records such as:

- Daily log book and daily report system
- Progress reports on a systematic basis
- Correspondence file
- Payment file
- Change order file
- Shop drawing and sample submittal file
- Substitutions file
- Test and inspection results file
- Site conference file

The site inspector may be a full-time employee of the mine owner if the designer and regulatory agency can be assured that he has the necessary knowledge, skill, and integrity to perform the inspection duties in a professional manner. However, an inspector, employed by the designer, who is highly trained and knowledgable in the field of construction inspection, would be preferable from a technical standpoint.

2. <u>Inspection Requirements or Objectives</u>

a. <u>Owner</u> - The owner/operator of a facility must assign someone to represent him adequately during the construction work. The assigned representative must be given enough authority to make timely decisions on the part of the owner. The owner should establish a sufficient allowance in the project budget to provide for the services of the construction inspector and/or the construction inspection staff to control construction of all structural elements of the disposal systems including the necessary dams and retaining structures (usually made of refuse material). Inspection will have to be full-time or part-time depending upon the nature of the work, the estimated length of construction, and how critical the element under construction is to the performance of the system when completed.

(1) <u>Requirements of Plans and Specifications</u> - The person in charge of performing the work, the inspector checking the operation, as well as the operator, have the responsibility to see that plans and specifications are clear and that these documents are not misinterpreted. Therefore, a thorough study of the construction documents will be required by those performing the work and inspections prior

to commencement of construction. Any errors, inconsistencies, or omissions discovered must be properly dealt with prior to construction, if possible, or as soon as recognized if construction has commenced.

(2) Verifications of Design Assumptions - Inspection and testing are possibly more important for each structures than most other works, because of potentials for deviations in actual materials properties from those assumed in the design. By inspection and testing during fill placement, it will be possible to check characteristics of the materials against those assumed in the design. If the conformance is not proper, the inspector must inform the person in charge of the construction so that timely and proper modifications can be made. If the material from a particular area will not meet specification requirements, it may be necessary to seek out another source or possibly continue placing the same material under a modified design. Any design modification must be reported to and approved by the regulatory agency prior to commencement of the modified construction work.

(3) Site Inspector's Functions - Proper material gradation is of utmost importance in zoned embankments such as the starter dam for a tailings dam. Another important aspect is to continually check material compaction by field density tests. This will serve the constructor in his efforts to attain the goal set for material strength and compression. If such testing should indicate densities below those assumed in the design, additional compactive effort, possibly under changed moisture content, or by the use of different compaction equipment, or a combination thereof, may be required. If significantly greater densities are being achieved than anticipated during design, it may be possible, under certain limited conditions, to reduce the compactive effort with a resulting savings in construction cost.

Proper recording of the construction operations and results achieved will provide a basis for evaluating the effectivenss and efficiency of the design, equipment, and procedures. The results of these evaluations could result in design modifications, the selection of more efficient equipment or change in procedures which could provide significant economical benefits. These economical benefits might be realized on the project under construction and they may also be applicable to similar jobs in the future.

The importance of a competent construction inspector cannot be overemphasized. Good inspection can be worth many times its cost in preventing errors and omissions of construction that might impair the safety and durability of the project and interfere with obtaining value for the money invested. Good inspection demands the results needed but also relieves any unnecessary requirement or impediment to the program that can be eliminated without adverse result to the program. This means that improved procedures can be used if they produce results compatible with the design requirements and specifications.

The construction inspector's basic function is to assure that the most reasonable compliance with the construction specifications is achieved, consistent with the design objectives. In addition, he serves as an extra pair of eyes and should not be satisfied with merely reporting mistakes in the work after they are made. He can avoid misunderstandings by continually reviewing the construction documents and working in conjunction with the person in charge of construction. He should look ahead and be fully acquainted with the construction documents and all phases of the work. He can thus help avoid costly and time-wasting mistakes and foresee bottlenecks due to delayed delivery of material or improper scheduling of the work. By promptly inspecting delivered materials and observing the preparation and installation, he can prevent costly tear-out, replacement, or re-doing of the work. In these and other ways, he can perform a real service to the operator and designer. He thus becomes an important member of the team needed to ensure a smooth-running construction process and a safe and properly constructed project.

The construction inspector must be continually alert to any condition that could impair the safety or functioning of the completed project. In addition, modifications to existing structures, as well as construction of new projects, can create temporary hazardous conditions if the inspector is not alert. Such things as temporarily oversteepened slopes, loose temporary fills, blocked streams, etc., should be carefully observed and their potential for creating a hazard judged.

Note, however, that he is not responsible for and should not, in most instances, undertake responsibilities that are not a part of his services; for example:

- Trying to tell the constructor how to construct the work. This is the responsibility of the constructor.
- Guaranteeing that the work is constructed in strict compliance with the contract documents. This is the responsibility of the constructor.
- Interpreting or ruling on the intent of the construction documents. This is the responsibility of the designer.
- Methods of operating equipment, including safety. This is the constructor's and health and safety regulatory agency's responsibility.

(4) Safety, Effectiveness, and Economy - Disposal of refuse carried out in accordance with plans and specifications under the guidance of a competent inspector will hopefully achieve continual safety, not only during the active life of the facility, but also after its abandonment. Provisions of guidelines, coordination of efforts, and cooperation between the inspector and those disposing of the refuse material will increase effectiveness. Effectiveness, in turn, will be economically beneficial.

b. Regulatory Agency - The regulatory agency should receive and review a complete set of plans and specifications, including corrections and amendments thereto. These will be evaluated from the standpoint of adequacy, completeness, construction safety, and potential for creation of future hazards. The approval of the plans and specifications for construction will be based on such review. Approval of plans and specifications for construction does not imply that the completed project will not be disapproved if construction is not performed in accordance with the plans and specifications.

The regulatory agency should have its inspection staff regularly check the construction operations. As a minimum, the site should be visited when foundations are exposed and prepared for placement of materials, whenever a new operation commences, and at regular intervals. During these visits, inspectors should cover the entire site, paying particular attention to the following:

- Foundation conditions and preparation
- Unusual site conditions not anticipated in the design
- Construction procedures
- Methods of on-site inspection and control
- Test frequencies, methods, and results
- Any hazardous conditions, and
- Rate of progress

A complete written record must be made of each inspection and photographs should be taken of critical items, as well as general site pictures and operations. If any deficiencies are observed, they must be recorded and reported to the operator's representative. It is the operator's responsibility to devise a method of correcting the deficiency. The regulatory agency must make certain the deficiencies are corrected, but they cannot infringe upon the operator's authority by dictating the method of correction.

3. Techniques of Construction Inspection

The methods of inspection and testing to be applied during construction will depend, to a considerable extent, on the provisions of the specifications. The inspection techniques will be dictated by the type of specifications--method specifications or performance specifications.

In method specifications, as they are defined herein, the method of construction is outlined so that the constructor may produce the finished product by following a specified method of work. It, therefore, becomes necessary to observe construction to ensure that the specified method is followed and periodically test the placed materials as the work progresses. Obviously, method specifications impose greater burden on the designer; the product can only be as good as that resulting from the specified method of construction. If an inadequate product results, revised construction techniques or design revisions will have to be made, as an adequate product must be produced.

On the other hand, performance or end result specifications allow the constructor to carry out the construction work as he chooses. However, he must produce the required product. The adequacy of the product can be measured by tests, as noted under testing in the following section, similar to those performed under conditions of method specifications.

a. <u>If Method Specifications Are Used</u> -

(1) <u>Operations</u> - As the specifications outline the thickness of material lifts, the number of passes to be applied to each lift, and the type of compaction equipment to be used for compaction, the inspector will have to check that the constructor complies with these specifications. Furthermore, the constructor must use the specified material type and place material at the specified moisture content.

The latter may be difficult to comply with due to weather conditions. Also, the available materials may be somewhat different from those anticipated. For these reasons, specifically, modifications in the plans and specifications may be required to obtain the desired end product. The inspector should also assure that the constructor complies with plans and specifications as they relate to zoning in an impoundment facility, the required final grades, and the like.

(2) <u>Testing</u> - The primary tools for evaluating the degree of compaction are earthwork control tests consisting of in-situ density and moisture content. The control standards for accepting or rejecting a given test are usually developed in the laboratory and define the maximum dry density and optimum moisture content for the various laboratory compaction methods. The test results will assist the inspector or technicians, as well as the constructor, in moisture conditioning during construction so that the minimum compactive effort will suffice to achieve the required compaction. In addition, the control tests will serve the purpose of evaluating whether the required fill compaction is met. This, in turn, will indicate whether the required strength of the placed material is as specified. Gradation tests to check actual drainage characteristics of the materials used are also required during construction. Some fine-grained soils must have specific plasticity characteristics. Atterberg Limits testing is generally performed as a check to confirm these characteristics.

b. <u>If Performance Specifications Are Used</u> -

(1) <u>Observations</u> - As the constructor in this case will not be guided as to how to perform the work, but rather will have to guarantee that the product is in compliance with requirements, he may exercise his own judgment with respect to construction procedures. The inspection procedure will take a somewhat different form in comparison to that

required when method specifications are used. Checking of lift thickness of the material placed and the number of passes over each lift with the compaction equipment will not be required. The inspector will, however, be required to observe to see that the general construction procedure is adequate and that improper materials are not placed.

Extensive testing will, in this case, be required to evaluate the consistency of the product with plans and specifications. The tests will indicate whether or not the product may perform as anticipated and serve the intended purpose. If negative results are indicated, removal of the placed materials and replacement with adequate materials will be required if material gradations are improper, or the material would need reworking if, for example, moisture conditioning is improper or compacted densities are inadequate.

If the constructor consistently cannot produce the required product by the construction procedure he follows or other methods he may try, the designer may be forced to modify the specifications to a method specification. However, this should be avoided if at all possible. It will be preferable that the constructor modify his construction procedure so that the required product can be produced.

(2) Testing - Testing procedure should be similar to those outlined above. The number of tests would most likely have to be greater. Hence, a greater number of technicians should be anticipated in comparison to those required when method specifications are used.

4. Documentation of Inspection Control Results

It is always necessary to provide written correspondence among the parties to fulfill the requirements of the specification documents and/or regulatory agency requirements. In addition, the orderly construction of the work requires distribution of information to many sources, and this is best done in writing.

Correspondence is achieved through the use of letters, memoranda, forms, reports, graphs, electronic devices, etc. It is recommended that adequate documentation should be developed during the construction phase as a good practice by all the parties. Many types of forms have been developed, and it can be said that there is a form for any need. Many organizations, individually or through collaboration with other organizations, have developed forms in an effort to standardize, but completely unanimity as to type, contents, arrangement, etc., is not always achieved.

On the proper forms, the inspector, having assured proper compliance with plans and specifications, should provide confirmation to the interested parties. The reports should contain a summary of the construction procedure followed and the results of all field and laboratory tests. These reports should be submitted on a regular schedule to the regulatory agency.

The construction procedure and test results should be reviewed with the design organization during construction. This may be advantageous from the standpoint of initiating timely and beneficial construction revisions to possibly obtain the required result for less cost.

E. EMBANKMENT SURVEILLANCE AND INSTRUMENTATION

Surveillance as used herein is defined as the routine visual inspection of a structure's performance as well as the systematic collection, analysis, and interpretation of data obtained from various types of instruments installed within a dam to aid in monitoring and evaluating the performance of a structure. Routine surveillance should be performed by responsible company personnel, as well as regulatory agency inspectors, that are familiar with factors that cause hazardous and environmentally degrading conditions. The big advantage of company inspections is the day-to-day familiarity with site conditions as they develop. Also, there should be no need for more than quarterly or bi-annual inspections by agency personnel, if the facility is properly inspected, documented, and maintained by company personnel.

Good surveillance and recording techniques can add to the body of knowledge concerning the performance of embankments and impoundments. The recorded performance should be compared to the performance anticipated during the design and analysis phase, or with a developed historical record of structure response. Special monitoring of a tailings or leach dump deposit is required where it was allowed to develop in an uncontrolled manner and/or where signs of instability or environmental degradation are detected. Where such conditions exist, data from instrumentation arrays may be required to adequately judge the condition of the deposit. The selection and installation of instruments must be performed by or under the supervision of a person experienced in the techniques. Interpretation of the results of specialized monitoring data usually requires sophisticated analysis. For example, if the purpose of instrumentation is to determine stability, the study must be performed by an experienced soils engineer.

