INCORPORATION OF SPATIAL VARIABILITY OF MILL TAILINGS HYDRAULIC PROPERTIES INTO A NUMERICAL MODEL: IMPLICATIONS FOR MOVEMENT & RETENTION OF MOISTURE

by

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This study was conducted to develop a methodology for incorporati the spatial variability of mill tailings impoundments' hydraul properties into a numerical model of seepage. An extensive data ba was generated to characterize the spatial variability of an abandon lead-zinc mill tailings impoundment in South Central New Mexico. T data base was developed through laboratory analysis of tailings sampl obtained with 60 cm thin wall samplers, and in-situ moistu measurements made with a neutron probe. Parameters measured inclu saturated hydraulic conductivity, K_{sat}, moisture content-negati pressure head realtionships, θ-ψ, porosity, n, particle si distribution and in-situ volumetric moisture contents. Difficulties we encountered during sampling of the slime zone and foundation materia Neutron probe calibration problems encountered prevented reliab measurements in moist ($\theta > 0.35$ cm^3/cm^3) areas of the impoundment.

Characterization of the spatial variability of mill tailin hydraulic properties was performed by Gary Johnson (1987). The prima input from Johnson's analysis to this work is a two-dimension regression model of saturated hydraulic conductivity along the nor trending sampling transect. The regression model is used to incorpora the spatial variability of the impoundment's hydraulic properties in the numerical model.

The numerical model used to study seeepage is UNSAT2 (Davis a Neuman, 1983). Steady state simulations were conducted along t vertical cross section where samples were collected to characterize t mill tailings' hydraulic properties. Boundary conditions for t simulations were based on in-situ measurements of moisture at t impoundment surface and in the foundation material prior to and aft ponding of water in the spring and fall of 1986. In homogeneous areas the impoundment, the numerical model predictions of water content agre with observed values. In heterogeneous zones, numerical results a inconsistent with observed data. Results of the numerical simulatio also indicate that the interior of the impoundment remains at great than 90 percent saturation, that movement of moisture is predominate downward except near the southern edge, and that an extended period ponding produces saturated flow of limited extent immediately below t pond.

TABLE OF CONTENTS

Pag

ABSTRACT . . . .
TABLE OF CONTENTS i
LIST OF ILLUSTRATIONS i
LIST OF TABLES vi
ACKNOWLEDGEMENTS vii

I. INTRODUCTION . . . .
II. DESCRIPTION OF FIELD SITE . . . .
Geology . . . .
Hydrogeology . . . .
Soils . . . .
Description of Tailings Impoundment . . . .

III. TAILINGS CHARACTERIZATION 1
Heterogeneity 1
Origins of Spatial Variability of Mill Tailings
Hydraulic Properties 1
Preliminary Field Work 2
Base Map 2
Locations of Sampling Transects and Neutron Access Tube 2
Collection of Samples 2
Sampling Method 2
Sampling Problems 2
In-Situ Moisture Measurements 2
Installation of Access Tubes 2
Neutron Probe Calibration 3
Sources of Calibration Error 3
Laboratory Analysis 4
Saturated Hydraulic Conductivity 4
Method 4
Calculations 4
Sources of Error 4
Sample Removal from Shelby Tubes 5
Unsaturated Hydraulic Conductivity 5
Method 5
Sources of Error 5
Moisture Retention Relationships 5
Method 6
Sources of Error 6
Porosity 6
Particle Size Analysis 6

IV. NUMERICAL SIMULATIONS 6
Review of Numerical Simulation of Seepage in Tailings . . . 7
Capability of UNSAT2 7
Model Verification 7

TABLE OF CONTENTS--Continued

Pag

- Problem Definition 7
- Results and Discussion 7
- Method 8
  - Assumptions and Limitations 8
  - Characterization of Spacial Variability 8
  - Boundary Conditions 9
  - Initial Conditions 9
  - Time Step Size and Total Simulation Time 9
  - Model Discretization 9
  - Model Calibration and Validation 9
- Results and Discussion 10
  - Foundation Material 10
  - Simulation Time .10
  - Numerical Simulation of Moisture Content Along Vertical Transects 10
  - Two-dimensional Profiles 11
  - Discussion of Errors 11

V. SUMMARY AND CONCLUSIONS 11

VI. RECOMMENDATIONS FOR FUTURE WORK 12

VII. REFERENCES 12

APPENDIX A 12
- Neutron Probe Data .12
- Regression Program .14

APPENDIX B 14
- Program to Calculate Saturated Hydraulic Conductivity from Permeameter Data 14
- Example of Program Output 15
- Saturated Hydraulic Conductivity and Porosity Data for Horizontal Transects 15
- Saturated Hydraulic Conductivity and Porosity Data for Vertical Transects 16

APPENDIX C 17
- van Genuchten Computer Code 17
- Unsaturated Hydraulic Conductivity and Laboratory θ-ψ Data 17

APPENDIX D 28
- Particle Size Analysis Data 28

APPENDIX E 31
- Computer Code for the Solution of Philip's Equations 31
- UNSAT2 Computer Code 32

LIST OF ILLUSTRATIONS

Page

Figure

1. Locations of Mining and Processing Wastes 2
2. Location Map 5
3. Water Table Map of Magdalena Mountains 7
4. Soil Survey Map of the Magdalena Area 8
5. Eastern View Across the Waldo Mine Mill Tailings Impoundment . .10
6. Cross Section of Tailings Impoundment Along N Trending Transect Line .12
7. Schematic of Upstream Method of Tailings Dam Construction . . .17
8. Least Squares Regression of Saturated Hydraulic Conductivity . .18
9. Base Map of Tailings Impoundment 22
10. Location of Sampling Transects and Neutron Access Tubes 23
11. Location of Neutron Access Tubes Along Sampling Transect Cross Section 30
12. Neutron Probe Calibration Curve 34
13. Aerial Extent of Ponding on Layer Two 35
14. Shelby Tube Permeameter .43
15. Schematic Diagram of Shelby Tube Permeameter 44
16. Position of Samples for K_s Measurements Along Horizontal Sampling Transects 47
17. Position of Samples for K_s Measurements Along Vertical Sampling Transects 48
18. Fluctuation in Saturated Hydraulic Conductivity for a Tailings Sample .50
19. Permeameter Apparatus for Quantifying Boundary Flow 52

LIST OF ILLUSTRATIONS--Continued

Page

20. Effect of Texture on Hydraulic Conductivity with Changing Negative Pressure Head 54

21. Comparison of van Genuchten Two and Three Parameter Model Fit to Observed θ-ψ Data 57

22. Effect of Texture on Moisture Retention in Tailings Material . .60

23. Graphical Representation of Hysteresis 61

24. Hanging-Water-Column Apparatus 63

25. Schematic of Pressure Plate Apparatus 65

26. Position of Free Surface for Different Profile Configurations .71

27. Finite Element Grid and Column Used in Test Case 76

28. Position of Wetting Front over Time 79

29. Change in Infiltration over Time 80

30. Cumulative Inflow Depth over Time 81

31. Impoundment with Neutron Probe and Sampling Locations, Plane of Symmetry 86

32. Cross Section of Impoundment Along North Trending Transect with Neutron Probe Tube Locations 87

33. Contoured Cross Section of the Two-Dimensional Regression Fit to the Log K Data 89

34. True-to-Scale Cross Section Along Sampling Transect 91

35. Finite Element Grid for Two-Dimensional Simulations 98

36. Comparison of the Effect of Foundation Material on Moisture Content Profiles 102

37. Comparison of the Effect of Simulation Time on Moisture Content Profiles 104

38. Simulation of Moisture Contents Along Vertical Transects . . . 106

39. Hydraulic Head Distribution After Initial Drainage 111

40. Hydraulic Head Distribution After Ponding 112

LIST OF ILLUSTRATIONS--Continued

Page

41. Percent Saturation After Initial Drainage 113

42. Percent Saturation After Ponding 114

LIST OF TABLES

Pag

Table

1. Results of Analysis on Dry Tailings Samples 3

2. Results of Chemical Analysis on Shelby Tube Leachate and Impoundment Pond Water 3

3. Hydraulic Parameters for Two-Dimensional Simulations 9

4. Hydraulic Parameters for One-Dimensional Simulations 9

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I. INTRODUCTION

Mill tailings are crushed depleted ore, a by-product in the init: refining steps of the mining industry. Tailings are deposited tailings dams or impoundments, varying in size from a few acres several square miles. These tailings impoundments are located through the United States (figure 1). Particle size of the tailings range f sand down to clay. The degree of heterogeneity within a tailings pile a function of several factors including characteristics of the produc area of a mine, and the volume rate of discharge from the mill over life cycle of the impoundment. Thus hydraulic properties controll seepage from tailings can vary over several orders of magnitude wit one impoundment.

In the past, interest in the environmental hazard posed by th waste piles focused on uranium tailings impoundments. Recen impoundments which pose a lesser environmental risk such as lead-z and copper tailings impoundments are also being scrutinized. The U Bureau of Mines is considering a program to characterize impoundme and to evaluate their environmental hazard (Stanczyk, perso communication, 1986).

One means of quantifying the seepage is the use of numerical mod to elucidate flow dynamics through an impoundment. Although numeri models can provide useful flow analysis, accuracy of the results limited by the quality of the input parameters. Therefore it

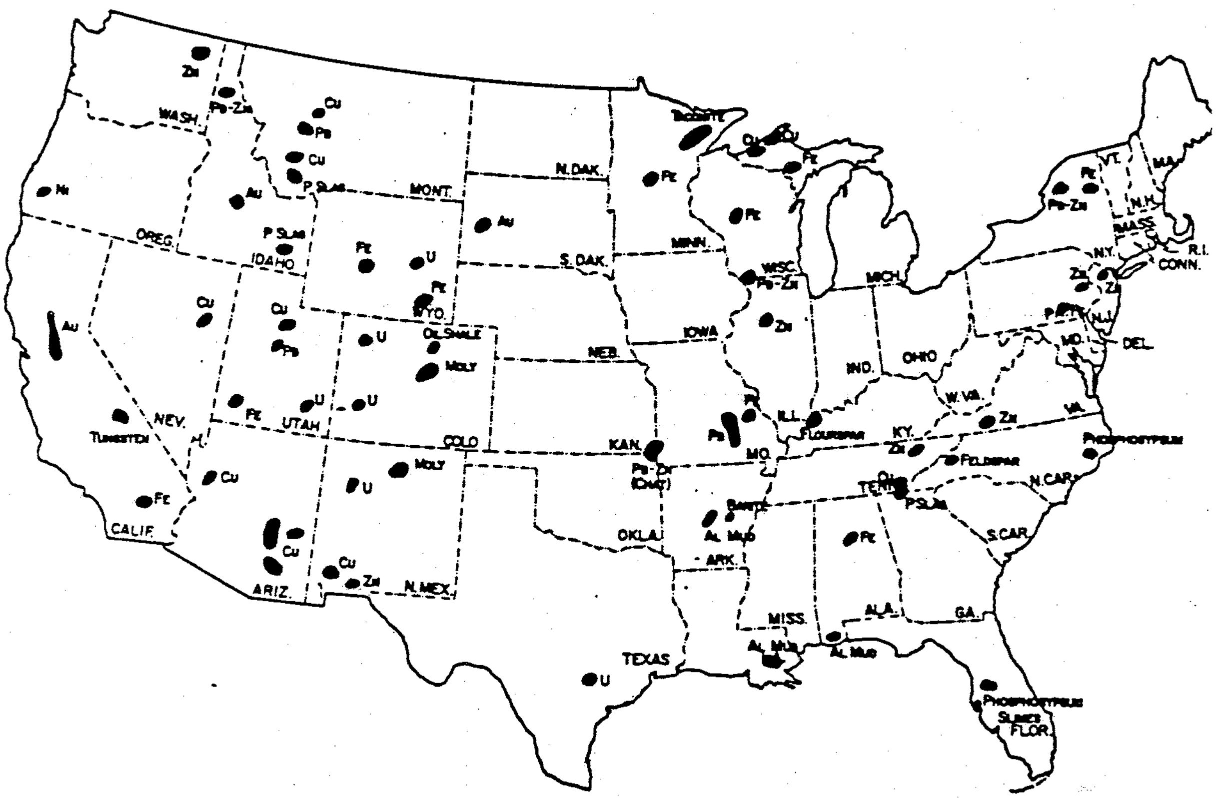


Fig. 1. Locations of Mining and Processing Wastes

(Source: Stanczky, 1986)

important to be able to characterize and incorporate the spati variability of important hydraulic properties into numerical models.

The objectives of this study were to:

1) Develop a methodology to effectively sample and analy tailings material while generating an extensive data base hydraulic properties from an abandoned mill tailir impoundment;
2) Characterize the spatial variability of the importa hydraulic properties and;
3) Develop a methodology to incorporate the spatial variabili into a mathematical model and study the input of paramet spatial variability on moisture movement, distribution a retention.

The first phase of this study was conducted by myself and Ga Johnson over a two year period (September 1984 to October, 1986). T second phase was completed by Gary Johnson (Johnson, 1987). The thi phase of the study is presented in this report.