During the course of investigation for the three sites reported on in Volumes 2, 3, and 4 of this report, a limited surveillance and inspection program was developed in order to determine both the gross magnitude of pore pressure and movement developed at typical deposits and the reliability and success of utilizing currently available instruments and installation techniques for use in the mine waste disposal area.

1. Surface Monuments

The installation techniques for each monument included the setting of a 3- or 4-foot long section of rebar into a 12-inch diameter by 12-inch deep concrete collar. This method of installation is relatively fast and inexpensive. Two men can easily install 8 to 10 or more monuments in one day.

The total number of surface monuments will vary at each site depending on the size of each dam and the method of construction being used. For example, on any dam being constructed by the upstream method, surface monuments should be installed on each major bench at the quarter points (distance between each monument equal to approximately 25 percent of the total berm length) if the berm is less than 2,000 feet in length, the fifth points (20 percent of the total berm length between monuments) if the berm length is between 2,000 and 5,000 feet in length, or at 1,000-foot stations if the berm length exceeds 5,000 feet. If the dam is being constructed by the downstream or centerline method however, the installation of surface monuments cannot be completed until such time that a berm has been constructed which usually occurs near the end of complete construction.

It was determined that the time interval of readings of surface monuments for tailings dams being constructed by peripheral discharge methods can be scheduled to provide a maximum amount of information. Survey readings should be scheduled such that three or four sets can be obtained at equal time intervals during deposition and then at monthly intervals after the pond has been filled until it is observed that major horizontal and vertical movements due to pond filling has ceased. It is convenient to plot the resulting data on semi-logrithmic paper (one log cycle by 70 divisions) with the time in days from point of first filling as the abscissa and settlement and/or horizontal movement in tenths of foot as the ordinate. Long term monitoring data for each monument should be plotted on an arithmetic grid with settlement or horizontal movement vs day of the year. Significant data regarding the loading history, such as day of first and final filling of a pond should be superimposed on both graphs referenced above to aid in the interpretation of resulting data.

2. Piezometers

Although open well piezometers were used during the present research program, it was determined that these types of piezometers do not respond quickly enough to changes in pore pressure to be used in copper tailings dams. The use of pneumatic piezometers is preferred because of their more rapid response time.

With regard to locating piezometers in the field, it is better to select certain areas of the dam as test sections and concentrate instrumentation efforts rather than randomly installing a number of instruments throughout the deposit. The number of test sections required will, of course, vary depending on the size and type of the structure to be instrumented, and the method of construction; however, two test sections having 3 to 6 piezometers each should be considered as a minimum. For tailings dams being constructed by the upstream method, a typical pattern of piezometer location at each test section may consist of the following:

a) Existing Tailings Dams - On a bench located at less than one-half the height of the structure, piezometers should be placed using a down-hole technique at an approximate elevation corresponding to the one-third and two-thirds height of the dam as measured from the berm elevation to the foundation. This installation technique should be repeated at approximately 50-foot height intervals.

b) New Tailings Dams - The installation technique and number of piezometers to be used in a new structure is dependent on the construction method to be used. For dams using a centerline or downstream method, it may only be necessary to install several piezometers in the downstream half of the embankment in order to determine the location of the phreatic surface with regard to the foundation contact or drainage collection system (if used). For new dams using an upstream method, a technique similar to that referenced above for existing dams should be considered except that at approximately 50-foot height intervals, piezometers should be installed at a depth of 10 and 30 feet in each of two holes located about 100 and 200 feet inside the crest of the dam. The above scheme will provide a more thorough picture of pore pressures acting within the exterior shell of the dam than that proposed for existing dams.

c) Leach Dumps - As discussed in more detail in Volume 4 of this report, a measurable phreatic surface was not detected during the course of our research work at the Chino Leach Dump. This is not to say that measurable water pressures cannot develop at similar deposits, but rather any potential problem regarding the buildup of water pressure at a leach dump would, most likely, be preceded by outward signs of seepage such as discoloration, slope ravelling, etc. It would appear, therefore, that piezometer installation at leach dumps should be reserved for those areas of long-term observed seepage or any new areas that could forewarn pending instability.

3. Internal Movement Devices

As discussed in Section B of this chapter, the installation of a device to monitor internal movements within a tailings dam or leach dump can provide valuable information regarding historical trends for a given construction method. Although the costs associated with installation and data collection are by no means insignificant, serious consideration should be given to including at least one internal measurement device for any major structure. The location and installation techniques similar to those used for the Morenci site (see Volume 2) were successful and are recommended for consideration.

CHAPTER VIII

GENERAL PRINCIPLES AND TAILINGS TECHNOLOGY MANUAL OUTLINE

CHAPTER VIII

GENERAL PRINCIPLES AND TAILINGS TECHNOLOGY MANUAL OUTLINE

A. GENERAL

Recent failures and reports of failures at metal/nonmetal tailings disposal sites have served to augment the need for improved tailings technology. The failure of the coal refuse dam on the Middle Fork of Buffalo Creek on February 26, 1972, while not directly applicable to metal/nonmetal disposal practices, precipitated an intense interest in refuse disposal by national and state legislators and administrators along with citizen groups and the general public. It is to the credit of the Bureau of Mines that research work on tailings disposal technology, both by Bureau and contractor personnel, had already been in progress for several years before the Buffalo Creek disaster. However, since that failure, a greater than usual degree of visual inspection and evaluation has been performed by USBM and MESA (Mining Enforcement and Safety Administration) personnel.

Visual inspection and evaluation of tailings disposal facilities alone will not, however, suffice to achieve the long-term goal of the Bureau for safe and environmentally acceptable tailings disposal sites. The immediate effort of visual inspection has been directed toward eliminating or reducing any readily recognizable tailings disposal hazards. This short-term program will serve to reduce the potential for immediate disasters by helping to identify surficial conditions of instability. Such a surficial program cannot, however, control or identify the long-term, latent, deep seated hazards. These latter hazards can only be identified by thorough field evaluations based on a well-planned subsurface exploration program, and accompanying sampling, testing, analysis, and design considerations.

B. REGULATORY AGENCIES

Since the inception of the research project which forms the basis for this report, the regulation of metals/nonmetals mine and refuse disposal sites has been separated from the USBM Health and Safety group and a new regulatory agency, MESA, created. MESA, in early 1974, had not appreciably changed from its antecedent Health and Safety image, and was divided into three major groups: coal mining activities, metal/nonmetal activities, and a technical support function. While the MESA Office of Technical Support has, and will continue to have, a research oriented interest in mill tailings disposal technology, the prime area of interest for the MESA groups will be in the development, promulgation, and enforcement of mining health and safety regulations. Thus, the Bureau of Mines can, and has, returned to its primary concern as a resource and research agency chartered with the responsibility for on-going research in tailings disposal technology. All the work necessary to reduce the recognizable hazards noted in Section A cannot be completed by the MESA field personnel alone. Consequently, for some interim period while the now separated USBM and MESA groups are clearing their respective files of suspect disposal sites, there will necessarily be much coordinated field work. The USBM long range program will, however, be dedicated to the on-going development of Bureau research staff, industry personnel, and regulatory agency groups in the area of improved tailings disposal technology. This technology must result in the organization of a fund of knowledge that will permit the economic construction of disposal sites that are safe for the industrial site personnel and the surrounding public and environmentally acceptable during both the operating and final abandonment stages.

C. REGULATORY POLICY

Although the USBM is not directly involved in the regulation of disposal sites since the creating of the MESA agency to assume the enforcement phase of tailings disposal, a brief discussion of regulatory philosophy and policy will serve to indicate the role that future research must take in assisting those who are to act as regulators. While more than one Federal agency may be involved at a particular site as a regulator (the Environmental Protection Agency, the Bureau of Land Management, the Forest Service, and others), along with State agencies (Water Resources, Mining Agencies, Fish and Game groups, and others) it is imperative that all agencies be coordinated to achieve the single goal of economic construction of safe and environmentally acceptable disposal facilities. As a result, any single element, dear as it may be to the heart of a single agency, must be combined with all other elements in the light of the goal defined above. Thus, emphasis on clear water emissions cannot take precedence, as it apparently did at Buffalo Creek, over the stability of the embankment unless other design measures are accomplished to allow the two elements to be achieved simultaneously.

1. Acceptance of Design

A single responsibility for the acceptance of design must be assigned. Depending upon the circumstances at a given disposal site, this may be a single Federal or State agency, or it may be some combination of these. In any case, the responsibility must be defined, and the authority to direct the completion of the various portions of the design, construct, and operate cycle assigned. In general, the district or subdistrict office of MESA will be the agency with this responsibility and authority. A cardinal tenet of the responsible agency must be that they do not design the disposal facility. The responsibility for design is entirely upon the mine or mill operating management. The reasons for this assignment of responsibility are simple: if the regulatory agency is the one which designs the disposal facility, then this agency must also assume the responsibility for the adequacy and safety of that design; additionally, designs of facilities must, for economic reasons, combine safe designs with practical operating requirements at a particular site and only the owner can best develop this. Thus, the owner/operator conceives and completes the design, along with the field sampling and testing program to establish the site and materials parameters that support the completed design. The regulatory agency accepts (or rejects) the design based on their judgment of the material presented. If the design is rejected, the regulatory agency can and should indicate the reasons for the rejection, but should not recommend or advise a new design. Such recommendations would place the agency in the role of responsibility for the adequacy and safety of the new design, and restrict the owner in development of procedures which are compatible with operation of the facility.

2. Data Required and Criteria for Review

The amount of material required to permit the regulatory agency to assess the adequacy of a disposal site design is considerable. The reader is referred to a report prepared by W. A. Wahler and Associates under USBM Contract S0122084 entitled "Coal Mine Refuse Disposal Practice and Technology" for a much more rigorous treatment of the subject.

As a minimum requirement, the following data elements must be included in the design submittal:

Site Conditions
- General Description
- Hazard Potential Information
- Environmental Impact Considerations
- Geotechnical Considerations
  - Physiography
  - Geology
  - Seismicity
- Hydrologic Investigation
- Site Information
  - Topographical and Geologic Maps
  - Trench and Test Pit Data
  - Drill Logs and Test Hole Locations
  - Geophysical Surveys (if applicable)
  - Laboratory Test Results
  - Instrumentation (where applicable to existing portions of the proposed facility)

Materials Characteristics and Properties
- General Description of Disposal Generation Process
- Field Determinations
  - Moisture Content and Dry Density
  - Penetration Resistance
  - Shear Strength (if applicable)
  - Permeability (if applicable)
- Laboratory Determinations
  - Classification and Index Properties Tests
  - Moisture Content and Dry Density
  - Specific Gravity

Compaction and/or Relative Density
Permeability
Consolidation
Shear Strength (by most applicable method)

Analytical Procedures
Details of Analysis Procedures
Seepage
Stability Analysis (by most applicable method)
Finite Element Analysis (if applicable)
Settlement Analysis
Details of Facilities
Foundation
Dump or Embankment
Impoundment
Appurtenant Structures

Design Details
Embankments
Spillways or Decant Facilities
Diversion Facilities
Operational Considerations
Surveillance Program
Abandonment Procedures

3. Surveillance

As part of the design submittal for regulatory agency approval, a construction surveillance procedure and reporting system should be defined. As with the original design, it is the responsibility of the owner/operator to maintain the construction surveillance program. Such a surveillance program is necessary, since the best designed structure is only as good as the assurance that design features have been implemented during the construction program. Since most tailings disposal facilities are dynamic and never really leave the construction phase until they finally reach the abandonment point, construction and operation surveillance are much the same thing. It is the role of the regulatory agency to see that the surveillance program is being maintained, and that the data resulting from the surveillance is in accord with the parameters used in the design analysis. Thus, if the design is predicated on a given density of the material, the data generated by the surveillance program should be checked to verify that the design density is indeed being achieved. Another aspect of the regulation of the surveillance program is to verify that the testing and inspection procedures are proper, and that fallacious (or even fictitious) data is not being generated. An adequate surveillance program must be defined at the time of design approval, and must include the reporting procedures, definition of the testing procedures that are integral to the program, and a long-range time table for checkpoints on both surveillance and design.