II. DESCRIPTION OF FIELD SITE

The field site for this work is the abandoned Waldo Mine mi tailings impoundment located in South Central New Mexico, 2.4 kilomete south of the town of Magdalena (figure 2). The impoundment, owned b the American Smelting and Refining Company (ASARCO), is situated on th west side of the Magdalena mountains at an elevation of 2,088 mete above mean sea level. Vegetation in the surrounding area is juniper a pinon pine (Summers et al., 1972), although the tailings are complete void of vegetation. Average annual precipitation is 28.6 cm Climatological data were obtained from the U.S. Forest Service Range Station in Magdalena.

Geology

The Magdalena Mountains are a north-trending block faulted mounta range in the Basin and Range physiographic province (Blakestad, 197 Krewedl, 1974). The area has undergone extensive uplift, erosion, a faulting, followed by a period of intrusion by dikes and sills.

The oldest exposed rocks are Precambrian argillites, felsite gabbro and granites which are unconformably overlain by Mississippia and Pennsylvanian limestone and Permian age sandstones. The sedimenta rocks are overlain by a thick sequence of silicic Tertia volcanoclastic sediments, lavas and ash-flows. Quaternary deposits i the area of the field site include landslide deposits, alluvium, a talus.

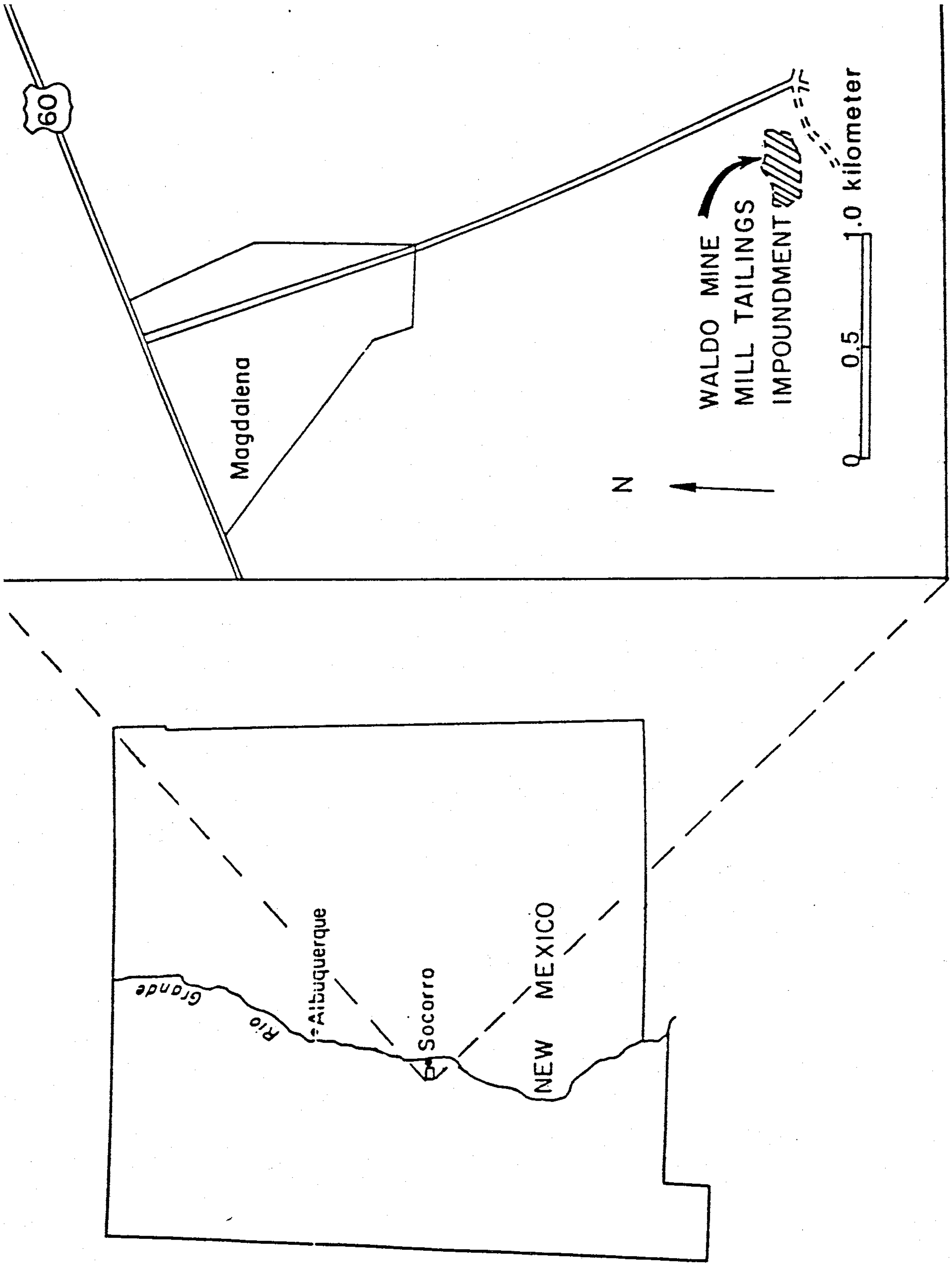


Fig. 2. Location Map

Mineralization occurred by hydrothermal alteration, primarily alor faults cutting limestones; the faults acted as conduits for hydrotherma fluids (Blakestad, 1978). The solutions formed limestone replacemer deposits adjacent to the fault zones. Mineralization was als associated with dikes and sills. Metals mined in the area include zinc lead, copper, gold, silver, manganese, tungsten, barium and vanadiu (File, 1965).

Hydrogeology

Information regarding the hydrogeology of the area is limited ar dated. Wells within two kilometers of the impoundment were completed i alluvium and volcanic sediments (Summers et al., 1972). Yields rang from 0.08 to 0.20 m^3/min. The two wells on ASARCO's property adjacer to the impoundment have collapsed and have been abandoned. The genera direction of ground water flow beneath the impoundment is northwes towards Magdalena. Figure 3 illustrates the approximate configuratic of the water table in the vicinity of the impoundment. Recer information from a well 0.8 km up gradient from the impoundmer indicates that the depth to ground water is at 79-91 meters (Morgar 1986). Based on available data, depth to the water table beneath th impoundment is estimated to be 80 meters.

Soils

The tailings impoundment overlays two soil mapping units, th Manzano silt loam (#424) and Lupdun-Datil association (#460) (figure 4 (Soil Survey of Socorro County, U.S. Dept. of Agriculture, Soi

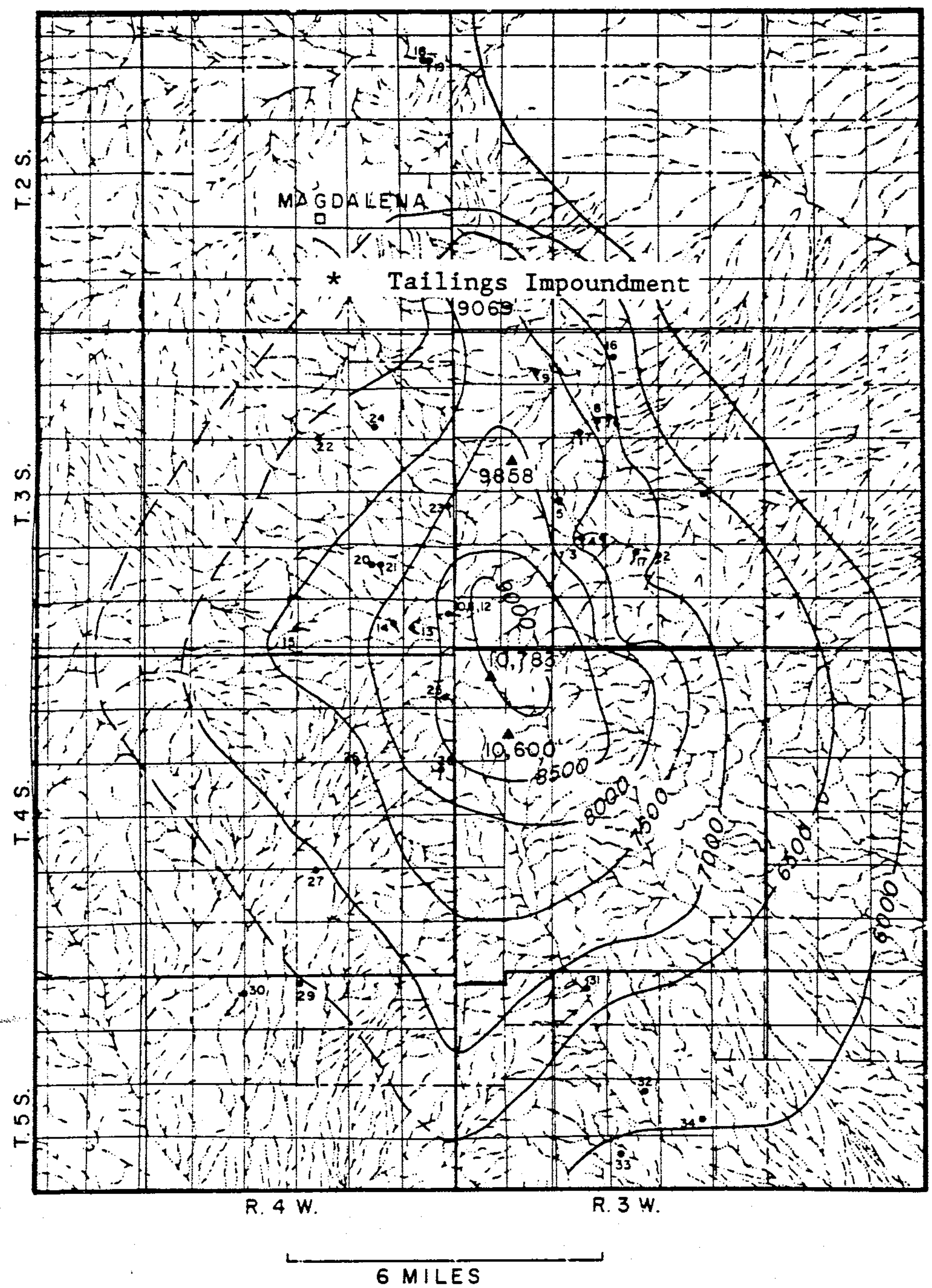


Fig. 3. Water Table Map of Magdalena Mountains

(Source: Summers et al., 1972)

Fig. 4. Soil Survey Map for Magdalena Area

(Source: U.S. Soil Conservation Service)

Conservation Service, Socorro, New Mexico, unpublished). Manzano si loam is deep (> 152.0 centimeters), with moderately low permeabili (0.5-1.5 centimeters per hour), and is formed in recent alluvium. Soi which make up the Lapdun-Datil association are deep (> 152 centimeters), and have moderate permeabilities (1.5-5.0 cm/hour). Bo soils are formed in alluvium derived from volcanic rock. The location the contact between the mapping units is approximate and has not be verified in the field.

Description of Tailings Impoundment

The tailings impoundment (figure 5) consists of a slag pi generated from a smelter and three distinct layers. These laye include a poorly contained bottom layer, which lies on native soil, a two well-contained second and third layers.

The history of the pile and deposition of the layers is not we documented. The mill which produced the tailings was erected in 19 and was operated intermittently until its closing and subseque dismantling in 1950. The mill, a 181 metric ton/day capacity flotati plant, primarily processed zinc-lead sulfides and lead carbonates (Lus 1947). Peak production years centered around World War I and World W II. The depositional history of the pile was deduced from a series U.S. Forest Service aerial photos, first-hand accounts of former mi employees and physical examinations of the site.

The first layer was deposited between the years 1913 (when the mi was constructed) and 1943. The lateral boundaries of this layer are t most poorly contained of the three layers. Crude retaining walls we apparently built on the north and west edges of the first layer, a

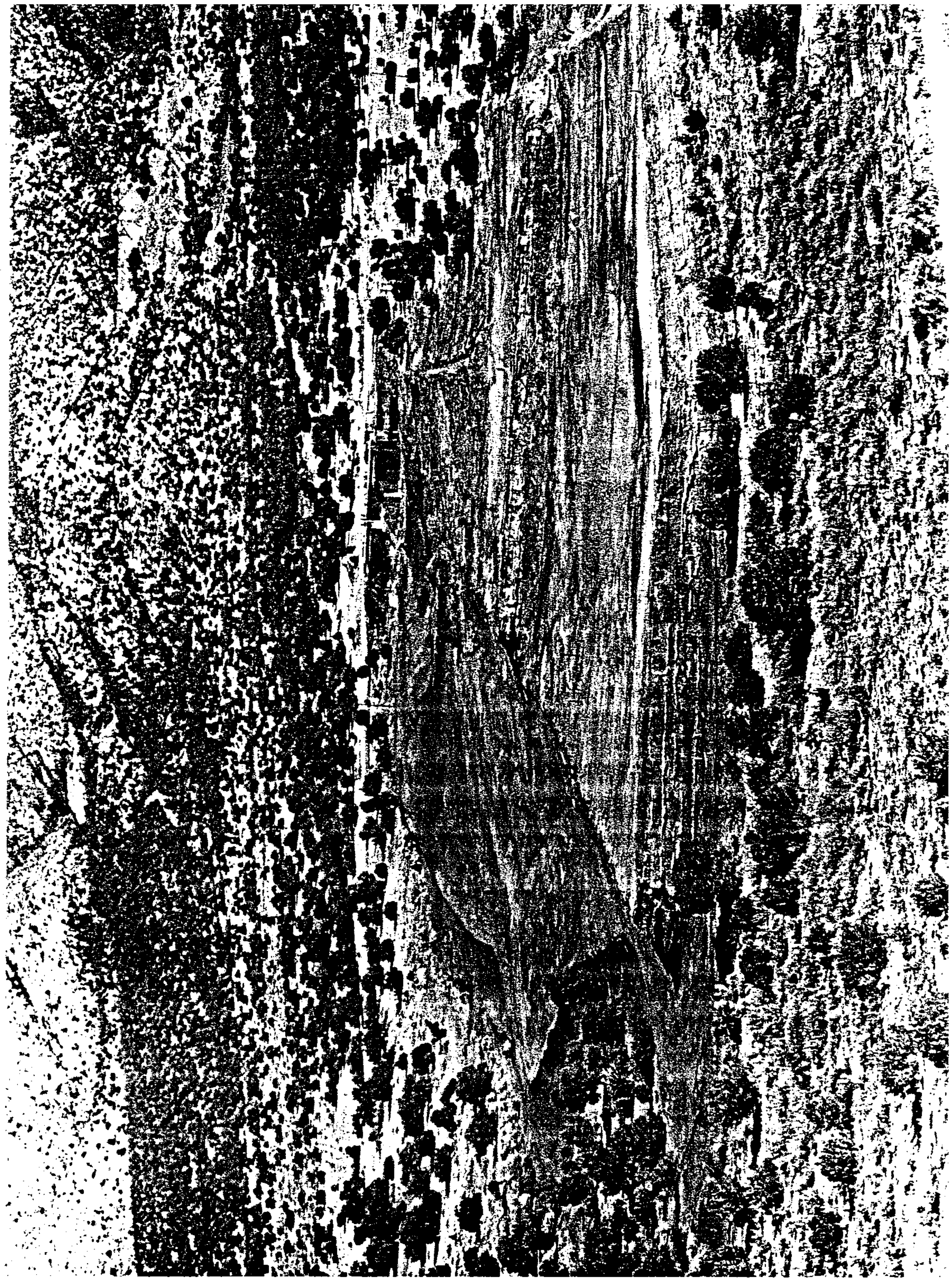


Fig. 5. Eastern View Across the Waldo Mine Mill Tailings Impoundment
(1986)

tailings deposition was controlled in by the land surface topograph The second layer (which partially overlies the first layer, figure was deposited in approximately 1943, with the third layer (whic overlies a portion of the first and second layers) deposited sometin prior to the closing of the mill in 1950.

The upstream construction method was most likely used to construc the impoundment. Remains at the site imply that wooden retaining wall were built on the downhill sides of layer two and three to support th dikes. Tailings were delivered to the pile in elevated flumes whic almost completely surrounded the pile. Chutes were spaced along th flumes to direct the flow of material to different areas. Excess wate from the tailings was collected in central drains, pumped back to th mill house and recycled.

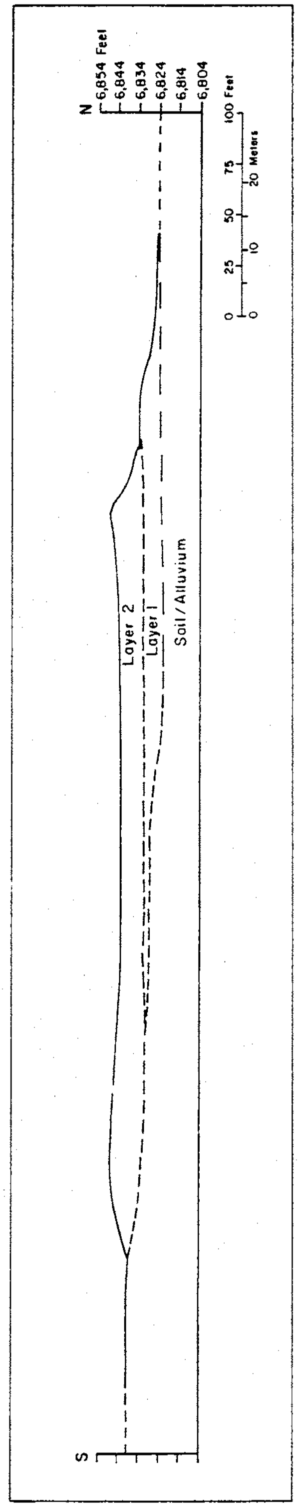


Fig. 6. Cross Section of Tailings Impoundment

Along North Trending Transect

III. TAILINGS CHARACTERIZATION

Heterogeneity

Hydraulic conductivity can vary both through space and with th direction of measurement at a point within a porous media. If hydrauli conductivity is independent of position within a porous media, then th media is homogenous, otherwise it is heterogeneous (Freeze and Cherry 1979; Bear, 1972). There are many types of heterogeneou configurations. Two types common to tailings impoundments are layere and trending heterogeneities, both of which can result from sedimentar depositional processes. Layered heterogeneity results from th deposition of distinct layers of material. Each layer is homogeneous but the hydraulic properties of the layers differ from each other Trending heterogeneities common to deltic and alluvial fan deposits result from sedimentation of detrital material with gradual changes i fluid velocity. A trending heterogeneity can be described as a trend i the mean value of the probability distribution (Freeze and Cherry 1979).

A porous medium is isotropic at a point if hydraulic conductivit at the point is independent of the direction of measurement. If th measurement of hydraulic conductivity is directionally dependent, the the porous media is anisotropic at that point. According to Yeh et al (1985), in an unsaturated, stratified porous media, effective anisotrop of the strata is not constant but variable with fluid saturation. I the theoretical discussion, Yeh et al. showed that the anisotropy rati (horizontal/vertical) of the effective mean unsaturated hydrauli conductivity increases with decreasing moisture content. Also, as th soil becomes drier, the variability of capillary pressure or moistu content increases. Other researchers have documented the significar impact heterogeneities can have on moisture movement (Martin et. al 1980, Poulovassilis and Psychoyou, 1985, Zaslavsky and Sinai, 1981, ar Heermann, 1985).

Martin et al. (1980) in their work which characterized inacti uranium mill tailings sites found that the alternating sand/slin layering formed barriers or "capillary breaks" to fluid movement. As result of the layering, the piles retained significant amounts c fluids. Alternating layers of sand/slime have been observed durin trenching operations at the field site for this work, the Waldo mil tailings impoundment. These layers of fine-grained tailings, or slimes were observed to be wet while adjacent sand layers were relatively dry.

Poulovassilis and Psychoyou (1985) studied the effect of layerin in a soil profile on evaporation and reported findings similar to Marti et al. (1980). At the boundary between different materials, the soi water pressure head may exhibit a discontinuity. The characteristics c the break were a function of the type of layering and prevailin pressure head. The sequence of layering and pressure head at th boundary can have a significant impact on the evaporation rate. For water table at a constant depth, the evaporation rate attained a maximu value where the soil profile included a coarse layer underlying a fir layer. The evaporation rate was minimized with the opposite layerin sequence.

Zaslavsky and Sinai (1981) found that in a layered media horizonta hydraulic conductivity, K_h, can be several times larger than vertica hydraulic conductivity, K_v. Kealy (1970) determined an average K_h/K ratio of five to one in lead-zinc tailings. Laboratory studies c unsaturated flow through layered material by Heermann (1985) have als demonstrated this phenomenon.

The importance of incorporating the heterogeneous nature of porou media into a mathematical model of seepage flow was stressed by Siege and Stephens (1980). Siegel and Stephens compared an analytica solution, developed by McWhorter and Nelson (1979), which predicts th advance of a wetting front beneath a lined pond, to a numerica solution. The analytical solution, which is for one-dimensior homogenous isotropic conditions, gave similar results to the numerica solution under isotropic conditions. However under anisotropi conditions the analytical solution over-estimated the advance of th wetting front by as much as fifty percent.

Origins of Spatial Variability of Mill Tailings Hydraulic Properties

The environment of deposition and the physical characteristics c the material being deposited are primary factors in determining whethe a porous media will be homogenous or heterogeneous, isotropic c anisotropic. Tailings, a waste product of the mining and smeltir industry, are finely ground rock (Rutherford et al., 1982) and are heterogeneous mixture ranging from sand to clay size particles. The are generally transported to a disposal site hydraulically at concentration of forty to fifty percent by weight (Klohn, 1979). Th watery slurries are contained in a tailings pond, or impoundment whi(allows solids to settle and water to be recycled. Deposition (tailings in an impoundment can be compared to depositional process(that occur in deltas.

Tailings impoundments are constructed using a variety (techniques. Upstream construction (figure 7) is the oldest and cheape: method (Klohn, 1979). from available evidence this method appears t have been used to construct layers two and three at the Waldo Mine mil tailings impoundment. In the upstream method a starter dike or dam i built to form the perimeter of the impoundment. Local material or th coarse fraction of the tailings are used to construct the dikes. Th tailings slurry is discharged along the dike and flows towards th interior of the impoundment. As the fluid velocity decreases, materia is sorted by size and density, with the smallest, lightest materia deposited furthest from the discharge point. This type of depositiona process, common to tailings disposal, combined with the particle siz range of tailings produces trending heterogeneities. Figure exemplifies the impact of such heterogeneities on hydraulic properties The solid line is the least squares regression through the saturate hydraulic conductivity values measured from Waldo tailings impoundmen samples taken at a depth of 192 centimeters.

Impoundments vary in the degree of uniformity, depending upon th mining and milling operations. The characteristics of ore produced fro a mine and the volume rate of discharge from the mill house, can b quite variable during the lifetime of an operation. These variables i a mining and milling operation produce different degrees of layere heterogeneity unique to each impoundment. An impoundment may be unifor

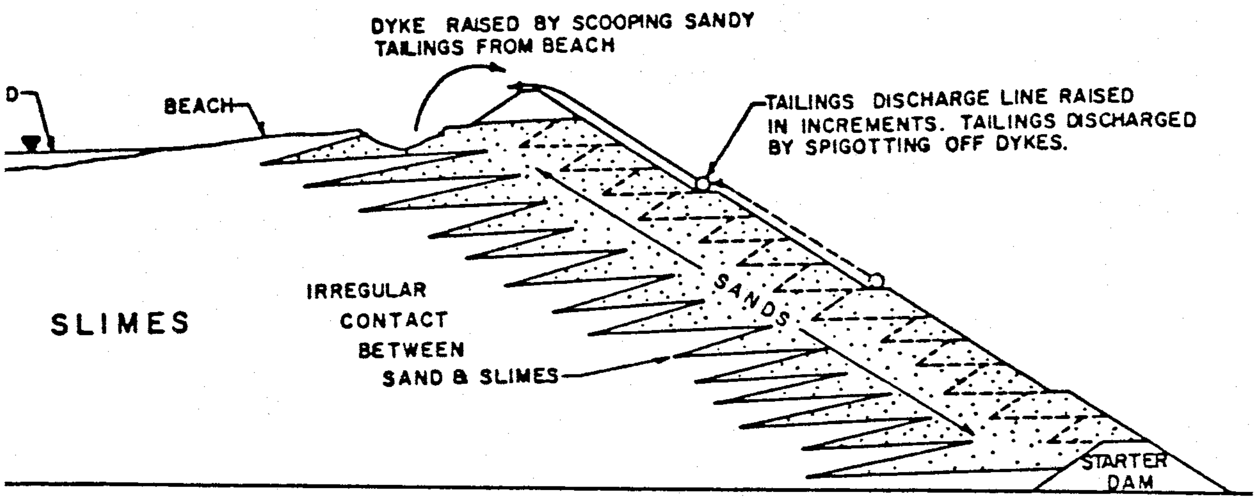


Fig. 7. Schematic of Upstream Method of Tailings Dam Construction

(Source: Klohn, 1979)

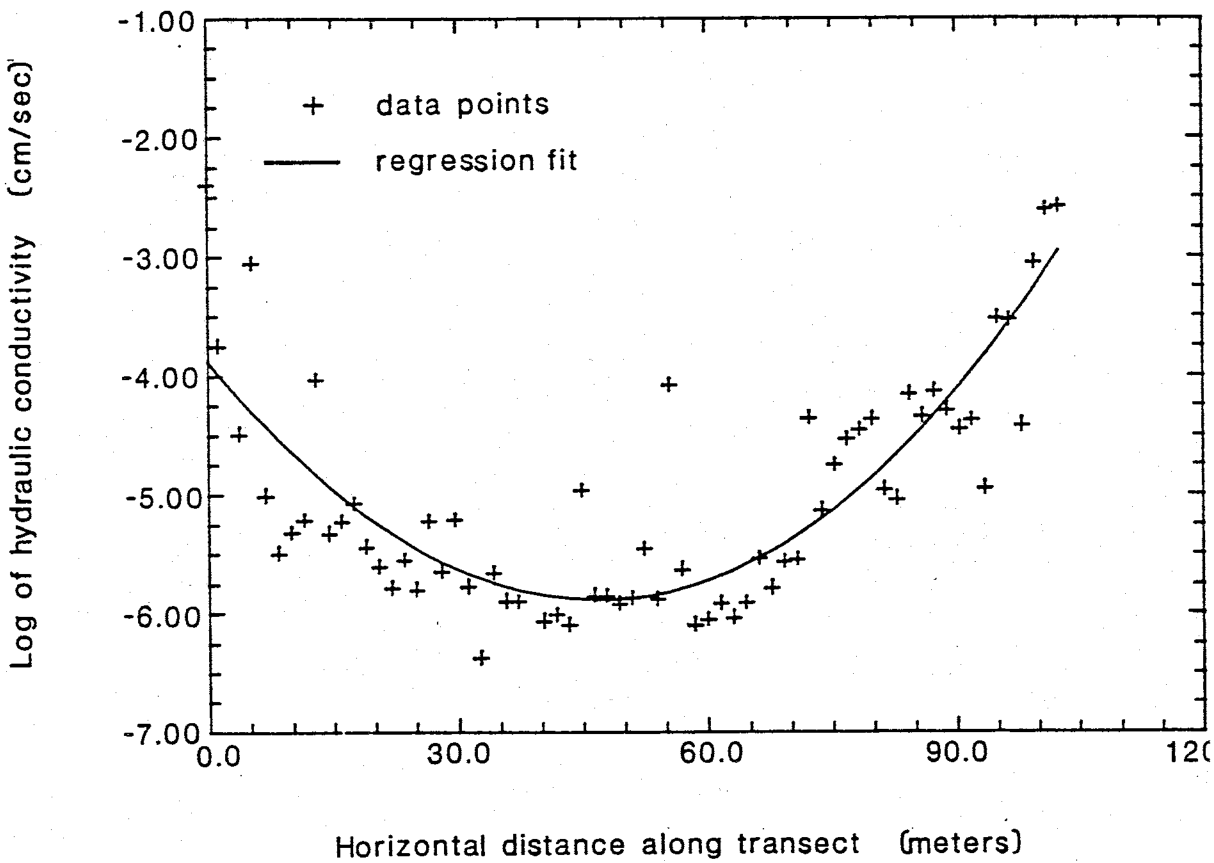


Fig. 8. Least Squares Regression of Saturated Hydraulic Conductivity Versus Distance along Sampling Transect (192 cm depth)

with sharp delineation of slime and sand, or heterogeneous with layer and lenses of slime intermixed throughout a pile (Wardwell et al. 1982).