4. Existing Disposal Sites

While most of the foregoing discussion applies most directly to new or proposed disposal facilities, much of the philosophy and practice can be applied to existing facilities. However, since there is a finite point in time at which the regulatory agency assumes authority over a given site, considerable judgment must be applied to determine how immediate the need is for detailed design studies. A review of available data on the original site topography, along with basic construction and operational data can often assist in the evaluation of a disposal site. The owner/operator can utilize such historical data in the same manner as the development of the design for a new site. However, the regulatory agency must require well documented verification of any such historical data where it might critically influence the stability of the existing disposal facility.

D. ROLE OF USBM IN TAILINGS TECHNOLOGY DEVELOPMENT

As noted previously, since the initiation of this contract, the role of the USBM has changed dramatically in that prime responsibility for the enforcement of refuse disposal regulations has been vested in the newer MESA organization. Thus, the prime role of the USBM in the development of modern tailings disposal technology will be as a research group working to advance the state-of-the-art. Since mine, mill, plant, and smelter refuse disposal systems are influenced by site conditions, materials characteristics, design concepts and requirements, operational requirements, and available construction techniques, the development of the needed technology is not a completely straightforward matter. Not all of the factors listed have been adequately evaluated or the techniques developed. Consequently, technology must be borrowed from the fields of civil engineering, engineering geology, soil mechanics, rock mechanics, earth-dam engineering, and hydrologic and hydraulic structure engineering until a complete applied technology can be developed to fit the specific needs of the mining industry. In order to systematically develop the required technology, a long-range research program should be developed leading toward preparation of a technology manual along the outline given below. It is important that this manual be written so as to provide the technology for industrywide application and to provide the guidelines within which regulation can operate. However, the manual must not codify requirements to the extent that sites cannot be treated on an individual basis. There must be room, within reasonable limits, for the use of innovative engineering techniques to solve specific problems.

OUTLINE

TAILINGS TECHNOLOGY MANUAL

I. Industry Practices and Problems
   A. Historical Background
      1. The overall disposal problem
      2. Development of the disposal problem
   B. Elements of Tailings Disposal
      1. Types of tailings disposal deposits
      2. Methods of tailings disposal
   C. Overview of Industry Practices
      1. General industry view
      2. Variation of practices topographically
      3. Variation of practices geographically
   D. Current Trends in Tailings Disposal Practices
      1. Technology
      2. Regulations
      3. Education and training

II. Refuse Disposal System Development
   A. Disposal System Requirements
   B. System Design Considerations
      1. Site characteristics
      2. Materials characteristics
      3. Design criteria
      4. Design analysis
   C. Disposal Plan Development
   D. Auxiliary Discipline Needs

III. Site Conditions
   A. Hazard Potential Evaluations
   B. Environmental Impacts
   C. Geotechnical Considerations
   D. Hydrologic Investigations
   E. Site Exploration Methods
      1. Topographical and geological mapping
      2. Trenching and test pits
      3. Drilling and sampling
   F. Other Site Studies
      1. Geophysical studies
      2. Seismic studies
   G. Logging and Sampling of Field Exploration Work
   H. In-Situ Testing of Site Materials
   I. Instrumentation, Prior to New or Modification Construction

IV. Tailings Material Characteristics and Properties
   A. Field Determinations
      1. Moisture and density
      2. Shear strength
      3. Permeability

B. Laboratory Determinations
   1. Classification tests
   2. Index properties
      a. Grain-size distribution
      b. Atterberg Limits
      c. Specific gravity
   3. Moisture-density tests
   4. Compaction and relative density tests
   5. Permeability
   6. Consolidation
   7. Shear Strength
      a. Direct shear tests
      b. Triaxial shear tests
      c. Dynamic triaxial tests (where warranted by site seismicity)

V. <u>Disposal Facility Design and Analysis</u>
   A. Distinction Between Analysis and Design
   B. Engineering Analysis as a Design Tool
   C. Factors Influencing Analysis and Design
      1. Tailings material characteristics
      2. Tailings placement techniques
      3. Site characteristics
      4. Areal climatology
      5. Community considerations
   D. Analytical Procedures
      1. Types of analysis
      2. Application to existing facilities
      3. Application to new or proposed facilities
      4. Spillways and other appurtenant structures
      5. Water diversion facilities
      6. Foundations
      7. Operational considerations
      8. Abandonment program

VI. <u>Review and Approval of Plans and Specifications</u>
   A. Objective of Review and Approval
   B. Standardization of Review and Approval Techniques
   C. Necessary Data for Application Requirements

VII. <u>Construction and Disposal Techniques</u>
   A. Types of Impoundments
      1. Cross-valley
      2. Side-hill
      3. Diked ponds
      4. Incised ponds
   B. Methods of Conveyance and Placement
   C. Adequate Versus Inadequate Techniques
   D. Application of Construction Techniques

VIII. Embankment Construction Inspection
- A. Inspection Requirements and/or Objectives
  1. Requirements of plans and specifications
  2. Verification of design assumptions
  3. Function of site inspector, owner/operator
  4. Function of site inspector, regulatory agency
- B. Techniques of Construction Inspection
  1. Method specifications
  2. Performance specifications
- C. Inspection During Construction with Disposal Materials
  1. Operational procedures
  2. Testing

IX. Surveillance
- A. Difference Between Surveillance and Inspection
- B. Surveillance During Construction
- C. Surveillance During Operation
- D. Surveillance After Abandonment

CHAPTER IX

NEEDED FUTURE RESEARCH

GENERAL

DISCUSSION OF PROPOSED RESEARCH PROJECTS

CHAPTER IX

NEEDED FUTURE RESEARCH

A. GENERAL

As a part of the overall research effort, it was determined that a major emphasis in the final report should be directed towards a discussion of needed future research in the area of geotechnical engineering pertaining to metals and nonmetals mine and mill refuse disposal. This research, which is presented in this Chapter in outline form, is necessary, in our opinion, to advance a basic understanding of the technical aspects associated with mill tailings disposal practices and potential tailings embankment stability problems.

The descriptions of specific research programs are presented in order of priority. Although the programs are not described in sufficient detail to determine the probable associated cost, we have attempted to present the basic need for each program, major work elements, and the major and overall objectives.

B. DISCUSSION OF PROPOSED RESEARCH PROJECTS

1. Development of Basic Investigative Equipment

As a result of our experience gained during the detailed investigations at the Morenci and Magna sites, it became evident that new methods of developing, compiling, and analyzing in situ engineering properties of tailings material are needed. These techniques are needed to reduce the high investigative costs associated with the conventional field exploration approach which includes drilling, trenching, and sampling of material which is difficult and expensive to sample. We are of the opinion that the Dutch Cone Penetrometer could possibly be developed into a valuable field testing device to provide rapid and repeatable data on in situ characteristics for engineering analysis. This tool could be used as a direct measurement of strength or to determine the variability of the material, thus providing a basis for determining the representability of a few expensive sampled holes. It might also be used in subsequent years to determine changes in the material with time, thus reducing the cost for thoroughly testing a large embankment. The program would be oriented toward field and laboratory correlation in the following manner.

a. First Year Investigation -
(1) Fabricate and modify as necessary a completely electronic Dutch Cone Penetrometer capable of in-situ testing to a depth of 300 feet. Portions of this equipment are currently available from the firm of N. V. Goudsche-Machinefabriek, Gouda, Holland. Certain components of the total system, such as the bonded strain gauge for detecting

load, the electronic recorder to automatically record the test and produce a paper tape for subsequent engineering analyses, and a transporting heavy duty vehicle to provide the necessary reaction should be purchased in the United States because of the advanced domestic state-of-the-art and technology in these specialized areas.

(2) Design and fabricate a large-scale anisotropic consolidation box, having approximate dimensions of 3 feet in width, 3 feet in length, and 4 feet in height, capable of applying triaxial stresses to exactly simulate actual field conditions existing within a typical tailings dam or coal refuse deposit. Actual tailings material will be compacted within this device under optimum control conditions to various representative field conditions of in-situ density and moisture content. A miniaturized Dutch Cone Penetrometer will be fabricated to determine the penetration resistance of the field representation of stress after which undisturbed samples will be extracted for appropriate triaxial and consolidation tests.

(3) Conduct a pilot field and laboratory investigation on Phelps Dodge Morenci Tailings Dam, located in Morenci, Arizona. The investigation of this particular site is recommended for the following reasons:

a) Excellent working relationships with Phelps Dodge have been developed under our current research program with the Bureau, and
b) These tailings deposits are considered representative and furthermore, extensive engineering analyses and data have been compiled, thereby minimizing the amount of extraneous data necessary for a pilot program of this scope.

(4) Analyze and assess the results of activities 1 and 2, above, to determine where modifications to techniques may be required and to plan in detail the second year's program.

b. <u>Second Year Investigation</u> -
(1) Modify and further develop the Dutch Cone Penetrometer based on any deficiencies as determined during the pilot field investigation.

(2) Conduct a major field investigation program using the modified Dutch Cone Penetrometer on at least 5 coal refuse and 5 metal/nonmetal tailings dams in order to provide a broad range of basic data representing a cross section of each industry's refuse disposal techniques.

(3) Conduct a major laboratory investigation program, using the equipment developed during the first year phase of the research program. Materials will be collected at each site and tests will be performed in order to simulate the full range of densities and

in-situ stresses as determined for each project. These data will be used to correlate the field data described above and will also form the basis for the analytical techniques discussed below.

(4) Develop and finalize the analytical techniques, including a computer program for use in the reduction of field data, for office analyses of resulting field penetration data.

(5) Finalize recommended field, laboratory, and analytical procedures for use of the Dutch Cone Penetrometer.

2. Development of Standard Engineering Analysis Techniques

With the advent of the finite element method of representation for the analysis of structure response, a new demand has been placed on the engineer reviewer of these structures. That is, one of determining what method of analysis is applicable for various engineering studies such as stability, compressibility, and permeability.

The preliminary results obtained at the Phelps Dodge Morenci Tailings Dam indicate that the consolidation and/or shear displacement that occurs as a result of tailings emplacement follows a predictable trend. In our opinion, these results are the most important contribution to the current research program and could lead through further research to a basic understanding of the stability of tailings dams. A major effort in the past ten years in the fields of geotechnical and earth dam engineering has been directed toward improved embankment or slope movement prediction. With the development of the nonlinear finite element computer program, the analytical techniques are now available to accurately model the stress-strain relationships of most soils. Because of the encouraging field data obtained at the Morenci site, an in-depth evaluation should be undertaken to determine the correlation of observed field movements with those that can be theoretically predicted.

a. Proposed Program -

(1) The initial study would include a complete review of and categorization of various types of tailings dam failures that have occurred throughout the metals and nonmetals industry.

(2) Investigate in detail the mechanics of dam instability and perform in-depth analyses of slope movements for one well-instrumented slope using the conventional limiting equilibrium, slip-circle, and nonlinear finite element analysis.

(3) Determine the influence of pore pressure response and the relationships with the rate of dam (pond) construction. Two recent failures of tailings dams in the Southwest suggest that the rate of pore pressure development can play a fundamental role in the safe rate of dam construction.

(4) An in-depth field and laboratory program would be performed to determine the sedimentation principals and nonlinear stress-strain relationships of fine-grained materials. All pertinent engineering parameters of strength, compressibility, and permeability would be determined on artificially sedimented samples in the laboratory and then correlated with similar results from undisturbed field samples. Such fundamental problems as layering, desiccation, chemical crustation and all other major forms of non-homogeneity would also be studied.

(5) All currently available analytical techniques would be evaluated and cataloged. A large number of computer programs currently exist to solve various types of geotechnical problems. This is both confusing and exasperating to the engineer in charge of analyzing a given structure in terms of how detailed a particular analysis should be. The results of the program outlined above would provide a detailed engineering manual with step-by-step approaches and suggestions for the solution to the geotechnical problems associated with mill tailings deposits.

3. Categorization of Mine Refuse Deposits

The need exists to compile a complete list and description of all mine and mill refuse deposits that exist throughout the United States. This program could be accomplished in much the same fashion as our "Reconnaissance Survey Report of Coal-Mine Refuse Dumps and Impoundments," USBM Contract No. S0122084. The results of such a survey would provide a means of correlating and cross-referencing all types of deposits as a function of ore product, embankment size, and method of construction. The proposed index or catalogue of mill and mining refuse deposits would be developed for computer storage, thus permitting retrieval of selected information regarding every site evaluated.

a. Proposed Program - The program would include a compilation of an index or catalogue of all existing mill and mine refuse deposits in the conterminous United States. Included in the inventory will be all solid refuse products from metal and nonmetal (excluding coal) mining operations dumped or placed on the surface of the ground, such as:

(1) Tailings from plants using wet concentration methods.
(2) Refuse materials from wash operations, such as rock, crushing, gravel, and aggregated plants, and placer operations.
(3) Other deposits such as coarse-grained refuse dumps, leaching dumps, and stockpiles.

Data necessary to identify and describe every deposit to be included in the catalogue will be obtained from the files of the U.S. Bureau of Mines, from bibliographic research, from contacts with owners or responsible agencies through letters and telephone calls, and through personal visits to selected sites.

Items to be included in the catalogue descriptions are as follows:

(1) Location: name, county, state geographical coordinates. Owner.
(2) Dimensions of each deposit: height, width, length. Shape, i.e., rectangular, triangular, elliptic, etc. Type: side-hill, cross-valley, diked pond, embankment, other.
(3) Volume: in yds^3, tons.
(4) External slopes: maximum, minimum, and average.
(5) Gradation distribution characteristics: maximum, minimum, and average grain-size. Layering characteristics.
(6) Decant system description.
(7) Water cycle: how much is introduced, recovered, evaporated, infiltrated, etc.
(8) Disposal system: flumes, pipes, dumped by trucks or trains, cyclones, etc.
(9) Activity state: active, inactive, used intermittently, emergency, reserve, etc.
(10) Rate of growth: tons per day, month, year; feet or meters per day, month, year.
(11) Site geologic, physiographic and hydrologic features.
(12) Distance to nearest town, facilities, or inhabited place downstream of dam (to determine critical area in case of failure).
(13) Jurisdiction of deposit: County, State, Federal.
(14) Responsible owner/personnel.
(15) Existing engineering studies: design, operation, maintenance, seismic factors.
(16) Special characteristics.
(17) References, bibliography.

The final report, one each for the six regional districts, would include reconnaissance level reports for all sites within the jurisdictional area for each district. A "Users Manual" would also be prepared to describe the developed computer program, and permanent file of site descriptions, as well as a system to maintain the file.

4. <u>Seismic Hazard Rating System</u>

From an earthquake hazard standpoint, dams and mine refuse deposits with water-retention capabilities constitute one of the greatest single categories of threat for potential widespread destruction existing in our modern society. Typical of the potential problems associated with such structures is the nearly catastrophic failure of Lower San Fernando Dam, a hydraulic fill type of embankment located in Southern California, during the earthquake of February 9, 1971. Fortunately, in this instance, the highly developed area downstream of the dam was spared from complete disaster by circumstances which, with only minor differences, could have resulted in a breaching of the dam embankment and emptying of the reservoir onto the downstream community. As a result of this incident, the State of California, Division of Safety of Dams, required that all hydraulic fill dams in the state be re-evaluated from the standpoint of safety against seismic hazards.

On the national level, the failure on February 26, 1972, of a coal refuse dam on Buffalo Creek in West Virginia caused some 125 fatalities and was one of the prime motivating events for the U.S. Congress to enact Public Law 92-367 (House of Representatives Bill HR 15951), which authorizes the Secretary of the Army to undertake a national program of inspection of dams. An important part of the safety evaluation of dams under this law will be the definition of potential geologic and seismic hazards associated with each individual dam, and the possible effects these hazards could have on dam safety. The first phase of this inspection program is now underway in the form of completing a national inventory of existing dams. Later phases will relate to dams on an individual basis.

As a part of this overall national effort, the need clearly exists for a research program to investigate the relationship between spatial and time distribution of earthquakes in the conterminous United States, and to develop a uniform system for rating seismic hazards associated with dams and reservoirs, so that the potentially most hazardous structures can be recognized at an early date and can then be assigned the highest priorities for performance of more detailed investigations related to seismic safety. Because of the vast scope of the national program, great benefits could be realized by the development of a seismic hazard rating system which could be applied uniformly to dams and reservoirs throughout the nation, but which would be simple enough to be readily applicable, and yet comprehensive enough to produce meaningful results on an individual site basis, in order that the most potentially hazardous sites can be distinguished and receive the early attention which they deserve.

Although the proposed research program cannot be isolated only for mine refuse deposits, because of costs associated with such a major effort, we are of the opinion that a program such as that outlined below is vitally necessary to develop a practical means for assigning seismic hazard ratings to existing dams and reservoirs and mine refuse deposits on a nationwide basis. Perhaps it would be possible to obtain matching research funds from those other agencies that would benefit from such a research effort.

a. Objectives - The objectives of the proposed research program are relatively straightforward, but involve many important and detailed considerations which require mature judgment and considerable experience in the fields of earthquake engineering and dam analysis, design, and construction. Simply stated, the objectives of the program would be to:

(1) Define and select a basis for evaluating earthquake potential of any given area.

(2) Compile a comprehensive list of factors to be considered in the overall evaluation of potential earthquake-related hazards at any given site.

(3) Utilizing the data developed in Points 1 and 2, develop a seismic hazard evaluation and rating system which could be applied to dams and reservoirs on a national basis. This could be a general dam program or could be directed specifically to mine refuse structures--particularly hydraulic fill structures or any structure that could liquify in failure.

b. <u>Proposed Program</u> - Proposed research would involve the following principal activities:

(1) Select two limited and well-defined areas in the United States, one in California or Arizona and one in an eastern or central part of the nation, both of which contain several major dams and geologic and seismic settings, to utilize as study areas for development of the required principles, and for application and testing of hazard rating factors and techniques which will be developed.

(2) Review all presently available national and regional seismic zoning systems proposed by others and select or modify one system to provide the most rational basis for use in the proposed program. The necessity for microzonation to meet program objectives would also be carefully considered as a part of the study.

(3) Develop a preliminary dam seismic hazard evaluation and rating system to be used in the program. This system would include, but not necessarily be limited to, identification and integration into a rating system of such pertinent items as site location, regional and site geology and seismicity, reservoir operation criteria, type and condition of dam and appurtenant structures, foundation characteristics, potential for damage to downstream developments from seismic failure of dams and appurtenant structures, potential for earthquake-induced landslides into the reservoirs, and potential for damaging reservoir seiches.

(4) Test the developed rating system by applying it to at least twelve major structures in the two study areas. These sites would be selected, to the extent possible, to provide a representative cross section of all the major factors considered in the rating system. Sites which have the most readily available amount of required existing data would be given first consideration in order to minimize the required development of new information and to lend greater credibility to the results obtained.

(5) Assess the results of the preliminary rating system from the standpoint of reasonableness, adequacy of meeting overall objectives, and practicability of accomplishment on a large-scale basis.

(6) If necessary, make revisions in the rating system as dictated by the determinations made in 5, above, and reassess the results of the revised system to arrive at a rating system to be recommended for adoption.

The proposed research program would develop a practical means for assigning seismic hazard ratings to existing mine refuse dams and reservoirs on a nationwide basis, so that a national priority system could be established for more detailed early study of the sites possessing the highest risk. This hazard rating system could also easily be integrated into, and become an important part of, the work currently under way by the U.S. Army, Corps of Engineers, under Public Law 92-367. In addition, the proposed research work would provide an effective tool which could be used by engineers, planners, legislators and others responsible for developing and administering present and proposed national dam safety regulations, to help establish a level of confidence associated with seismic risk, and to reduce potential seismic hazards associated with dams and reservoirs at the most rapid feasible rate. The value of this research would be great for the national mine refuse safety program, but would also have general application to many other structures.

5. Dynamic Shear Strength of Tailings Material

a. General - One of the basic problems associated with evaluating the earthquake hazards of an earth dam, tailings dam, or for that matter, any structure constructed with or founded on soil or soil-like material, is a correct assessment of the dynamic response of the materials comprising the embankment and foundation. A significant amount of research of the dynamic response of soils has been completed in the past five years; however, the major emphasis of this research effort has been directed toward liquefaction characteristics of relatively clean sands. The rationale for concentrating the research effort on such sands is that liquefaction of sand foundations was the principal mode of failure observed in the Niigata, Japan, and "Good Friday" Alaska earthquakes. Unfortunately, there is only a limited amount of information available concerning the dynamic response characteristics of tailings materials.

As pointed out in our conclusions regarding the dynamic response analysis for the Magna Tailings Dam, a significant amount of laboratory research is necessary in the area of tailings material response characteristics. Specifically, the indication that tailings will liquefy, even under relatively minor simulated ground motions, must be studied in more detail.

The catastrophic liquefaction failure of 11 tailings dams in Chile as a result of the March 28, 1965, El Cobre Earthquake points out the sensitivity of tailings material to seismic loading. Although we are not forecasting a similar fate for the vast number of tailings dams in the Southwest, we do recommend that serious consideration be given to the needed research of dynamic response of tailings material.

b. Proposed Program - An in-depth laboratory study of the dynamic shear strength characteristics of tailings material would be performed at prescribed values of in-situ stress ratios and densities as follows:

(1) Typical samples of tailings material, representing the range of gradation and in-place dry densities expected from the principal methods of construction currently in use, would be tested.

(2) The majority of samples to be used for testing could be fabricated in the laboratory; however, some field work would be necessary to obtain undisturbed samples for check tests.

(3) A broad range of dry densities and sample gradations should be studied in order to develop the range of probable response characteristics.

(4) All dynamic triaxial tests should be performed on saturated samples at stress ratios (ratio of major to minor principal stresses which represent the in-situ state of stress acting within a given soil) of 1.0, 1.5, and 2.0.

(5) In addition to the testing program described above, we propose an investigation of the stress-strain characteristics for one or more of the materials utilizing actual stress histories as determined from the dynamic finite element results. The conventional method of dynamic testing usually incorporates a uniform cyclic load applied to the sample at a frequency of one to two cycles per second. The amplitude of the uniform cyclic load is varied for each sample tested in order to define failure over a reasonable number of stress applications. The dynamic shear strength is then determined by assuming an arbitrary failure criterion, such as liquefaction or 10 percent axial strain in 10 cycles. Recent modifications to the laboratory dynamic testing equipment at W. A. Wahler and Associates enables us to apply random axial dynamic loads to a sample while continuously monitoring the development of strain and pore water pressure. The study proposed herein would attempt to correlate the percentage of mobilized strength, under dynamic load conditions when a sample is subjected to load variations induced by actual ground accelerations, to that of the shear strength characteristics determined by conventional dynamic testing methods. This data could then be used

for analyses for design or check analyses with only correlation tests being run rather than each project having to support more than correlation tests.

6. Model Tailings Dam

With the development of pending ground-water litigation near Tucson, Arizona, it has become increasingly more obvious that the amount of degradation of ground water from a tailings pond seepage is not clearly understood by the mine owner, ground-water basin management or the geotechnical engineering profession. This very important pollution problem requires more study.

It would be entirely possible to find a representative location in the Tucson area to build a small, by comparison standards, model tailings dam. The following items could be considered individually or collectively as a combined research effort.

(1) How do the various elements of material type and vegetation influence the rate of water loss from the pond area? What is the evaporation rate from a wet tailings pond surface and how does the rate change as the surface desiccates and tension cracks develop? How much water is retained as soil moisture in tailings as they consolidate?

(2) Can the rate or volume of water loss by infiltration be minimized or otherwise effectively controlled by covering the original ground with slimes prior to general tailings disposal?