One aspect of the heterogeneity of hydraulic properties of mil tailings that is not considered by this work but may be important is th effect of chemical reactions on hydraulic properties such a permeability. In mine spoils that contain large amounts of pyrite weathering (oxidation) of metal sulfides produces a low pH (2.3) (Burto et al., 1978). This leads to low infiltration rates into mine spoil with associated precipitation of salts near the zone of oxidation at th surface of the mine spoils (Burton et al., 1978). Pyrite (iron sulfide occurs in ore taken from the Waldo Mine, from which the tailings wer generated. Oxidation of the pyrite leads to acidification of wate ponded on the surface of layer two. A pH of 2.25 was measured for ponde precipitation in the interior area of layer two during this fiel investigation. Thus by analogy to the study by Burton et al. (1978) the surface tailings material are likely to have a low permeability Sampling in this area of layer two required trenching that brough unweathered tailings material to the surface. Spatially variabl accumulation of white precipitates and blistering of the top fe millimeters of the tailings surface is evident following a rain or sno event. The chemical composition of the precipitates and mechanisms o blister formation was not studied. Other reactions occurring in th Waldo Mine tailings below the surface that may affect hydrauli conductivity include formation of iron and calcium cements, an associated hard pans. These features, both at the surface and at depth indicate chemical influences that may reduce permeability of th original tailings material both temporally and spatially. The influenc of geochemistry on hydraulic properties should be characterized furthe

One of the primary objectives of this research project, as outline in the original proposal to the U.S. Bureau of Mines Generic Researc Center, is the generation of an extensive data base of hydrauli properties for a mill tailings impoundment. The data base is to be use to characterize the spatial variability of the hydraulic properties c the impoundment. Decisions on which hydraulic parameters were to b measured, how to obtain the necessary samples, and how to analyze th samples are based on the following criteria:

1. Parameter(s) need to be measured relatively easily, quickly and inexpensively because of the large number of measurements required to adequately characterize an impoundment's spatial variability,;

2. The parameters must satisfy input requirements of the numerical model and;

3. The physical characteristics of the impoundment impose specific restrictions:
   - -sampling techniques limited by the thickness of the pile and presence of hard pans and tailings slime.
   - -low permeability of tailings material made it impractical to take large numbers of in-situ measurements of hydraulic properties with the exception of moisture content.
   - -a history of vandalism of equipment severely limited the type of instrumentation that could be left unattended at the site.

For a complete discussion and critique of available field/laborator methods to use in tailings characterization refer to Larson (1984).

Preliminary Field Work

Base Map

Prior to establishing sampling transects, sampling of tailings, ar installation of equipment a base map of the Waldo Mine impoundment wa developed (figure 9). No topographic base map was available. A alidade and plane table were used to survey the first, second, and thir layers. Survey work began September 1984 and was completed Decembe 1984. A USGS bench mark 500 meters northeast of the impoundment was use as the reference elevation.

Locations of Sampling Transects and Neutron Access Tube

Sampling of tailings material occurred along eight transects: tw horizontal transects and six vertical transects (figure 10). Th specific details of sampling and neutron logging methods are describe in subsequent sections.

All horizontal and vertical transects were located on the secor layer. Layer two was selected because of its size and the method c tailings deposition which was similar to methods used today. Layer tw is approximately two hectares in size, with a total surface relief c 1.8 meters. Thickness of the layer varies from 1.5 meters next to laye three to 7.6 meters at the northwest edge.

The two horizontal transects were in the same vertical plane whic trends N 6^{o} W, but each line of sampling was at a different depth Placement of the horizontal transects was based on the interpretation o the impoundment structure. Transects were laid out perpendicular to th

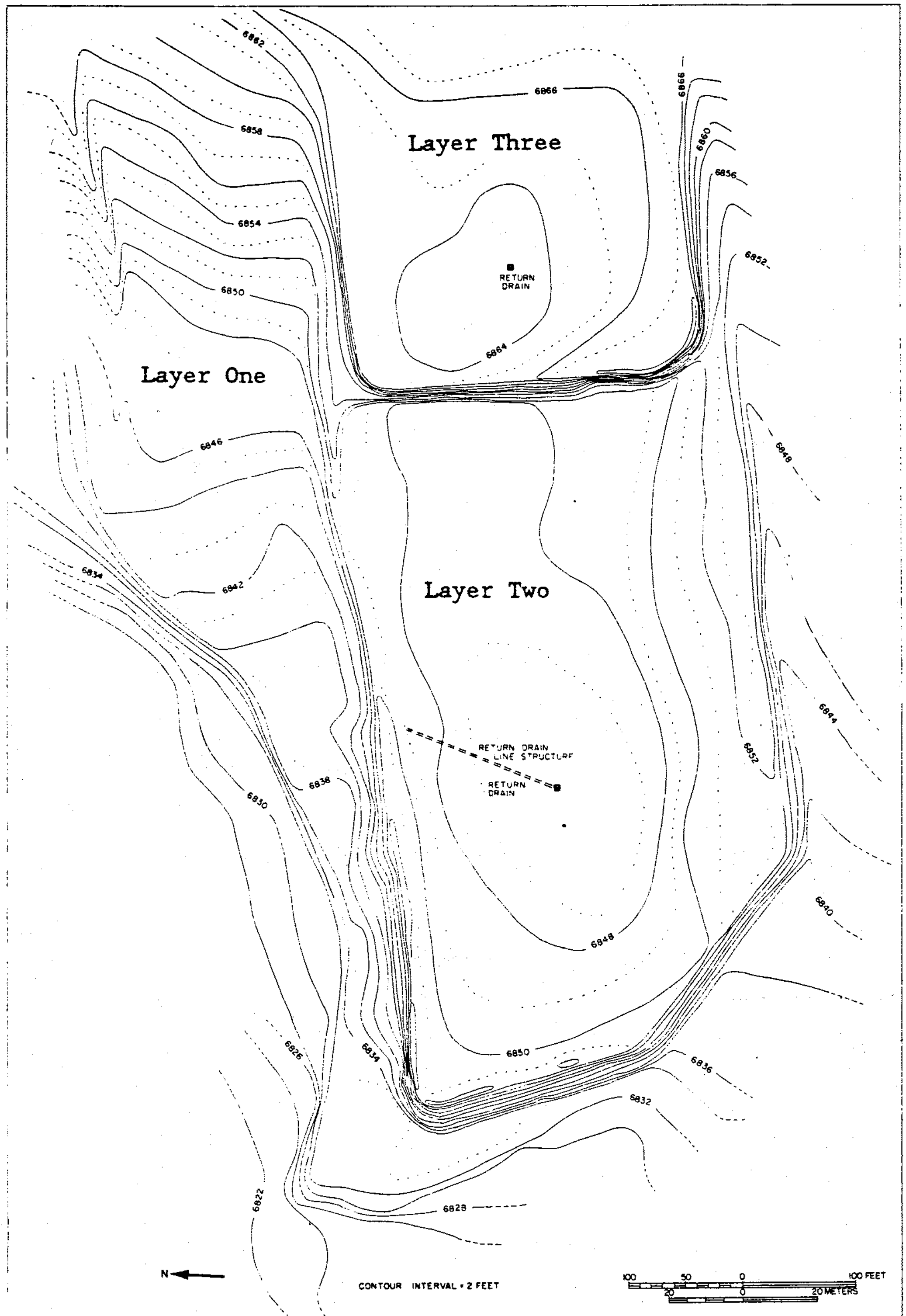


Fig. 9. Base Map of Tailings Impoundment

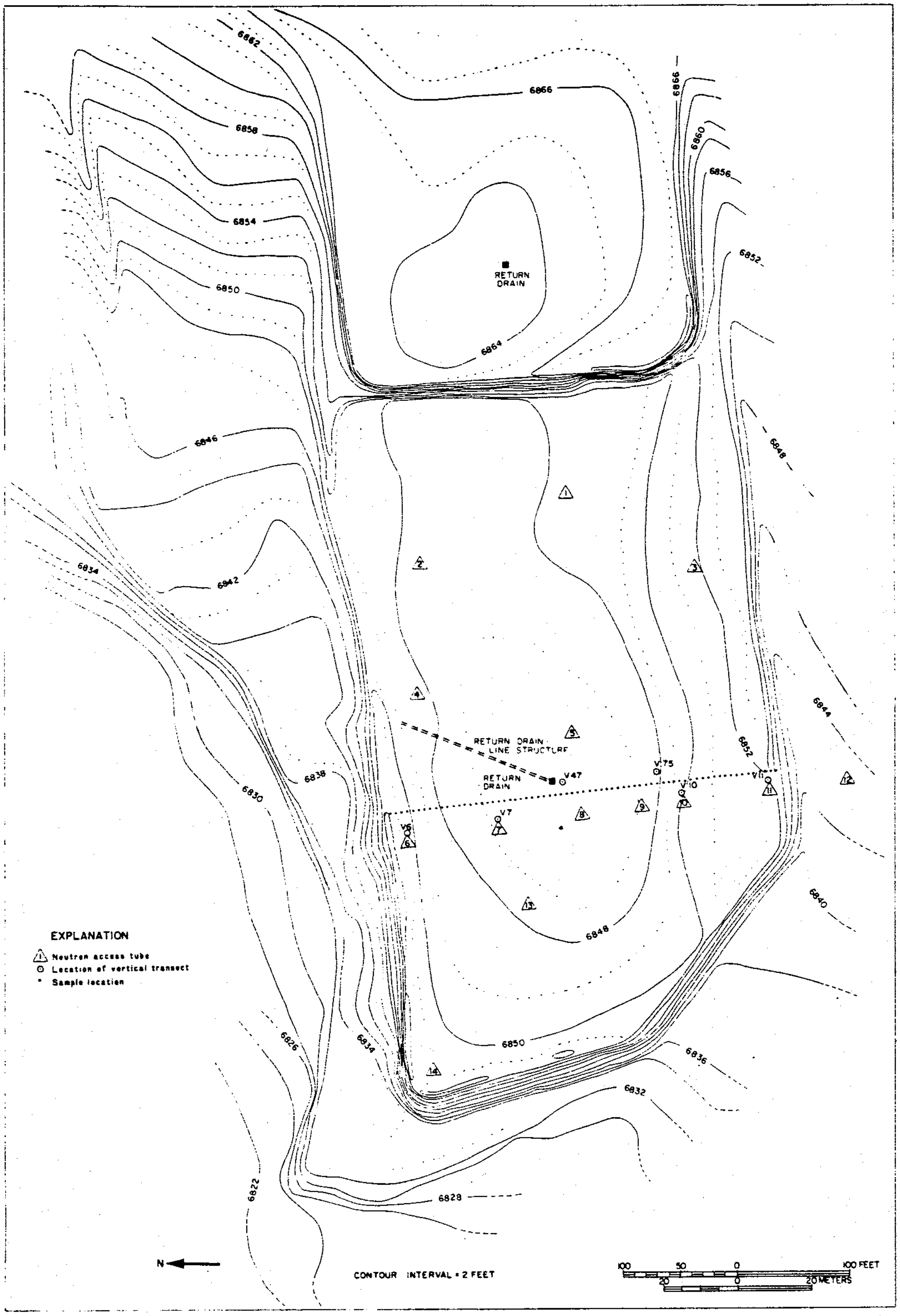


Fig. 10. Location of Sampling Transects and Neutron Access Tubes

plane of symmetry that divides the second layer into physically simil
halves and parallel to the primary direction of tailings discharg
Across the upper horizontal transect 24 vertical samples were tak
between the 15 to 69 cm interval. Sixty-nine vertical samples we
taken along the lower transect over the 152 to 205 cm depth.

The vertical transects were located adjacent to the horizont transects. Vertical transects V47 and V75 were located east of t horizontal transect, (figure 10). Both were located in the tailin slime zone. Samples from this zone required use of a backhoe to obta complete recovery. Placing V47 and V75 on the west side of t horizontal transects would have caused significant disturbance ne neutron tubes 8, 9, and 10 due to the use of a backhoe to retrie samples. The remaining vertical transects V6, V7, V10, and V11 we located two meters east of neutron tubes 6, 7, 10, and 11, respectivel along a line trending N 7.5^{o} W (figure 10). With few exceptions, ea vertical transect consisted of a continuous set of vertical samples fr the impoundment surface to 100 centimeters into the underlying nati soil.

Thirteen aluminum neutron-probe access tubes were installed rough parallel to the sampling transects and randomly throughout the seco layer. A single tube was placed in the native soil adjacent to t impoundment. Six tubes, varying in length from 4.5 to 7.6 meters, we installed parallel to the horizontal transect along a line, 7.5 mete west of the central drain, trending N 7.5^{o} W, (figure 10). Seven tube varying in length from 4.5 to 9.1 meters, were located randomly arou layer two. One 1.5 meter tube was installed in the native soil south layer two. Readings were taken at 30.5 cm depth increments in eac tube, using a 32 second counting period.

Collection of Samples

Sampling Method

Thin wall samplers (shelby tubes) pushed with a Mobile B-30 dril rig were used to extract tailings samples for laboratory analysis Different sampling equipment, such as 100 cm^3 ring samplers, wer evaluated in the field. However, thickness of the impoundment and th presence of hardpans made them impractical. The thin-wall samplers use (model DR-164C, Soil Test, Evanston, Il.) were 60.9 cm long, 7.6 c outside diameter (O.D.), and were made of galvanized steel. Galvanize steel tubes were chosen over standard steel units because of th corrosive nature of the tailings. The inside of each tube was spraye with a clear lacquer before use to further inhibit corrosion. coupling device (model DR-164W, Soil Test, Evanston, Il.) was used t attach each tube to the extension rod. A check valve in the couplin device allowed air to escape as the tube filled with sample. As th tube was extracted the check valve would seat, creating a partial vacuu above the sample, helping to retain the sample.

Taking a sample along the horizontal transect consisted of th following steps. At the sampling point a 10.2 cm diameter auger bit wa used to drill a pilot hole to within approximately 10 cm of the desire sampling depth. Following retraction of the auger a spare shelby tub was lowered into the hole to clean the sides and complete the hole t the desired depth. The spare tube was removed from the hole, and th depth of the hole from the surface was measured. A sample shelby tub was mounted to the coupler and pushed to the prescribed depth. The tub was extracted from the hole and the quality of the sample checked Plastic end caps and duct tape were used to seal the tube's ends t prevent loss of moisture and sample during transport back to th laboratory.

The procedure used in vertical sampling was similar to tha outlined above for the horizontal transects. However, it was nc necessary to drill and ream the hole prior to taking a sample becaus sampling was continuous from the surface of the impoundment into th underlying native soil (approximately 100 cm).

Sampling Problems

Several problem areas were encountered in sampling the tailing which in some instances prevented collecting a sample, or require alternate sampling technique. Sampling problems occurred in th interior portion of the pile which contained slime, along the perimete of the impoundment where extremely hard layers were encountered, ar where we sampled the native soil beneath the tailings.

Initial attempts to sample in the slime zone were unsuccessful The problem was due to the predominance of fine-grained materia consistently at a high moisture content. The topography of the pil causes ponding over the slime zone during precipitation events Tailings slime is a wet, fine-grained, very cohesive material Retaining a sample in a shelby tube is dependent on sufficien frictional forces between the sample and tube wall, and the vacuu created by the check valve to break the sample at the tubes cuttin edge. The high moisture content of the slime increased the cohesiv strength of the material and acted as a lubricant that reduced th frictional forces along the wall of the sampler. Using the sam sampling technique outlined above, the best results produced only partial sample. If the sample tube was pushed through uniform fine grained material, no sample was obtained. If the sample in the tub contained a coarse-grained layer, a partial sample was obtained becaus sufficient friction and vacuum existed to break and hold the sampl above the weakest point, the coarse-grained layer.

In an effort to find a solution to the slime sampling problem engineering consulting firms in New Mexico and Colorado experienced i sampling tailings were contacted. Their suggestions included twistin the shelby tube to shear off the sample off the sample at the cuttin edge, leaving the tube in place several minutes before retracting it over-pushing the tube, and coating the inside walls of the shelby tub with sand to increase the friction. One firm contacted resorted t using remolded samples because of their inability to obtain undisturbe samples. Using remolded samples was unacceptable to us, and none of th remaining methods proved to be viable.

The final solution involved use of a backhoe to retrieve samples After the sample tube was pushed to the desired depth a backho excavated a pit next to the tube. The sample was then manually cut an the tube capped before being extracted. The excavated material wa returned to the trench and compacted using the backhoe.

Use of a backhoe, however to obtain a sample is not a practica technique in most sampling situations, especially where disturbance o an impoundment must be minimized. For practical sampling an characterization of tailings impoundments to occur, new technologie need to be developed which will allow undisturbed samples from slim zones to be obtained.

Another sampling problem, extremely hard layers, was encountere along the perimeter of the impoundment. Exact origin of these layers i not known, but one theory is that cyclical wetting and drying ha resulted in dissolution and precipitation of calcium and iron deposit at specific depths. In some instances the indurated layer(s) prevente sampling with a shelby tube. The layer(s) had to be removed by drillin before sampling could continue. Fortunately, the aerial extent of th hard pans was small, so that there are only a few gaps in sampling data

Attempts to sample the underlying native soil also produced poo results. The native soil is dense and stoney with cobble siz particles. Shelby tubes perform poorly in material containing gravel o larger sized particles, because the tube deforms when large har particles are encountered. Where rocks were not encountered, th sampler had to be raised and lowered several times in attempts t penetrate the dense native soil. This technique usually produce unusable fragmented samples. The problem of sampling the natural soi was not resolved, and few samples were obtained.

In-Situ Moisture Measurements

Measurement of moisture content with a neutron moisture meter wa the only hydraulic parameter measured in-situ. The neutron prob contained a Model 503-DR-2 Hydroprobe (Campbell Pacific Nuclear Pacheco, CA) 50 m Ci Americium-241/Berillium neutron source (C.P.N. 1983). The original intent of in-situ moisture content measurement wa to determine indirectly the in-situ pressure head distribution acros the sample transect cross section to use as initial conditions for th numerical model. Pressure heads were to be determined from moistu contents measured in the six access tubes along the sampling transe and from the moisture-retention relationships (water content vers pressure head) determined from vertical transect samples. Further, th moisture content measurements along the profile were to have bee statistically analyzed in the companion research effort (Johnson, 1987) Additionally, results of neutron logging in the thirteen access tube installed in layer two were to be analyzed to clarify the effect of th impoundment's structure on three-dimensional moisture distribution a movement of moisture across the tailings-native soil interface. Result of neutron moisture measurements are included in Appendix A.

Installation of Access Tubes

Using a neutron probe usually requires the installation of acces tubes, although use of uncased holes in well indurated material ha been reported by Hammermeister et al (1985). Access tubes installed i the impoundment penetrated the entire thickness of the tailings a extended 50-100 cm into the underlying native soil (figure 11). Five (O.D.), 4.9 cm (I.D.), aluminum irrigation pipe was used as acces tubing. The bottom of each tube was sealed with a #10 rubber stopp and nut-bolt-washer assembly (Schwankl, 1986). A hole was cored throu each rubber stopper, and the bolt was placed through the hole. A lar washer was placed on each end of the bolt and a nut threaded onto t bolt. This stopper assembly was recessed into the access tu approximately 1.3 centimeters. Tightening the bolt compressed t stopper to form a water tight seal. The remaining space between t

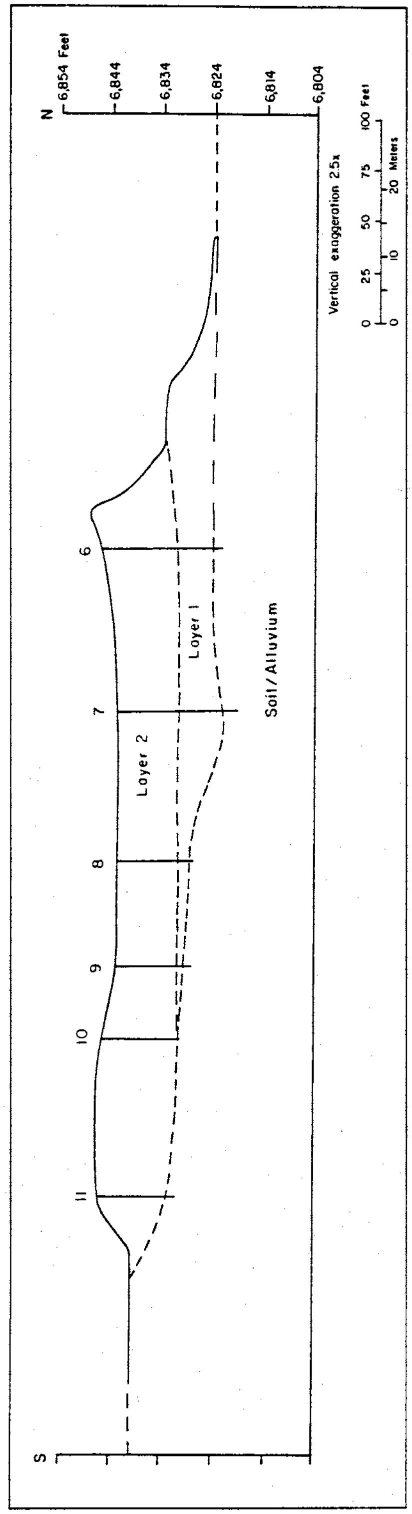


Fig. 11. Location of Neutron Access Tubes Along Sampling Transect Cross Section

stopper and end of the tube was filled with silicone to insure th integrity of the seal and protect the nut-bolt assembly from corrosion To prevent vandalism, the tops of the tubes were installed fiv centimeters below grade. Prior to burial, a #10 rubber stopper wa installed into the top of each tube, and a three inch PVC slip cap wa placed over each tube.

Normally short, 1.5 to 3.0 meter, lengths of access tube ar installed in soils or unconsolidated sediments using a five centimete diameter hand auger to form a tight fit between the outside of the tub and the sediment. Hardness of the tailings material and length of tube used, up to 9.1 meters, required the use of a drill rig, with a dril stem consisting of 1.5 meter lengths of five centimeter diameter auge drill. The manner in which the lengths were joined produced a nonrigi stem which wandered during drilling, producing a hole 5.7 to 6. centimeters in diameter. Following completion of the hole and settin the tube in place, dry surface tailings material was used to backfil the annular space between the access tube and hole. Only withi approximately 0.3 meter of the surface was it possible to directl compact the backfill.

Neutron Probe Calibration

Although each neutron probe is factory calibrated, usually calibration curve for each application must be produced. Initia sampling and neutron probe readings were made for calibration durin tube installation on March 19, 1986. In an effort to generate calibration curve in the high moisture range ($\theta > 0.35$), additiona samples were taken at a 0.3 meter radius of each tube on July 11 September 25, and October 3, 1986.

The calibration procedure followed that outlined by Schwank (1986). During drilling undisturbed samples were taken, using 100 cm ring samplers, from the hole at predetermined depths. The hand-hel sampling equipment limited sampling depths to less than three meters An access tube was installed following completion of each hole an readings were taken at depths corresponding to sample locations. Th undisturbed samples were immediately weighed in the field to determin wet mass, sealed to prevent moisture loss and returned to th laboratory. Samples were reweighed to insure accuracy of the fiel scale and placed in an oven for 24 hours at 105 ^{o}C. After removal fro the oven, samples were weighed to determine the dry mass. Th volumetric moisture content of a sample was determined using th following equation:

$$\theta = \frac{1}{\rho_w} \frac{M_w - M_d}{V_t} = \frac{V_w}{V_t} \qquad (1$$

where θ is volumetric moisture content (cm^3/cm^3), M_w is mass of th sample wet (gm), M_d is mass of the oven dried sample, V_t is total volum of the sample in cm^3, V_w is volume of water in the sample. Density o water (ρ_w) was assumed to be 1.0 g/cm^3 in using this method.