(3) How does water migrate from the tailings pond? What are the mechanisms of unsaturated flow and the effects on chemical composition of water? What is the shape of the wetted infiltration front or bulb in the zone of aeration and what is the retentive capacity of unsaturated soils in the arid climate?

(4) The dam would be instrumented at various sections with a number of different types of instruments in order to evaluate a controlled response. The data from such a study could provide a valuable correlation with all major design parameters of strength, compressibility, and permeability. Pore pressure response data would also be collected and analyzed.

APPENDIX A

FIELD AND LABORATORY TEST PROCEDURES

GENERAL

FIELD DETERMINATIONS

LABORATORY DETERMINATIONS

APPENDIX A

FIELD AND LABORATORY TEST PROCEDURES

A. GENERAL

Most soils are a heterogeneous accumulation of mineral grains that are not cemented together. However, the term soil or earth as used by the engineer includes virtually every type of uncemented or partially cemented inorganic and organic material found in nature. Only hard rock which remains firm after exposure is wholly excluded from the term. To the engineer engaged in the design, analyses, or construction of earth dams, tailings dams or impoundments made from soil or soil-like materials, the physical properties of the construction material, such as unit weight, permeability, shearing strength, compressibility, and interaction with water are of primary importance.

Physical properties, as shown in Table A-1, refer to both index properties and engineering properties which, in turn, reflect the physical makeup of the soil-like materials that have been or will be used for construction of a dam or impoundment. The construction materials may consist of naturally occurring materials, such as rock particles, gravel, sand, silt or clay, or disposable materials such as copper or gold tailings or coal refuse material. Regardless of the material type, the engineer must determine the physical properties on the basis of experience and/or field and laboratory tests in order to classify and determine the physical makeup and engineering characteristics of the material if he is to properly analyze an existing structure or utilize the material for new construction.

TABLE A-1

PHYSICAL PROPERTIES

A. Index Properties

1. Grain-size Distribution
2. Plasticity
3. Specific Gravity
4. Mineralogical Composition
5. Soil Structure

B. Engineering Properties

1. Moisture-Density Characteristics
2. Compaction and Relative Density
3. Permeability
4. Compressibility
5. Shear Strength
   a. Static
   b. Dynamic
6. Moisture-Volume Changes

This chapter presents a brief discussion on how soil materials are classified, describes the commonly used field and laboratory tests associated with the determination of physical properties, and presents a cross section of results specifically related to tailings and leach dump materials.

1. Unified Soil Classification System

It is advantageous to have a standard method of identifying soils and classifying them into categories or groups which have distinct engineering properties. This enables engineers working with these materials to speak the same "language," best facilitating the exchange of information and experience. In 1952, the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers, with Professor Arthur Casagrande of Harvard University as consultant, reached agreement on a modification of Professor Casagrande's airfield classification system for soils, which they termed the "UNIFIED SOIL CLASSIFICATION SYSTEM" (USCS). This system, which is particularly applicable to the design and construction of dams and impoundments, takes into account the engineering properties of the soils, is descriptive and easy to associate with actual soils, and has the flexibility of being adaptable both to the field and to the laboratory. Probably its greatest advantage is that a soil can be classified readily by visual and manual examination without the need for costly laboratory testing.

The USCS is based on the size of the particles, the amount and distribution of the various sizes, and the material's plasticity. Soils are divided into three major divisions: coarse-grained soils, fine-grained soils, and highly organic (peaty) soils. A complete description and simplified chart showing the use of the USCS is presented in Appendix B.

B. FIELD DETERMINATIONS

A number of important field tests applicable to mine refuse materials can be performed in order to determine certain physical properties. The type and number of field tests and sequence of a program depends on whether the results are being generated for an assessment of a potential borrow source, an on-going program of construction control or an investigation of a completed dam or deposit to determine its condition.

1. Moisture and Density

In-place determination of moisture and density or unit weight are usually performed in accordance with the American Society for Testing and Materials (ASTM) Test Method D-1556. This method involves excavating a hole from a horizontal surface, weighing the material excavated, and determining the volume of the hole by filling it with a sand of known density. A water content determination enables the dry density of the excavated sample to be calculated. Various devices using balloons and water or soil have been used to measure the volume of the hole, but the sand cone method is most common.

Depending on the maximum and average particle size of the material being tested, the size of the test hole and, therefore, the type of equipment to be used, will vary. For example, field density tests of pervious materials containing particle sizes in excess of 2 inches (5.1 centimeters) are usually performed by the water-volume method. This method, which requires the use of a 3-foot (0.9 meter) or 6-foot (1.8 meters) diameter ring, has not yet been standardized by ASTM, but has been used as a means of control on important earth dam projects such as Oroville Dam, the highest earthfill dam in the United States. Table A-2 shows the minimum desired volume of test hole, depending on the average gradation characteristics of the material being tested.

TABLE A-2

MINIMUM TEST HOLE VOLUMES AND MINIMUM MOISTURE CONTENT SAMPLES BASED ON MAXIMUM SIZE OF PARTICLE

Maximum Particle Size	Minimum Test Hole Volume, cu. ft.	Minimum Moisture Content Sample, grams
No. 4 Sieve (4.75 mm)[1]	0.025	100
1/2-inch (12.5 mm)[1]	0.050	250
1-inch (25 mm)[1]	0.075	500
2-inch (50 mm)[1]	0.1	1000
4-inch (102 mm)[2]	0.5	2000
Greater than 4-inch[3]	3.0	---

[1]6-inch diameter Sand Cone Method (ASTM D1556)
[2]12-inch diameter Sand Cone Method
[3]Water displacement method with 3.0 or 6.0 ft. (0.9 m or 1.83 m) diameter rings

Density tests are usually performed in backhoe pits, dozer pits or other types of excavations. Care should be taken to locate density tests in representative areas and, if the location of the tests has been prepared with the aid of motorized equipment, the level of the test should be at least 1 foot (0.3 meter) below the surface of excavation to minimize any disturbance caused by the excavating equipment. Extreme care should be exercised when performing field density tests in any type of exploratory pit because the sidewalls may be subject to instability or collapse. Federal Safety Standards regarding maximum allowable depth of trench excavation should be observed in all cases whenever men are working in unsupported trenches.

2. Shear Strength

Several methods exist for conducting in-situ shear strength tests. The vane shear apparatus, which is the most commonly used field method, shows little promise in the copper tailings field because of the grain-size characteristics of these materials. The vane shear apparatus was successfully used to determine the undrained shear strength of the finer-grained silt material at the Magna site but these materials were much finer grained than typical tailings. Static cone penetrometers, such as the Dutch Cone device, have found increasing popularity in the United States in recent years after long and proven success in Europe and other parts of the world. Much research is needed, similar to that discussed in Chapter IX of this report, to correlate penetration resistance and sleeve friction ratios with variations in density and shear strength before the Dutch Cone device can be successfully used in tailings. Standard penetration (dynamic) tests have been used to determine the relative density of coarse-grained, non-plastic materials with generally adequate results. This method more properly indicates the uniformity, or lack of uniformity, of a deposit, rather than directly indicating the shear strength.

3. Permeability

The coefficient of permeability as used by the soils engineer is the superficial velocity of water as it passes through a soil under a unit gradient. The value of the coefficient of permeability reflects the ease with which water will flow through a soil and must be known in order to calculate the quantity of flow. The range of permeability for soils is extremely great, varying from greater than 1 cm/sec (1,000,000 feet/year) for clean gravels to 10^{-8} cm/sec (0.1 inch/year) or less for clays.

Approximate values of permeability can be obtained by field testing procedures. The reliability of the values obtained depends on the homogeneity of the stratum tested and on certain restrictions of the mathematical formulas used. If reasonable care is exercised in adhering to the recommended procedures (see Hvorslev, 1949, or United States Bureau of Reclamation Test Method E-18), useful results can be obtained.

Two methods of determining the coefficient of permeability that are used most often in the field are the infiltration or pumping-in tests and the pumping-out test. In the first method, water is introduced into a drill hole, or test pit of known dimensions, and the rate of seepage observed under a fixed or variable head. The second, and less used, method involves the drawing out of water at a constant rate from a drill hole and observing the rate of drawdown of the water table in observation wells placed in a geometric pattern, usually radially at various distances from the point of water withdrawal. Interpretation of test data must be made on the basis of simplified formulas or flow net analyses with application of proper judgment regarding geological factors such as channeling, layering, and the anisotropic characteristics of deposits.

C. LABORATORY DETERMINATIONS

Laboratory tests are usually performed on three basic types of samples:

- Undisturbed tube samples obtained with special sampling equipment using a drill rig, and undisturbed hand-cut block samples.
- Disturbed samples, such as standard penetration samples, bulk samples, or drill cuttings.
- Compacted samples fabricated to represent material of known characteristics.

The hand-cut sample is rarely needed unless the material in question is very sensitive to standard sampling procedures or possesses a minor geologic feature which may be obscured or otherwise destroyed in the sampling process.

Good quality undisturbed samples are needed if engineering properties of in-situ materials, such as compressibility and shear strength, are to be obtained by laboratory testing. Special field techniques (see Hvorslev, 1949) are needed to obtain undisturbed samples and, once obtained, care should be exercised in shipping or transporting the samples to the laboratory.

Compacted or fabricated samples are prepared to represent soils having known moisture, density, and structural characteristics. These samples can be used in lieu of undisturbed samples of materials such as clean sand which cannot be sampled and transported without changes in density. Since the in-situ characteristics can be measured, the loose materials can be fabricated into samples that represent undisturbed conditions. These types of samples can also be used to test the characteristics of man-made or compacted materials.

1. Classification Tests

Tests required to perform classification according to the Unified Soil Classification System in the laboratory include gradation and Atterberg Limits tests.

a. Gradation - The gradation or grain size analysis of soils is performed in accordance with ASTM D-422 and D-1140, which involve both dry sieving for materials coarser than the No. 200 sieve and hydrometer analysis for materials finer than the No. 200 sieve. The results are presented in the form of percent of the total sample passing (based on dry weight) a given size sieve.

b. Atterberg Limits - A typical soil mass has three constituents: soil grains, air, and water. In soils consisting largely of fine grains, the amount of water present in the voids has a pronounced effect on the soil properties. Three main states of soil consistencies are recognizable:

- Liquid state, in which the soil is either in suspension or behaves like a viscous fluid;
- Plastic state, in which the soil can be rapidly deformed or molded without rebounding elastically, changing volume, cracking, or crumbling, and
- Solid state, in which the soil will crack when deformed or will exhibit elastic rebound.

In describing these soil states, it is customary to consider only the fraction of soil smaller than the No. 40 sieve (the upper limit of the fine sand component). For this soil fraction, the water content in percentage of dry weight at which the soil passes from the liquid state into the plastic state is called the Liquid Limit (LL).

A device which causes the soil to flow under certain controlled conditions is used in the laboratory to determine the LL. Similarly, the water content of the soil at the boundary between the plastic state and the solid state is called the Plastic Limit (PL). The laboratory test used to define this limit consists of repeatedly rolling threads of soil to 1/8-inch (3.2 millimeters) diameter until they crumble and then determining the water content. The difference between the liquid limit and the plastic limit corresponds to the range of water contents within which the soil behaves plastically. This difference of water content is called the Plasticity Index (PI). Highly plastic soils have a high PI value. In a nonplastic soil, the plastic limit and the liquid limit are the same and the PI equals 0.

These limits of consistency, which are called Atterberg Limits, after a Swedish scientist, are used in the Unified Soil Classification System as the basis for laboratory differentiation between materials containing appreciable amounts of plastic (clays) and slightly plastic or nonplastic materials.

2. Moisture-Density

The natural or in-place density and water content for samples obtained in the field are determined in the laboratory by carefully extruding the sample from its container, measuring the natural weight and dimensions of the sample, and then placing the material in an oven at a controlled temperature to evaporate all retained water. Once the dry weight of the material is determined, the total and dry unit weight (density) and water content are determined by the following:

$$w/c = \frac{W_w - W_d}{W_d} \times 100$$

$$\gamma_t = \frac{W_w}{V}$$

$$\gamma_d = \frac{W_d}{V}$$

where:

W_w = Wet weight of total sample in pounds

W_d = Dry weight of total sample in pounds

V = Volume of total sample in cubic feet

w/c = Water content, based on dry weight, in percent

γ_t = Total unit weight of material, usually expressed in pounds per cubic foot

γ_d = Dry unit weight of material, usually expressed in pounds per cubic foot.