The neutron probe can express moisture content in a variety o units, including volume. To generate a calibration curve, th laboratory determined moisture contents were plotted against th correlated neutron probe readings. A least squares regression analysi was used to fit a line through the data (figure 12). The computer co used to perform the regression analysis is included in Appendix A. Th equation of the line, a power curve, is

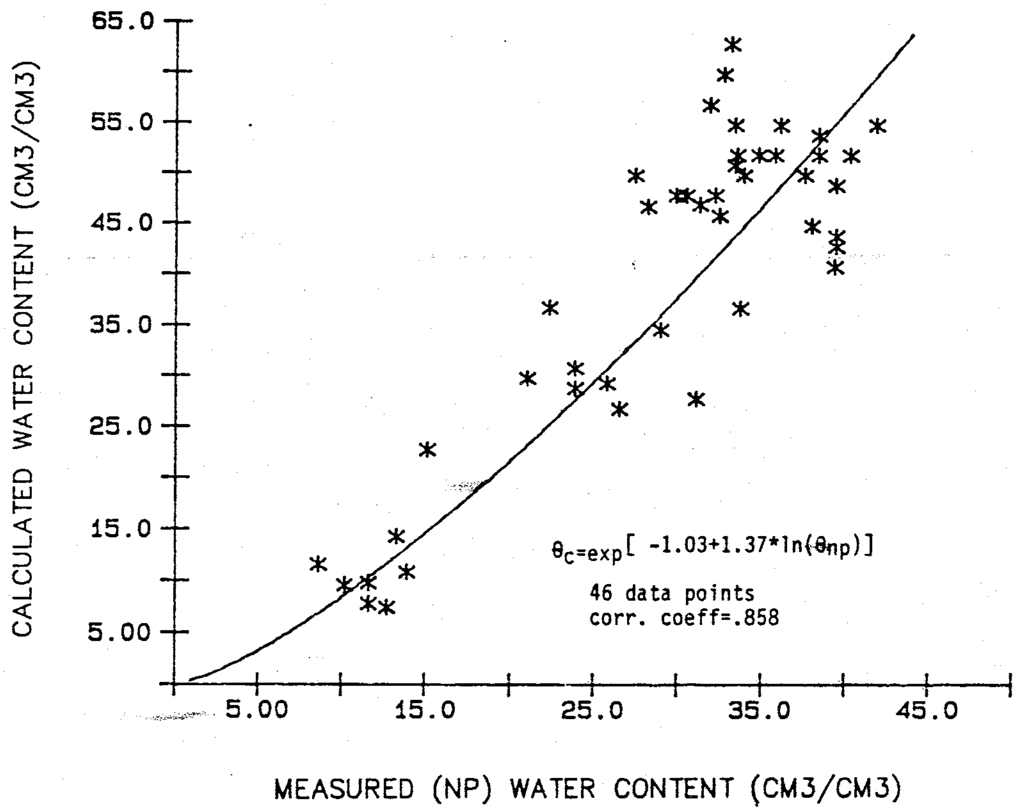
$$\theta_c = \exp[-1.03+1.37 * \ln(\theta_{np})] \quad (2$$

The correlation coefficient for regression analysis was 0.85 However, the high correlation coefficient is deceiving; the neutro probe did not provide uniform precision throughout the entire range o soil moisture. Attempts to use the probe to measure moisture content above 0.35 produced poor results. Although the design range of th probe is 0.0 to 0.32 cm^3/cm^3 (C.P.N., 1983), calibration of the probe a higher moisture contents should be possible (Mr. John Mancuso, Campbe Nuclear, Pacheco, CA, 1986, personal communication). Attempts t calibrate the probe to moisture contents greater than 0.35 (using data sets in the θ > 35 % range) produced a poor correlati coefficient of 0.006.

Sources of Calibration Error

We considered several sources of error in probe calibration relat to the manner in which the access tubes were installed. Those relat to preferential moisture flow water down the backfilled annular spac and the presence of a low bulk density backfilled annulus we investigated.

Late May through October of 1986 was unusually wet, producing a po of large aerial extent and duration on layer two (figure 13). Initial



Calculated values were determined in the laboratory; measured values were direct readings from the neutron probe.

Fig. 12. Neutron Probe Calibration Curve

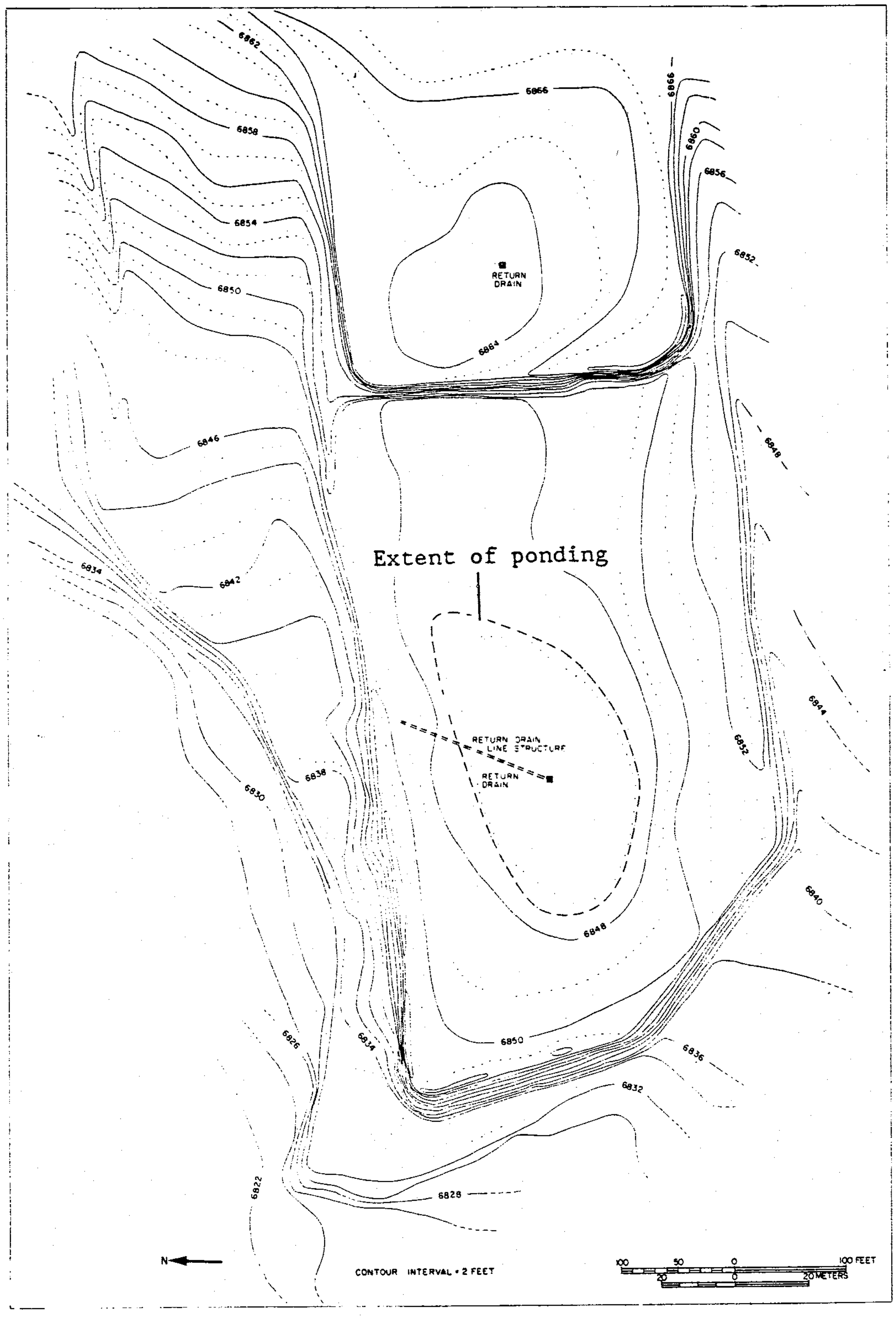


Fig. 13. Aerial Extent of Ponding on Layer Two

piping was thought to have occurred along the tubes as a result o ponding. Under conditions of piping, high moisture contents should hav been recorded not only near the surface but at depth. Examination o the logs from access tubes 5, 7, 8, 9, 13 (located within the are subject to ponding) gave no indication of piping. During this period measured increases in moisture content with depth occurred gradually, i at all. The annulus may have been a zone of enhanced permeability as result of the low bulk density of backfilled material below th compacted zone. Neutron probe measurements were taken durin calibration work below the compacted zone in tubes located within th slime zone prior to the onset of ponding. Volumetric moisture conten readings, θ, were 0.15 to 0.20 (cm^3/cm^3) lower than values observed i corresponding calibration samples. These observations indicate movemen of moisture down the annular space was not a significant error i calibrating the neutron probe in the high moisture ranges.

The backfilled annulus with a lower bulk density was als considered as a possible source of error. Maximum width of the annulu was 0.6 cm. Hammermeister (1985) reported, that the USGS working a Yucca Mountain, Nevada, achieved good calibration results, (correlatio coefficient of 0.94 for laboratory calibration in the moisture conten range of 0.0 to 0.25 cm^3/cm^3, and 0.95 for field calibrations) using CPN 503 DR-1 probe to log both cased and uncased holes having a 12.7 c inside diameter (I.D.). The 503 DR-1 probe has an outer diameter (O.D. of 3.8 cm; therefore there is a large void space between the probe an the wall of the formation. The 503 DR-2 probe used in our work has 4.7 cm diameter probe, and coupled with the 4.9 cm (I.D.) access tube tight fit was produced. Based on the results reported by Hammermeister the 0.6 cm backfilled annulus should have not prevented reasonable calibration results from being obtained in the high moisture range. Further, the backfilled annulus did not preclude obtaining good calibration results in dry areas of the impoundment.

The principle upon which the neutron probe measures moisture content is thermalization of fast neutrons by hydrogen atoms in water molecules (Black, 1965; Hillel, 1980; Schwankl, 1986). However, there are other sources of hydrogen atoms in porous material including clays and organic matter. In addition, other elements have the ability to moderate or capture fast neutrons including boron, chlorine, iron, calcium, titanium, and cadmium (Hammermeister et al., 1985; Cotecchia et al., 1968). Table 1 lists the results of chemical analysis conducted on dry tailings samples. The analysis indicates significant levels of iron and calcium with minor amounts of titanium. Several different clay minerals were also detected which have water or hydrogen incorporated in their crystal structure. Table 2 summarizes the results of the chemical analysis on water ponded on the tailings impoundment, which show a high concentration of iron.

Other sources of hydrogen ion, in addition to water, are derived from chemical reactions that occur in the pile. For example, pyrite associated with the ore taken from the Waldo mine under oxidizing conditions in the presence of water undergoes the following reactions to produce dissociated hydrogen ions (Stumm and Morgan, 1981):

$$FeS_2(s) + 7/2O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (3)$$

$$Fe^{2+} + 1/4O_2 + H^+ = Fe^{3+} + 1/2H_2O \quad (4)$$

$$Fe^{3+} + 3H_2O = Fe(OH)_3(s) + 3H^+ \quad (5)$$

$$FeS_2(s) + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (6)$$

The presence of iron in the tailings (table 1) when considered with a measured pH of 2.25 in a water sample taken from the interior of the impoundment where rain had collected over a period of several days suggest that the reactions shown above may be sources of hydrogen ion that could influence neutron probe readings of in situ moisture.

The characteristics of ore produced from a mine can be quite variable during the life time of an operation. The variability of the tailings chemical composition and diversity of the moderating, diffusing, and capturing properties of the various components appeared to have had a significant influence on neutron probe measurements. Hence, use of a single calibration curve to interpret neutron probe readings in the high moisture range, $\theta \geq 0.35\ cm^3/cm^3$, in tailings was not feasible. Impoundments with a very high degree of chemical spatial variability may require such a large number of calibration curves so as to preclude use of a neutron probe for moisture monitoring in tailings.

With rising interest in the characterization, evaluation, and monitoring of impoundments (Stanczyk, U.S. Bureau of Mines, Tuscalosa, Al, 1986, personal communication) the calibration problems discussed above deserve additional research.

Laboratory Analysis

The hydraulic properties determined in the laboratory were saturated hydraulic conductivity, moisture retention characteristics, porosity, and particle size distribution. Analysis in the laboratory followed a consistent routine. Saturated hydraulic conductivity was determined in a constant head permeameter. Moisture characteristic curves were developed with a hanging column apparatus in the low suction range, and a ceramic plate extractor was employed to determine moisture content at high values of suction. Porosity was measured on a volumetric basis. Standard sieve and hydrometer techniques were used to determined particle size distribution.

Saturated Hydraulic Conductivity

Hydraulic conductivity at saturation, K_s, is the constant of proportionality in Darcy's equation:

$$q = -K_s \frac{dh}{dl} \tag{7}$$

where q is the fluid flux (L/T), h is hydraulic head (L), l is the length over which head change is measured (L), K_s is saturated hydraulic conductivity (L/T), and the negative sign indicates flow is in the direction of decreasing head. Darcy's equation as stated describes fluid flow through a saturated porous media. Saturated hydraulic conductivity ranges in value from 10^{-11} cm/sec in shales and fractured metamorphic and igneous rocks to 10^{2} cm/sec in gravels (Freeze and Cherry, 1979). The saturated hydraulic conductivity of the Waldo Mine Mill tailings ranges from 10^{-3} to 10^{-8} cm/sec.

Hydraulic conductivity is a function of both the fluid and porous media, as expressed in the following equation:

$$K_s = \frac{k\rho g}{\mu} \tag{8}$$

where k is intrinsic permeability or simply the permeability (L^2). The important fluid properties are density, ρ, (M/L^3) and dynamic viscosity, μ, (M/LT). Acceleration due to gravity is g (L/T^2). Permeability describes the ability of a porous media to transmit a fluid. The physical properties of a porous media that determine k include particle size distribution, shape of the grains, specific surface area and porosity (Bear, 1979).