3. Specific Gravity

The specific gravity is defined as the ratio of the weight in air of a given volume of a material at a stated temperature to the weight of an equal volume of distilled water at a stated temperature. The specific gravity for material finer than the #4 sieve is determined in accordance with ASTM D-854 and for materials predominantly larger than the #4 sieve, in accordance with ASTM C-127. The specific gravity of a material must be known or assumed in order to calculate the void ratio and percent of saturation of a given material. The following formulae relate void ratio, specific gravity, saturation, water content, and dry unit weight:

$$e = \frac{G\gamma_w}{\gamma_d} - 1$$

$$S = \frac{wG}{e}$$

where:

e = Void ratio (ratio of volume of voids to volume of solids)

G = Specific gravity

γ_d = Dry unit weight of soil

γ_w = Unit weight of water

S = Saturation in percent

w = Water content based on dry weight

4. Compaction and Relative Density

The moisture-density relationships of soils determined in the laboratory are performed in accordance with ASTM D-1557. The prescribed method covers the determination of density when compacted in a mold of a given size with a 10-pound hammer dropped from a height of 18 inches. Four alternative procedures are provided as follows:

Method A - A four-inch mold with material passing the #4 sieve.

Method B - A six-inch diameter mold with material passing a #4 sieve.

Method C - A four-inch mold with material passing a 3/4-inch screen.

Method D - A six-inch diameter mold with material passing a 3/4-inch screen.

The method to be used should be indicated in the specifications for the material being tested. If no method is specified, the provisions of Method A are usually incorporated.

The energy imparted using the procedures specified in the referenced standard is equal to 56,250-foot pounds per cubic foot (ft-lb/cu ft) and was originally established as a means of laboratory control for air-field construction where heavy compaction equipment was required. The earth dam field, primarily through the work of the California Department of Water Resources (DWR), has adopted a lighter compaction standard to more realistically reflect the compaction effort likely to be achieved in the field. The standard used by DWR, which is the standard used by W. A. Wahler and Associates, is a compactive energy equal to 20,000 ft-lb/cu ft. The 10-pound hammer falling 18 inches is used in this test similar to that specified above and, therefore, when performing a test in accordance with Method A using a four-inch diameter mold, the number of blows per layer is reduced from 25 to 15 and the number of compacted layers is reduced from 5 to 3.

For materials with up to about 12 percent passing the No. 200 sieve, water will not act as a lubricant in the compaction process and a well-defined moisture density relationship cannot be developed. For these soils, the compaction standard used is ASTM D-2049 which utilizes vibratory equipment. The results are in the form of maximum and minimum densities, and in general, the maximum density by vibratory methods will generally be more than by impact methods.

Relative density is defined as the state of compactness of a soil with respect to the loosest and densest states at which it can be placed by the laboratory procedures described in the ASTM D-2049 standard. It is expressed as the ratio of the difference between the void ratio of a cohesionless soil in the loosest state and the actual void ratio, to the difference between its void ratios in the loosest and densest states. The mathematical expressions for this definition are presented below:

$$D_d = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$$

where:

D_d = Relative Density of field samples in percent

e_{max} = The void ratio corresponding to the loosest laboratory density

e_{min} = The void ratio corresponding to the most compact laboratory density

e = The void ratio corresponding to the field density

5. Permeability

The fundamental property involved in fluid flow is permeability. Because soil permeability depends very much on the arrangement of individual particles and on whether or not the deposit is stratified, and because of the difficulty associated with obtaining representative samples, field determination of permeability often is required in order to determine the average permeability. Laboratory determinations of permeability are much easier to make than field determinations and permit the relationship of permeability to void ratio to be studied and, therefore, are usually performed whether or not field measurements are made.

Among the methods used in the laboratory to determine permeability are:

- Falling, or variable, head permeameter
- Constant head permeameter
- Direct or indirect measurements from the consolidation tests

For relatively free-draining materials with less than 10 percent passing the No. 200 sieve, the coefficient of permeability should be determined in accordance with ASTM D-2434 which uses a constant head method. For materials with more than 10 percent passing the No. 200 sieve, the influence of saturation can have a marked effect on the results, (some materials exhibit a coefficient of permeability 100 percent greater at a saturation of 100 percent as compared to a saturation of 80 percent), and it is suggested, therefore, that the testing procedure used must guarantee that the sample is completely saturated before performing the permeability test.

The permeability of fine-grained materials can be determined from the results of one-dimensional consolidation tests using the following relationship (see Taylor 1948):

$$k = \frac{c_v a_v \gamma_w}{1 + e}$$

where:

k = Coefficient of permeability (ft/day)

c_v = Coefficient of consolidation (ft^2/day)

a_v = Coefficient of compressibility $(lb/ft^2)^{-1}$

γ_w = Unit weight of water (lb/ft^3)

e = Void ratio

6. Consolidation

The application of stresses to any material causes strains. In certain materials, such as clays, silts, or sands and gravels containing sufficient quantities of clays and silts, a certain time is required for the occurrence of the strains. In such materials, the stresses, strains, and the time bear certain definite relationships to each other; these relationships are mechanical properties of the material, and are called stress-strain-time relationships. The stress-strain-time relationships, commonly referred to as the consolidation characteristics of a soil, are determined in accordance with ASTM D-2435.

The two soils properties determined from the one-dimensional consolidation tests are:

C_c = The compression index which is used to calculate the magnitude of the settlement.

c_v = The coefficient of consolidation which is used to calculate the rate of settlement.

7. Shear Strength

The evaluation of soil shear strength is essential for the determination of safety for any dam or deposit. Shear strength cannot be estimated from the angle of repose but must be physically measured in the field or laboratory.

The shear strength of soil and particulate rock materials is given by the Mohr-Coulomb Failure Law[1] as:

$$s = \bar{\sigma} \tan \phi' + c'$$

where:

s = Shear strength

$\bar{\sigma}$ = Effective normal stress

ϕ' = Angle of internal friction as determined by effective stress

c' = Cohesion as determined by effective stress

a. Direct Shear Test - The shearing resistance of soils can be determined by use of a simple shear box wherein a soil sample is confined by a normal pressure and the force developed during shear is monitored. The advantage of direct shear testing is that it is relatively uncomplicated and the equipment is not expensive. The disadvantages are that failure is forced to occur on a horizontal plane, the test must be run in a drained condition and, using conventional equipment, the maximum particle size should be limited to about 1/4 inch.

b. Triaxial Test - Determination of shear strength by means of the triaxial test requires extensive knowledge and experience. Test results can be influenced by many factors such as size of sample, method of sampling, degree of saturation, rate of strain, rate and method of load application, drainage conditions, and method of failure interpretation. Testing procedures are usually identified with the use of a three-letter designation as follows:

First letter - defines how the stresses are applied to the sample

- I - Isotropically consolidated prior to application of failure load
- A - Anisotropically consolidated prior to application of failure load

Second letter - defines whether the sample was consolidated or unconsolidated prior to application of the failure load

- U - Unconsolidated
- C - Consolidated

Third letter - defines the drainage conditions which existed during application of the shearing force

- U - Undrained
- D - Drained

[1]Conventional shear strength theory is based on the work originated by the French mathematician Coulomb in 1776 and extended by Otto Mohr, who first wrote about general strength theory in 1882.

The four most commonly used triaxial tests are:

IUU - Isotropically Unconsolidated Undrained
ICU - Isotropically Consolidated Undrained
ICD - Isotropically Consolidated Drained
ACU - Anisotropically Consolidated Undrained

The triaxial test results are interpreted by the use of the Mohr circle of stress at some point during the progress of the test. Three types of failure criteria may be used to interpret the test results; the actual method selected will depend on material type and the method of analysis that the results are to be used for.

Maximum Obliquity - Defined as the maximum ratio of major to minor principal stresses during shear.

Maximum Deviator Stress - The major and minor principal stresses occurring at the point of maximum deviator stress.

Specific Percent Strain - The major and minor principal stresses occurring at some specific percent axial strain.

c. Dynamic Triaxial Test - The above discussion on the triaxial testing is applicable for the evaluation of shear strength under static loading conditions. If the stability of a dam or deposit is to be evaluated under earthquake loading conditions, then the shear strength under dynamic loading conditions should be evaluated. The testing procedures as described above for the static test are used in the dynamic test except that after the sample has been consolidated by either isotropic or anisotropic means, the sample is failed by applying cyclic, rather than static loads. For a given consolidation stress, several samples will be required in order to define the influence of the magnitude of the cyclic stress and the corresponding number of load applications required to cause failure. Failure may occur, depending upon the type of material, as the result of liquefaction or excessive axial strain. Whereas only 3 samples are necessary to adequately define the static shear strength for a material, 10 to 30 samples may be required to adequately define its dynamic shear strength characteristics.

APPENDIX B

SUMMARY OF UNIFIED SOIL CLASSIFICATION SYSTEM

GENERAL

UNIFIED SOIL CLASSIFICATION SYSTEM

PROPERTIES OF SOIL COMPONENTS

APPENDIX B

SUMMARY OF UNIFIED SOIL CLASSIFICATION SYSTEM

A. GENERAL

It is advantageous to have a standard method of identifying soils and classifying them into categories or groups which have distinct engineering properties. This enables engineers in the design office and those engaged in field work to speak the same language, thus facilitating exchange of information and experiences. Knowledge of soil classifications, including typical engineering properties of soil of the various groups, is especially valuable to the engineer engaged in prospecting for earth materials or investigating foundations for structures. To a limited extent proper soil classification can be used to estimate numerical values of engineering characteristics of soils for use in low dams where adequate safety factors are provided.

In 1952, the Bureau of Reclamation and the Corps of Engineers, with Professor Arthur Casagrande of Harvard University as consultant, reached agreement on a modification of Professor Casagrande's air field classification which they termed the "Unified Soil Classification System." This system, which is particularly applicable to the design and construction of dams, takes into account the engineering properties of the soils, is descriptive and easy to associate with actual soils, and has the flexibility of being adaptable both to the field and to the laboratory. Probably its greatest advantage is that a soil can be classified readily by visual and manual examination without the necessity for laboratory testing.

B. UNIFIED SOIL CLASSIFICATION SYSTEM

The Unified Soil Classification System is based on the size of the particles, the amounts of the various sizes, and the characteristics of the very fine grains and is fully described in ASTM D-2487.

A soil mass consists of solid particles and pore fluids. The solid particles generally are mineral grains of various sizes and shapes, occurring in every conceivable arrangement. These solid particles can be divided into various components, each of which contributes its share to the physical properties of the whole. Soil classifications can best be understood by first considering the properties of these soil components.

1. Soil Components

a. Size - Particles larger than 3 inches are excluded from the Unified Soil Classification System. The amount of each oversized material, however, may be of great importance in the selection of sources for embankment materials; hence, logs of exploration always contain information on quantity and size of particles larger than 3 inches.

Within the size range of the system, there are two major divisions; namely, the coarse grains and the fine grains. The major divisions along with the major letter assigned to each of the four major soil constituents, are shown in Table B-1

TABLE B-1

GRAIN SIZE DISTRIBUTION

MAJOR DISTINCTION

More than 50% Passing #200 Sieve ←	→ Less than 50% Passing #200 Sieve
FINE GRAINED	COARSE GRAINED
Clay (C) Silt (M)	Sand (S) Gravel (G)

Coarse grains are those larger than the #200 sieve size (0.074 mm.) and they are further divided as shown below.

Gravel (G), from 3 inches to #4 sieve (3/16 inch);

Coarse gravel - 3 inches to 3/4 inch
Fine gravel - 3/4 inch to #4 sieve

Sand (S), from #4 sieve to #200 sieve;

Coarse Sand - #4 to #10 sieve
Medium Sand - #10 to #40 sieve
Fine Sand - #40 to #200 sieve

For visual classification, 1/4 inch is considered equivalent to the #4 sieve size and the #200 sieve is about the smallest size of particles that can be distinguished individually by the unaided eye.

Fine grains or fines are smaller than the #200 sieve size and are of two types: Silt (M) and Clay(C). Older classification systems defined clay variously as those particles smaller than 5 microns (0.005 mm.) or 2 microns (0.002 mm.) and they defined silt as fines larger than the clay sizes. It is a mistaken idea, however, that the typical engineering characteristics of silt and clay correspond to particular grain sizes.

Natural deposits of rock flour that exhibit all the properties of silt and none of clay may consist entirely of grains smaller than 5 microns. On the other hand, typical clays may consist mainly of particles larger than 5 microns but containing small quantities of extremely fine, colloidal size particles. Size distinction is not made between silt and clay in the Unified Soil Classification System; rather, the two materials are differentiated by their behavior with the addition of water.

Organic material (O) is often a component of soil, but it has no specific grain size. It is distinguished by the composition of its particles rather than by their sizes, which range from colloidal-size particles of molecular dimension to fibrous pieces of partly decomposed vegetable matter several inches in length.

b. Gradation - The amounts of the various sizes of grains present in a soil can be determined in the laboratory by means of sieving, for the coarse grains and by sedimentation (wet mechanical or hydrometer analysis) for the fines. The laboratory results are usually presented in the form of a cumulative grain-size curve. For soils consisting mainly of coarse grains, the grain size distribution reveals something of the physical properties of the material. On the other hand, the grain size is much less significant for soils containing a predominance of fine grains.

Typical gradations of soils are:

Well graded (W) - Good representation of all particle sizes from largest to smallest.

Poorly Graded (P) - Uniform, most particles about the same size; or skip (or gap) gradation - absence of one or more intermediate sizes.

2. Soil Moisture

A typical soil mass has three constituents; soil grains, air, and water. In soils consisting largely of fine grains, the amount of water present in the voids has a pronounced effect on the soil properties. Three main states of soil consistencies are recognizable:

1) Liquid state, in which the soil is either in suspension or behaves like a viscous fluid;

2) Plastic state, in which the soil can be rapidly deformed or molded without rebounding elastically, changing volume, cracking, or crumbling; and

3) Solid state, in which the soil will crack when deformed or will exhibit elastic rebound.

In describing these soil states, it is customary to consider only the fraction of soil smaller than the #40 sieve (the upper limit of the fine sand component). For this soil fraction, the water content in percentage of dry weight at which the soil passes from the liquid state into the plastic state is called the liquid limit (LL).

A device which causes the soil to flow under certain conditions is used in the laboratory to determine the liquid limit. Similarly the water content of the soil at the boundary between the plastic state and the solid state is called the Plastic Limit (PL). The laboratory test used to define this limit consists of repeatedly rolling threads of soil to 1/8 inch diameter until they crumble and then determining the water content. The difference between the liquid limit and the plastic limit corresponds to the range of water contents within which the soil is plastic. This difference of water content is called the plasticity index (PI). Highly plastic soils have a high PI value. In a nonplastic soil, the plastic limit and the liquid limit are the same and the PI equals 0.

These limits of consistency, which are called Atterberg Limits, after a Swedish scientist, are used in the Unified Soil Classification System as the basis for laboratory differentiation between materials of appreciable plasticity (clays) and slightly plastic or nonplastic materials (silt). With sufficient experience, a soils engineer may acquire the ability to estimate the Atterberg Limits of a soil. However, three simple hand tests have been found adequate for field identification and classification of fine soils and for determining whether the fine grain fraction of a soil is silty or clayey, without requiring estimation of Atterberg Limits. These hand tests, which are part of the field procedure in the United Soil Classification System are as follows: Dilatancy (reaction to shaking), dry strength (crushing characteristics), and toughness (consistency near the plastic limit).

3. Laboratory Tests

Although most classifications of soils can be accomplished by visual examination and by simple hand tests, the Unified Soil Classification System does provide for precise delineation of the soil groups by mechanical analyses and Atterberg Limits tests in the laboratory.

The grain-size curve is used to classify soil as being coarse-grained or fine-grained by using the 50 percent criterion on the #200 sieve. For the coarse-grained materials, the percentage of materials passing the #200 sieve as well as the distribution of the individual particles is used to further classify as shown in Table B-2.

TABLE B-2

CLASSIFICATION OF COARSE-GRAINED MATERIALS

Percent Passing No. 200 Sieve	Possible Soil Groupings	Laboratory Classification Criteria
less than 5	SP,SW,GP,GW	Uniformity Coefficients
more than 12	SM,SC,GM,GC	Atterberg Limits
5 - 12	Borderline cases requiring use of dual symbols	Uniformity Coefficients and Atterberg Limits

Within the coarse-grained materials, soils containing less than 5 percent finer than the #200 sieve size are considered "clean" and are then classified as well-graded (W) or poorly graded (P) according to their coefficients of uniformity and curvature which are defined below.

$$\text{Coefficient of Uniformity} = C_u = \frac{D_{60}}{D_{10}}$$

$$\text{Coefficient of Curvature} = C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$$

where,

D_{10} = The soil diameter at which 10 percent of the soil weight is finer

D_{30} = The soil diameter at which 30 percent of the soil weight is finer

D_{60} = The soil diameter at which 60 percent of the soil weight is finer

In order for a clean gravel to be well-graded (GW), it must have both a C_u greater than 4 and a C_c between 1 and 3; otherwise it is classified as a poorly graded gravel (GP). A clean sand must have a C_u greater than 6 and C_c between 1 and 3 to be a well-graded sand (SW); otherwise it is a poorly graded sand (SP).

C. PROPERTIES OF SOIL COMPONENTS

Gravels and Sands - Both of the coarse grain components of soil (gravel and sand) have essentially the same engineering properties, differing mainly in degree. The division of gravel and sand sizes by the #4 sieve is arbitrary and does not correspond to a sharp change in properties. Well-graded, compacted gravels or sands are stable materials. The coarse-grained soils, when devoid of fines, are pervious, easy to compact, little affected by moisture, and not subject to frost action. Although grain shape and gradation, as well as size, affect these properties, gravels are generally more pervious, more stable and less affected by water or frost than are sands, for the same amount of fines.

As the sand becomes finer and more uniform, it approaches the characteristics of a silt, with corresponding decrease in permeability and reduction in stability in the presence of water. Very fine, uniform sands are difficult to distinguish visually from silt. Dried sand, however, exhibits no cohesion (does not hold together) and feels gritty in contrast to the very slight cohesion and smooth feel of a dried silt.

Silt and Clay - Even small amounts of fines may have important effects on engineering properties of the soils in which they are found. As little as 10% of particles smaller than the #200 sieve size in sand and gravel may make the soil virtually impervious, especially when the coarse grains are well graded. Also, serious frost heaving in well graded sands and gravels may be caused by less than 10% of fines. The utility of coarse grained materials for surfacing roads can be improved by the addition of just a small amount of clay to act as a binder for the sand and gravel particles.

Soils containing large quantities of silt and clay are the most troublesome to the engineer. These materials exhibit marked changes in physical properties with change of water content. A hard, dry clay, for example, may be suitable as a foundation for heavy loads so long as it remains dry, but may turn into a quagmire when wet. Many of the fine soils shrink on drying and expand on wetting, which may adversely affect structures founded upon them or constructed of them. Even when the water content does not change, the properties of fine soils may vary considerably between their natural condition in the ground and their state after being disturbed.

Deposits of fine particles which have been subjected to loading in geologic time, frequently have a structure which gives the material unique properties in the undisturbed state. When the soil is excavated for use as a construction material or when the natural deposit is disturbed, for example, by driving piles, the soil structure is destroyed and the properties of the soil are changed radically.

Silts are different from clays in many important respects, but because of similarity in appearance, they often have been mistaken one for the other, sometimes with unfortunate results. Dry, powdered silt and clay are virtually indistinguishable, but they are easily identified by their behavior in the presence of water. Recognition of the fines as being silt or clay is an absolutely essential part of the Unified Soil Classification System.

APPENDIX C

HAZARD RECOGNITION SUMMARY

APPENDIX C

HAZARD RECOGNITION SUMMARY

A. GENERAL

While it is true that many tailings dams and impoundments have been standing for considerable periods of time, this should not be taken as any guarantee that a given dump or impoundment is not unstable today. A slope of an embankment may remain relatively undisturbed for many years even though it is in a metastable condition; that is, the factor of safety is only slightly greater than one. Any change in the condition of the slope or its material constituents can cause a concomitant change in its stability. The following diagram indicates the three basic elements of interest in recognizing how changes in slope properties can create stability hazards.

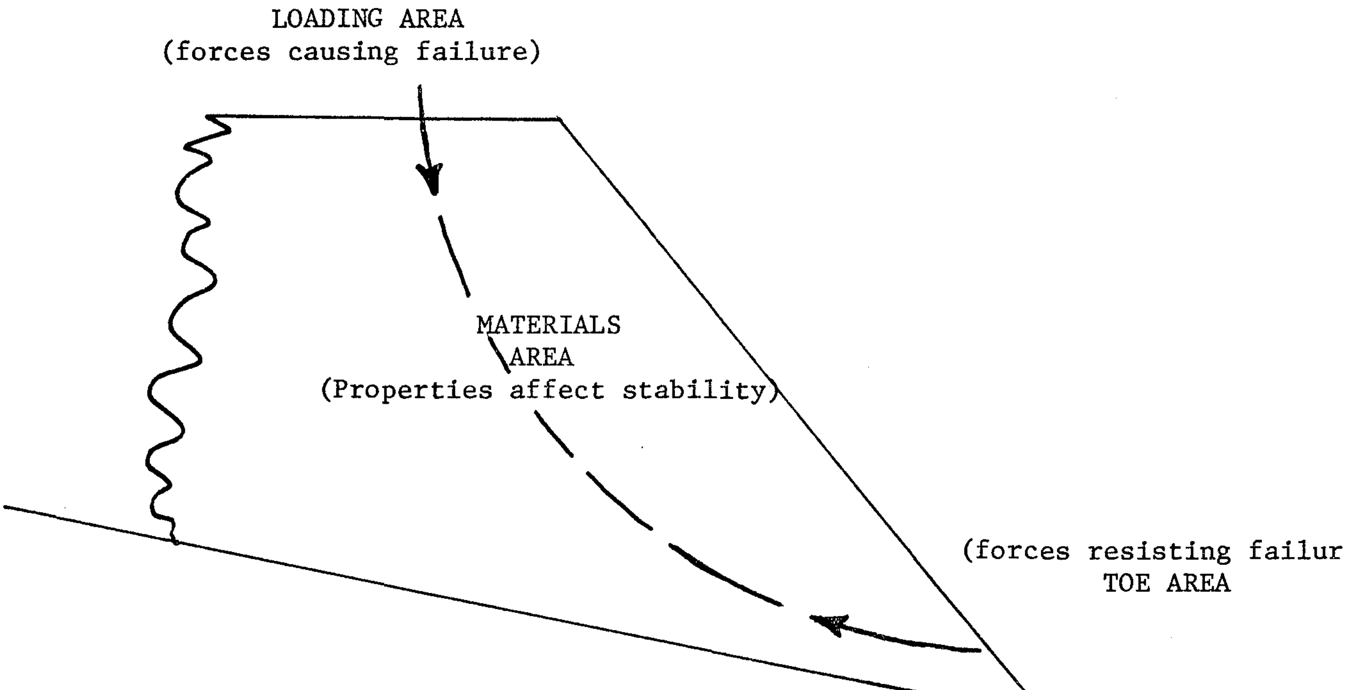


Figure C-1

Basic Stability & Hazard Diagram

(Excluding Water Effects)

More detailed discussions of stability analyses are available elsewhere in this report, and in referenced literature. The purpose of this section of this report is to present a basic summary of hazard causes and their recognition.

B. FACTORS AFFECTING STABILITY

From the basic stability diagram (Figure C-1), it can be seen that any change in conditions in any one of the three areas will affect the overall stability characteristics of the embankment.