<u>Method.</u> Saturated hydraulic conductivity was measured using a constant head shelby tube permeameter (figure 14). This type of permeameter has also been used in modified forms by others (e.g. Kealy, 1970).

The permeameter consisted of a stand to hold the sample tubes, a series of manometers to measure changes in hydraulic head across the sample and a reservoir of water maintained at a constant head as illustrated in figure 15. To prevent loss of the sample, the bottom of each tube was wrapped with a series of fine screens. At the top and bottom of each tube, strips of rubber and tape were attached to act as water tight gaskets and a plastic bottle slipped over each end of the tube was held tight with a band clamp. In the top of each bottle a cored #3 rubber stopper was inserted, through which a 7.6 cm length of 0.6 cm (O.D.) copper tubing was inserted. The bottle-stopper-tube assembly at the bottom of each thin-walled sample tube acted as a collection point to determine the flux of water passing through each

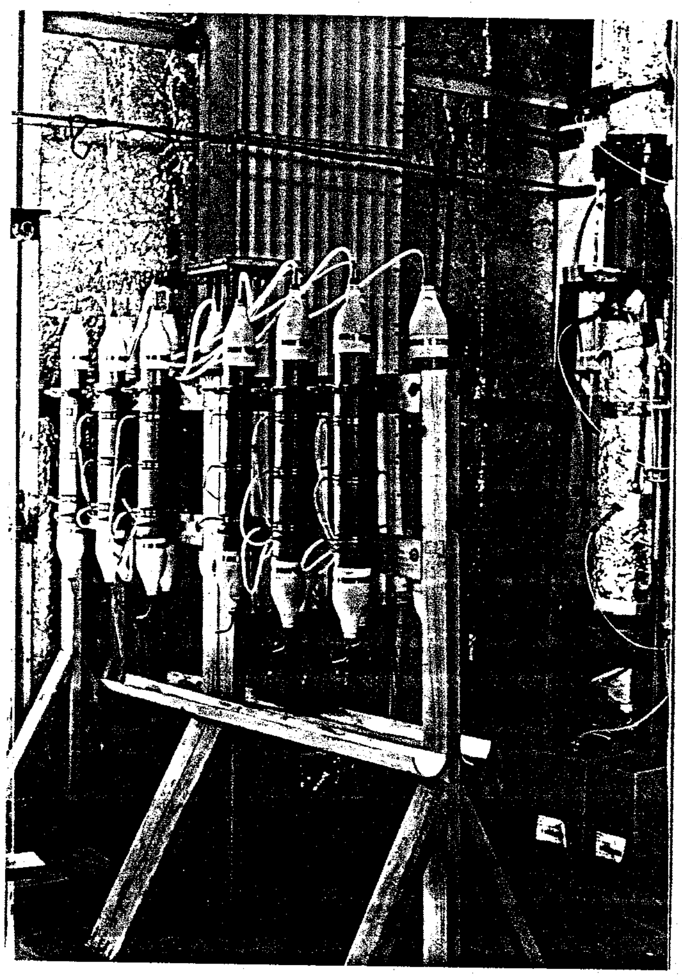


Fig. 14. Shelby Tube Permeameter

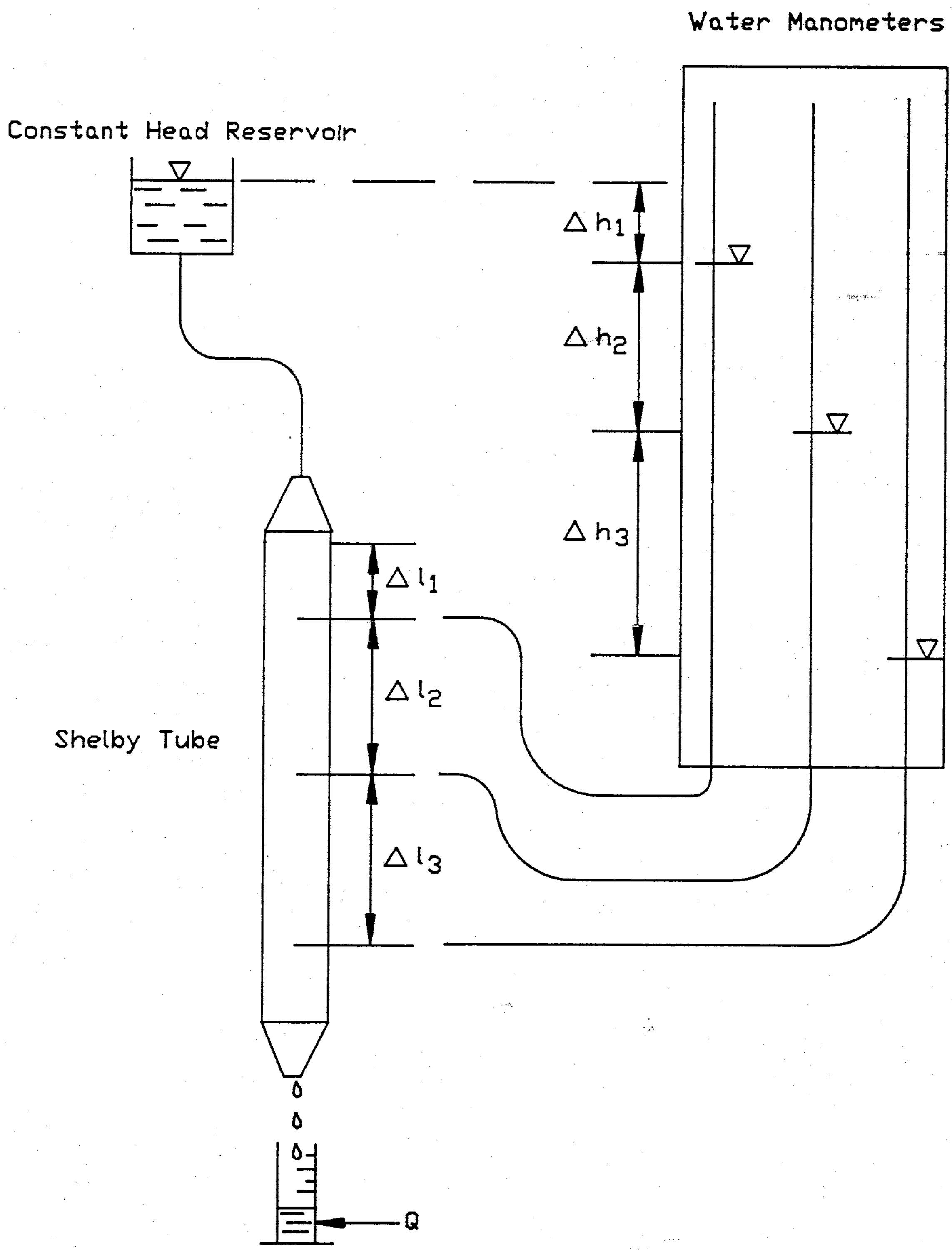


Fig. 15. Schematic Diagram of Shelby Tube Permeameter

sample. The top assembly functioned as an adapter through which water from the reservoir was introduced via Tygon tubing, 0.5 cm (I.D.), 0.8 cm (O.D.). Prior to attaching the water source inlet hose, CO_2 gas was applied to the sample at two liters per minute for ten minutes or approximately 20 pore volumes to minimize the effect of entrapped air. Along the length of each tube at 13.3 cm intervals, measured from the bottom, three holes, 0.3 cm diameter, were drilled into which 7.6 cm lengths of copper tubing, 0.3 cm (O.D.), 0.08 cm (I.D.) were inserted 3.8 cm into the tube. Two rubber gaskets followed by a band clamp secured the tube in place. A 2.5 cm piece of Tygon tubing (0.4 cm (O.D.), 0.24 cm (I.D.)) was used to adapt the Tygon manometer tubing (0.5 cm (O.D.), 0.3 cm (I.D.)) to the copper tubing. Rubber cement was applied to the two Tygon tubings to insure a water-tight fit. The Tygon manometer tubes were filled from the bottom with deaired water to a height where the meniscus was above the constant head reservoir. Each manometer tube was clamped off near its end, to prevent water from moving into the sample, and attached to copper tubes. Each tube was then connected to the water supply and the lines purged of air. To simulate field conditions, only distilled water was used in the system because it is chemically similar to rainwater (Branvold, 1985, personal communication), and atmospheric precipitation is now the sole source of moisture input into the tailings impoundment. Water passing through the shelby tubes was not recycled. Each shelby tube was allowed to wet-up a minimum of one day or until a minimum flux of one milliliter per hour was achieved. After each thin-walled sampling tube was saturated, clamps on the manometers were removed and the tubes were allowed to reach equilibrium before measurements began. Equilibration usually required approximately twelve hours. Readings were taken for seven to nine days and included manometer levels, water flow rates, and temperature of leachate. Measurements were made each day at the same time to minimize the significance of temperature related fluctuations.

Calculations. Installation of the three manometers allowed hydraulic conductivity to be calculated over four intervals of the sample. Calculations to determine K_s were performed on an IBM personal computer (using a program written in basic). A copy of the program and typical output are included in Appendix A. Darcy's equation (Eqn 7) was applied to calculate K_s. Figures 16 and 17 illustrate positions in the impoundment where samples were obtained for saturated hydraulic conductivity measurements.

All calculated K_s values were corrected to standard temperature of $20^{o}C$ to account for changes in hydraulic conductivity due to changes in the viscosity of water by the relationship (Klute, 1965);

$$K_{20} = K_T(\eta_T/\eta_{20}) \qquad (9)$$

where K_T is conductivity at the measured temperature (cm/sec), η_T is viscosity (cp) of water at the measured temperature and η_{20} is the viscosity (cp) of water at $20^{o}C$.

Measured saturated conductivities shown in Appendix B are generally the last measured value. Although many soil samples run in a

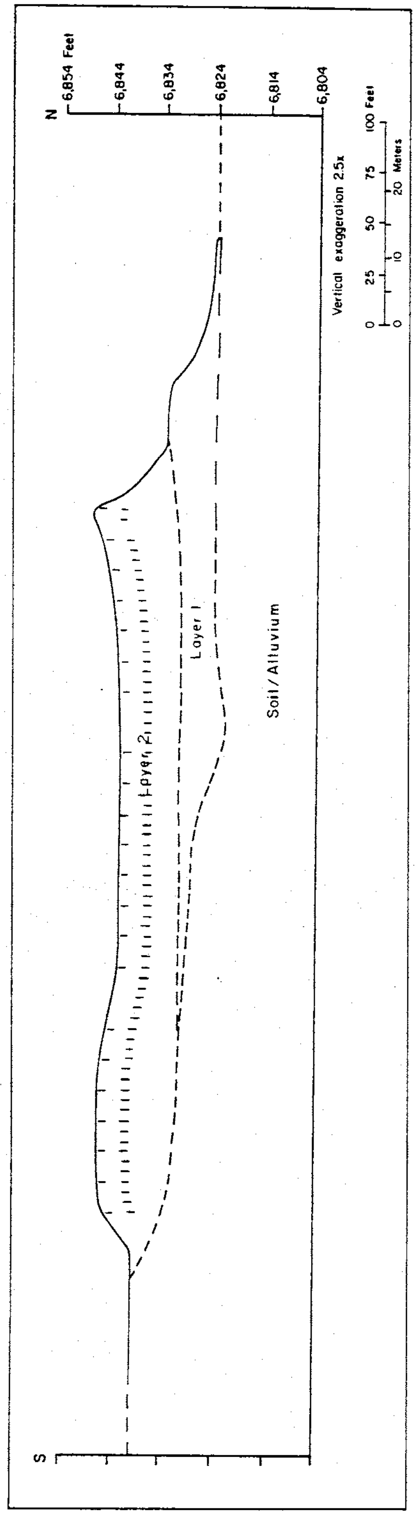


Fig. 16. Position of Samples for K_s Measurements

Along Horizontal Sampling Transects

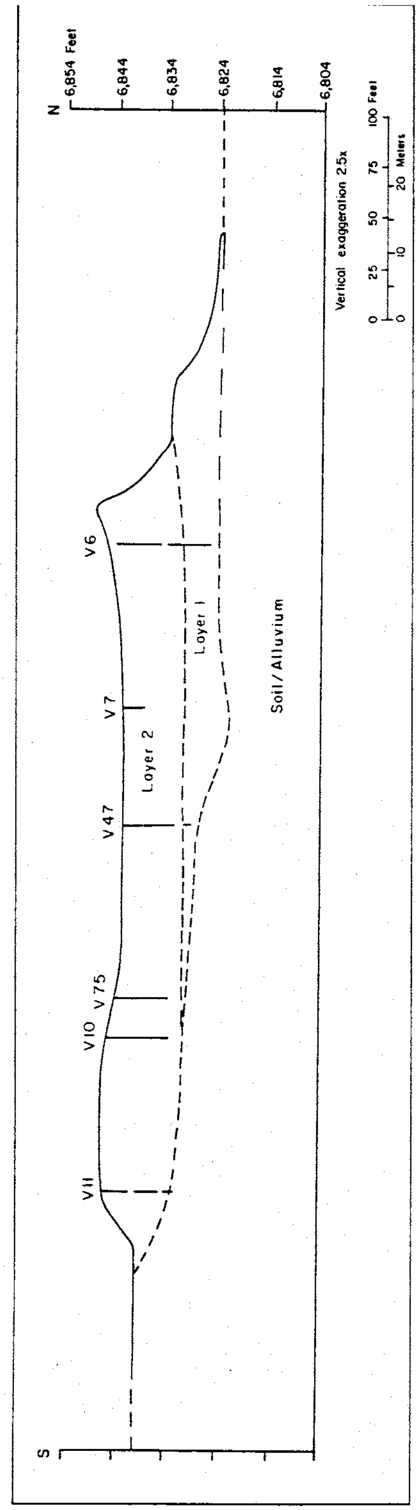


Fig. 17. Postion of Samples for K_s Measurements

Along Vertical Sampling Transects

permeameter eventually exhibit reduced permeabilities due to clogging of pores by bacteria, bacteria growth apparently was not a problem in the tailings. Figure 18 is a graph of the change in hydraulic conductivity over time for a representative tailings sample. The last hydraulic conductivity value obtained from the permeameter procedure was used in order to allow enough time for any structural defects, such as cracks, to have healed in the sample.