1. Loading Area

Additional loading can be due to additional materials placed on the crest for disposal, by heavy vehicles running on or near the crest, or by the introduction of water due to seepage from ponding on the upper surface of the embankment.

2. Toe Area

Removal of the material at the toe can decrease the forces resisting movement. Any other changes in the toe area caused by erosion of the surface, or by wave action from a pond created immediately downstream, will also affect this area. Excavation into the natural ground material in the immediate vicinity of an embankment can also have resultant effects, regardless of the purpose for the excavation.

3. Materials Area

Steepening of or overloading the slope can be caused by road construction on the face of the embankment, or by surface erosion caused by uncontrolled drainage on the slope face. In the case of overtopping of an embankment, rapid erosion will take place in tailings with resultant slope steepening and possible total loss of the impoundment.

If sudden vibratory stresses are applied to the materials in a relatively loose stage, particularly if they are saturated, a reduction in the effective stress between the particles can take place, thus reducing the shear strength. These vibratory stresses may result from blasting, equipment operating on the dump, mining subsidence, impact of dumped or sliding material, and finally from seismic shocks. In extreme cases, liquefaction of the material can result from this type of embankment loading, with resultant disastrous failures.

Any increase in the water level (the phreatic surface) within the materials area can produce a reduction in effective shear strength. This increase in water level, or pore pressure, can be caused by surface water entering the material, seepage water from the pond behind the embankment, blockage of diversion culverts under or within the embankment, or the construction of an embankment over an area with natural springs. Other factors might include changes in permeability due to subsidence in the area, filter materials becoming inoperative or ineffective due to clogging, and chemical or weathering changes of the dump materials. Finally, in extreme temperature zones, freezing of the downstream face may cause buildup of seepage water because of the reduction in the permeability of the exit area.

C. FORMS OF INSTABILITY

Signs of distress or instability in an embankment are usually related to the factors discussed in Section B of this chapter. Many of the signs have unique visible characteristics which can aid in reducing the cause of the distress.

1. Rotational Slips

Movement of material under unstable conditions within a dump or impoundment frequently will be an approximate cylindrical or spherical surface. Other movements may take non-circular forms such as wedges, depending upon many factors including shear strength, cohesive and frictional components, foundation characteristics, and stratification of the tailings material.

Rotational slipping usually exhibits tension cracks at the top of the slope, accompanied by slumping or bulging of the material at the toe of the slope. If the foundation material is soft, the bulging may take place in the natural ground beyond the toe. Rotational slips develop at variable rates, and the signs may be visible for only a short period of time before failure, or they may be discernible over long, slow periods of deterioration.

2. Surface Slips

When impoundments or dumps are constructed with little or no compaction and the slope material is essentially at the angle of repose, sliding of shallow surface layers may take place in a manner resembling sheet flow.

3. Flow-Type Slides

Some granular refuse, such as leach dump materials, may be dumped in a manner that results in a material which will permit rearrangement of the granular mass into a more dense state under stress conditions. If the material is saturated, the attempt to achieve the more dense mass may be inhibited by the inability of the water to escape from the mass rapidly enough, resulting in the temporary suspension of the material in the water. The result is an unstable mass resembling a viscous liquid which will move as a flow slide.

A rapidly moving stream of water and water-borne particles may result from intense surface runoff on a slope, or from large piping volumes of water exiting from the mass. The suspension of solids will have a consistency near that of a heavy mud, and the flows are termed mud flows.

4. Other Slope Movements

a. Creep - When the materials that form an embankment move at a slow, steady rate down and parallel to the existing slope, the failure is known as creep. Since the rate of movement of all the materials on the slope may not be the same, the slide surface usually will not remain parallel, but will either form waves parallel to the crest length (when the upper portion moves faster than the lower portion), or create tension cracks parallel to and near the crest (when the lower portion moves faster than the upper portion). When a slope is in a metastable condition, a single action, such as cutting an access road on or near the downstream toe of an embankment, may initiate a creep failure. Should the failure accelerate, a flow-type slide may develop.

b. Back-sapping - When the flow of water on the downstream face of an embankment is intermittent, either due to piping or surface runoff, a concentrated area of erosion may be produced which continues to progress up the slope. Each subsequent movement of material will be of increasingly greater areal extent, and the resulting physical evidence is termed back-sapping. Excavation of slope material on a continuing basis can result in this type of slope movement.

D. GENERAL LIST OF FACTORS AFFECTING EMBANKMENT STABILITY

There are many factors that can and will affect the stability of an embankment. The majority of these factors are involved with water in its various roles, embankment size (height and other dimensions), and movement. A list of most of the factors that affect embankment stability follows, and must be included in any general data form being utilized for mine tailings disposal evaluations.

- Size: height, width, volume.
- Slope steepness.
- Slumping, sloughing, sliding--surficial or deep seated?
- Cracks--parallel to embankment crest or to stream direction?
- Seepage--location, volume, carrying solids?
- Elevation of free pond water with respect to embankment features.
- Boils in downstream toe area.
- Bank erosion.
- Embankment vegetation.
- Methods and location of current refuse disposal.
- Abutment conditions--can a slide above the embankment endanger it?
- Has mining taken place beneath the area--embankment, reservoir, etc?

These factors may be considered the more important ones affecting visible signs of instability. However, they are not the only factors of which one must be aware. The following lists pertain to important factors concerned with more specific areas such as appearance of the site, embankment characteristics, refuse disposal procedures, and water, both as it relates to the embankment and to possible flooding.

1. Appearance of the Site

In general, the better the physical appearance of the site and the disposal operation, the safer the facility. However, like most generalities, this is not always true, and one must be able to distinguish between cosmetic and real safety practices.

- Is the vegetation cleared from the pond and embankment areas?
- Is the disposal of the cleared material properly controlled?
- Is the materials handling equipment in good condition?
- Is the embankment graded? Groomed? Revegetated?

2. Embankment Characteristics

The following items describing the characteristics of the embankment should be noted.

- Is the embankment active, inactive, or abandoned?
- Is the embankment being enlarged? At what rate? How? Where?
- Has the same method of disposal always been used?
- Is the material being compacted? How? To what degree?
- How high is the embankment? What is the planned final height?
- How wide is the embankment? What is the top (crest) width? What is the base width? What are the slopes?
- Is the embankment being raised by the upstream method? The downstream method? Another method?
- Are there cracks in the embankment? Where? Direction of cracking?
- Have there been slides on the surface? What type? What extent?
- Does the embankment retain water? Is there a pond now? How close to crest?
- Is there a decant system in the pond? Is the system clear or obstructed? Can the water level be fully controlled?
- Is there seepage present? Where? What volume? Any coloration? Any solids being transported? Does the seepage pond on the slope?
- What is the embankment foundation? Was it stripped or grubbed? Was a key trench or any other barrier included in the foundation?
- Is there a starter dam? Is it impervious or pervious? To what elevation does it rise?

3. Tailings Disposal Considerations

The following items describing the characteristics of the embankment should be noted.

- At what rate are tailings being deposited? Continuously? Intermittently? Are there periods when the pond dries out?
- What preparations, if any, occur in the pond before tailings are discharged?
- Where are the tailings being deposited? Upstream or near embankment?
- What is the relationship between tailings, water, and available storage? How fast is available storage being filled? If the dam is across an active stream, is there adequate freeboard?

4. Water as it Relates to Embankment Stability

Many, if not most, of the signs that indicate embankment distress are associated in some way with either subsurface or surface water in relation to the retaining embankment.

- The less the difference in elevation between any seepage water on the downstream face and the water level in the pond, the greater the cause for concern. Try to relate how the embankment has been constructed with the location of any seepage and visualize the phreatic line. Remember that water emerging on the downstream face may not be free, that is, no apparent surface flow may be taking place.
- On the downstream face can you see:
    - Gross changes in color on an approximately horizontal line?
    - Vegetation differences in color or amount on this line?
    - Variations in surface erosion? (Often erosion is more pronounced below the zone of saturation).
    - Minor surface slides below the zone of saturation?
- If there is free water visible on the downstream face:
    - Identify the point or points where the water exits.
    - Estimate the quantity, temperature, quality, and clarity.
    - If the solids are being carried, estimate the quantity and source.
    - Determine if the seepage flows are causing erosion of the face.
    - Does the seepage flow pass beyond or is it ponded on the surface?
    - Try to relate present or past seepage areas to corresponding pond levels.

5. Water as it Relates to Flooding

Since a major rain storm and the resultant high storm runoff might substantially increase any hazard associated with the impoundment, the following factors should be determined if the dam is constructed across an active water course.

- What is the possible storage volume available?
- How much of the possible storage volume is filled with water?
- What is the size of the watershed behind the impoundment? Determine the runoff characteristics of the watershed such as amount of vegetation, infiltration potential, etc.
- Have any provisions been made to carry runoff around the impoundment? Are there diversion ditches? Are they functional and maintained? Would they be blocked by slides during high runoff?
- Is there a spillway? How was it constructed: Open cut? Pipe? What is the relationship of the spillway size to the estimated storm runoff? Does the spillway discharge pass over the embankment so as to erode the downstream slope?
- How would a rise in the pond water level affect the phreatic surface in the embankment? What affect would such a rise have on the embankment stability?

E. HAZARD RATING SYSTEM

When what appears to be a potentially disastrous condition at a refuse disposal site is identified or suspected, an Emergency Hazard Rating System is useful on which to base a degree of reaction and to facilitate communication. The setting of a numerical hazard rating on a site under study, while desirable from an administrative and field inspector's point of view, is a difficult, if not impossible, procedure. Since a single deficiency can be the cause for a site to require immediate review or action, a combination of minor deficiencies from several rating elements does not necessarily indicate that a site is safe or unsafe.

A simple direct system is best for this purpose, and an Emergency Hazard Rating System based along the following lines can be utilized:

I. High Potential for Loss of Life
II. High Potential for Loss of Property
III. Low Potential for Loss of Life or Property
IV. No Potential for Loss of Life or Property

It is also desirable to have a rating system for less immediate situations. In this context, a more complex system can be developed along the lines discussed below.

An evaluation system can be established based on the physical conditions of the deposit and the consequences of failure. The condition rating can be obtained from the results of the inspector's observations and data from basic data forms, such as size, storage volume, etc. The consequences of failure ratings can be assessed from the determination of the characteristics of the area that could be affected by a failure.

	Consequences of Failure		Condition
I.	High potential for loss of life and property.	A.	Major Deficiencies-Impoundment
II.	High potential for loss of property.	B.	Major Deficiencies-Dump
III.	Low potential for loss.	C.	Minor Deficiencies
IV.	No potential for loss	D.	No Deficiencies

The priority for review can be determined by combining the relative importance of each of the two categories, and placing the combined rating in descending order of importance as follows:

1.	IA	High potential for loss of life and property; Major deficiencies - Impoundment
2.	IB	High potential for loss of life and property; Major deficiencies - Dump
3.	IIA	High potential for loss of property; Major deficiencies - Impoundment
4.	IIB	High potential for loss of property; Major deficiencies - Dump
5.	IC	High potential for loss of life and property; Minor deficiencies
6.	IIIA	Low potential for loss; Major deficiencies - Impoundment
7.	IIC	High potential for loss of property; Minor deficiencies
8.	IIIB	Low potential for loss; Major deficiencies - Dump
9.	ID	High potential for loss of life and property; No deficiencies
10.	IIIC	Low potential for loss; Major deficiencies
11.	IVA	No potential for loss; Major deficiencies - Impoundment

12.	IID	High potential for loss of property; No deficiencies
13.	IVB	No potential for loss; Major deficiencies - Dump
14.	IIID	Low potential for loss; No deficiencies
15.	IVC	No potential for loss; Minor deficiencies
16.	IVD	No potential for loss; No deficiencies

These ratings, and the basis for them, are not intended to be stringent or constraining. They cannot be, due to the non-specific nature of the contents of the evaluation. They are only intended as a preliminary method upon which an order of priority for review of refuse deposits can be based. A certain degree of flexibility must be allowed because of the many variables involved.