Sources of Error. Sources of error in calculating saturated hydraulic conductivity in the shelby tube permeameter included entrapped air, loss of sample integrity, and boundary effects. Flooding samples with carbon dioxide gas and measurements over several days minimized the effects of entrapped air. Loss of sample integrity was a serious problem in certain samples, particularly in native soils. It was possible in most cases to determine which samples contained fissures, cracks or were fractured. The defects were manifested as anomalous manometer readings and extremely high flux rates accompanied at times by loss of sample. In addition, each sample was examined for structural defects as it was removed from the shelby tube.

In column-type permeameters boundary effects can significantly increase apparent K_s measurements. The degree of boundary effect is a function of the ratio of the cross-section to the circumference of the sample container. The larger the ratio, the smaller the wall effect. Larson (1984) observed this same effect when comparing K_s values of copper tailings obtained from shelby tubes and those from 100 cm^3 rings.

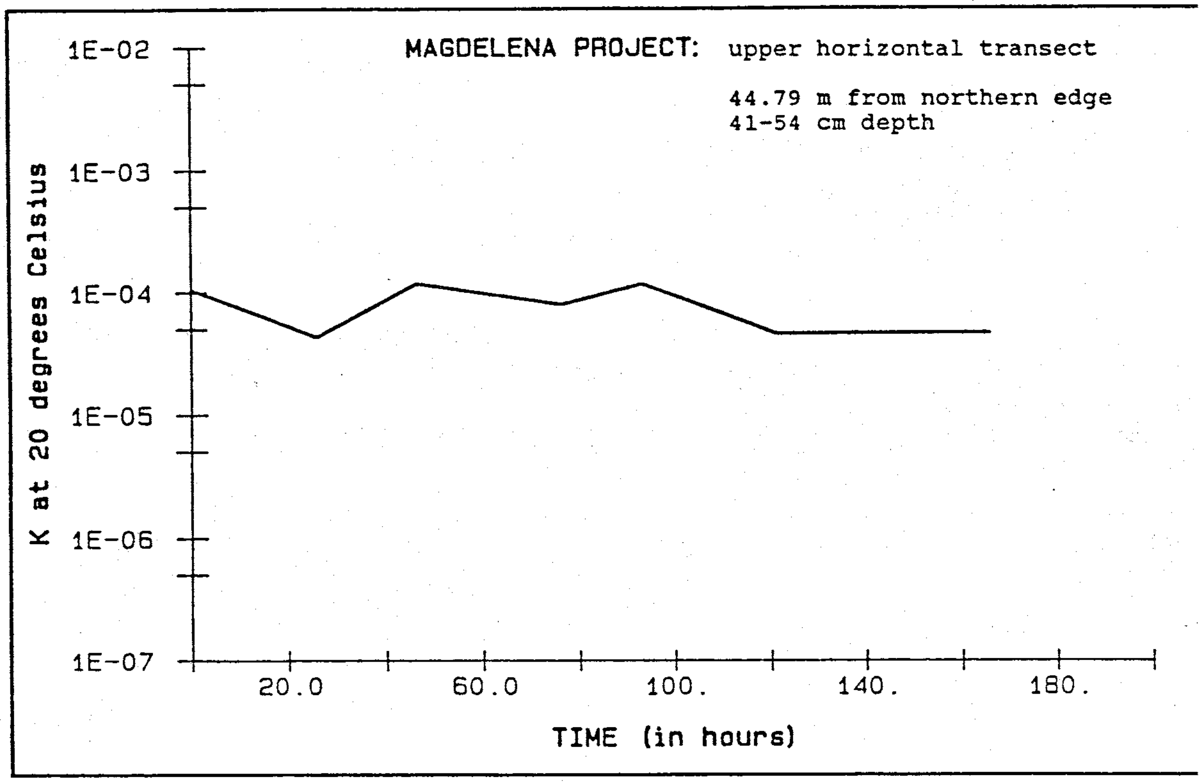


Fig. 18. Fluctuation in Saturated Hydraulic

Conductivity for a Tailings Sample

In future studies the magnitude of boundary flow in shelby tubes could be quantified adapting the special permeameter design described by McNeal and Reeve (1964) (figure 19) to the bottom of shelby tubes.

Sample Removal from Shelby Tubes. Following completion of K_s measurements, each sample was removed from its container using a model P-512 Vertijet (Soil Test Inc., Evanston, Il.). The Vertijet is a foot operated hydraulic press. Each increment of sample over which K_s was determined was extruded, catalogued and bagged for particle size analysis. A sample was taken from the bottom of each tube using a brass ring sampler for use in the hanging-column and pressure plate to determine moisture retention relationships and porosity. The brass cylinders (model A-145-4, Soil Test Inc., Evanston, Il.) were 5.5 cm diameter and 3 cm high.

Unsaturated Hydraulic Conductivity

The ability of a porous media to transmit water, a function of its hydraulic conductivity, is maximal when the media is saturated. Typically under saturated conditions a coarse-grained porous media will have a greater hydraulic conductivity than a fine-grained material. However, due to factors including particle size distribution, coarse material drains quickly over a narrow range of suction which impacts the material's ability to transmit fluid. Alternating layers of sand/slime were observed during trenching operations at the field site. The layers of fine-grained tailings were wet while adjacent sand layers were relatively dry. As the porous media drains air replaces water, the

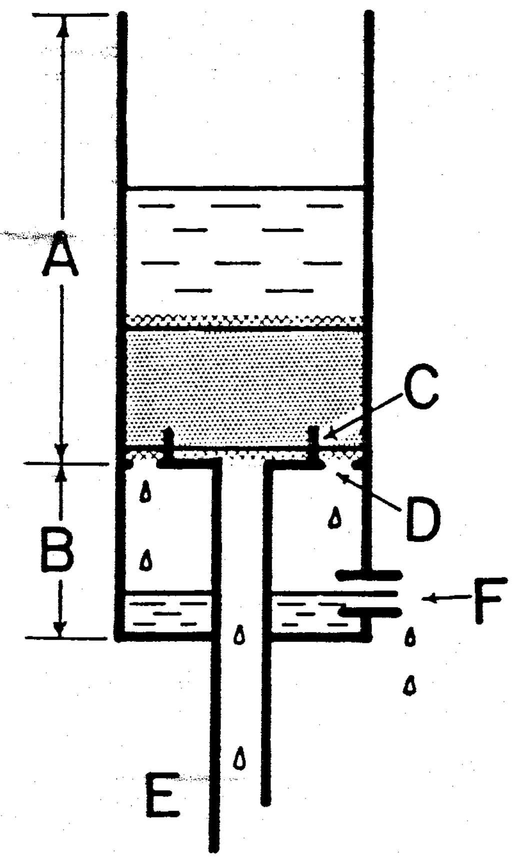


Fig. 19. Permeameter Apparatus for Quantiying Boundary Flow

(Source: McNeal and Reeve, 1964)

cross-sectional area available for fluid flow decreases, and tortuosity of the flow paths increases (Bear, 1979). In coarse-textured porous material, hydraulic conductivity decreases more rapidly with increasing suction compared to fine-grained material (figure 20). Eventually the hydraulic conductivity of the fine-grained material surpasses that of the coarse material. The relationship of unsaturated hydraulic conductivity-negative pressure head is affected by hysteresis. The K-θ_w relationship is not significantly affected by hysteresis.

Several numerical models such as TRUST (Reisenauer et al., 1982) and UNSAT2 (Davis and Neuman, 1983) can simulate seepage, but the accuracy of the results is dependent upon the quality of input parameters such as unsaturated hydraulic conductivity. Determination of accurate measurements of unsaturated hydraulic conductivity can be time consuming and expensive, especially in spatially variable environments such as tailings impoundments. There are a number of methods to estimate unsaturated hydraulic conductivities. Empirical/theoretical methods include Millington and Quirk (1961), Brooks and Corey (1964), and Mualem (1976). Laboratory methods include one-step outflow and volumetric pressure plate extraction. In the field, unsaturated hydraulic conductivities can be determined using instantaneous profile and borehole methods. The high degree of parameter characterization included in this project, required that an empirical/theoretical method be employed to determine unsaturated hydraulic conductivities.

Method. In this work a computer code written by van Genuchten (1978), based on the pore structure model developed by Mualem (1976),

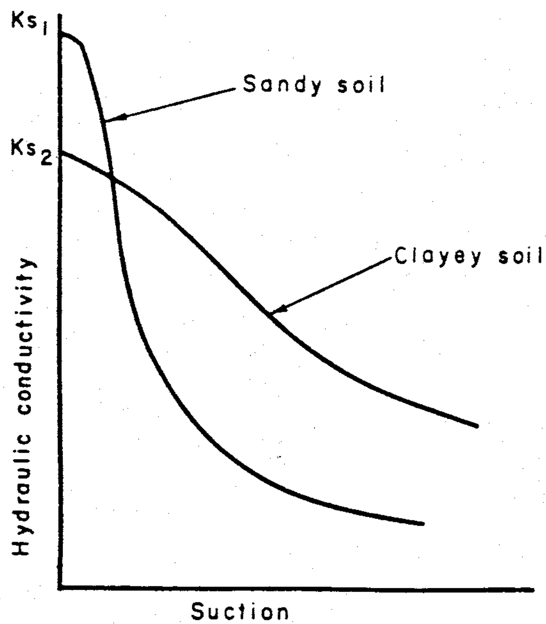


Fig. 20. Effect of Texture on Hydraulic Conductivity with Changing Negative Pressue Head

(Source: Hillel, 1980)

was used to estimate unsaturated hydraulic conductivities. Input requirements included parameters measured in the laboratory (moisture content at saturation, θ_s, saturated hydraulic conductivity, K_{sat}, and residual moisture content, θ_r. The residual moisture content was established at 15 bars, the maximum operating pressure of the pressure plate.

The method by Mualem to predict unsaturated hydraulic conductivity is based on a K_s value and the moisture retention relationship. Relative hydraulic conductivity, is calculated from:

$$K_r(S_e) = S_e^{1/2} \left[\int_0^{S_e} \frac{dSe}{\psi} \;/\; \int_0^1 \frac{dSe}{\psi} \right] \qquad (10)$$

where $K_r = K/K_{sat}$ (dimensionless), $S_e = (\theta - \theta_r)/(\theta_{sat} - \theta_r)$ (dimensionless), θ and θ_r are actual and residual water content, respectively.

van Genuchten derived a closed-form analytical solution based on Mualem's theory:

$$K_r(\psi) = \{1-(\alpha\psi)^{n-1}\ [1+(\alpha\psi)^n\ ]^m\ \}^2 \qquad (11)$$

where $m = 1-n$, and n and α are independent parameters determined by non linear least squares curve fitting to the observed θ-ψ curve. The three-parameter model estimates residual moisture content in cases where it is unknown. If the code is run as a two-parameter model only n and α are estimated, and θ_r is fixed at the input value of θ_r .

van Genuchten's method has been used by numerous researchers with good results. Unsaturated conductivity values estimated from van Genuchten's code have been found to compare favorably with laboratory and field data by other investigators as reviewed by Stephens and Rehfeldt (1985). Larson (1984), Lewis (1985), and Stephens and Rehfeldt (1985) found the two-parameter model produced accurate predictions of unsaturated hydraulic conductivity as compared to field and laboratory determined values for copper tailings and fluvial sands.

Stephens and Rehfeldt (1985) carried out a sensitivity analysis of van Genuchten's method, using the two- and three-parameter models, to estimate unsaturated conductivities for a fluvial sand. They observed that both the two- and three-parameter model did an equally good job of fitting the θ-ψ data. Also, they concluded that a good fit to the θ-ψ data did not guarantee accurate predictions of unsaturated hydraulic conductivities.

The Waldo Mine mill tailings are generally fine-grained, the lowest porosity value measured was 0.38 (cm^3/cm^3), with most values above fifty percent. Unlike the sands used by Stephens and Rehfeldt (1985), the tailings release moisture slowly over a wide range of pressure head. A comparison of the ability of the two- and three-parameter models to fit observed θ-ψ drainage data indicated that the three-parameter model produced a better fit to observed θ-ψ data (figure 21). Using the two-parameter model and a θ_r based on laboratory results severely over-estimated measured moisture values at high suctions in some cases. This in turn would have led to over-estimated hydraulic conductivity values in the very dry range. On the basis of fitting θ-ψ data the three-parameter model was assumed to provide better estimates of unsaturated hydraulic conductivities, although this was not confirmed by laboratory

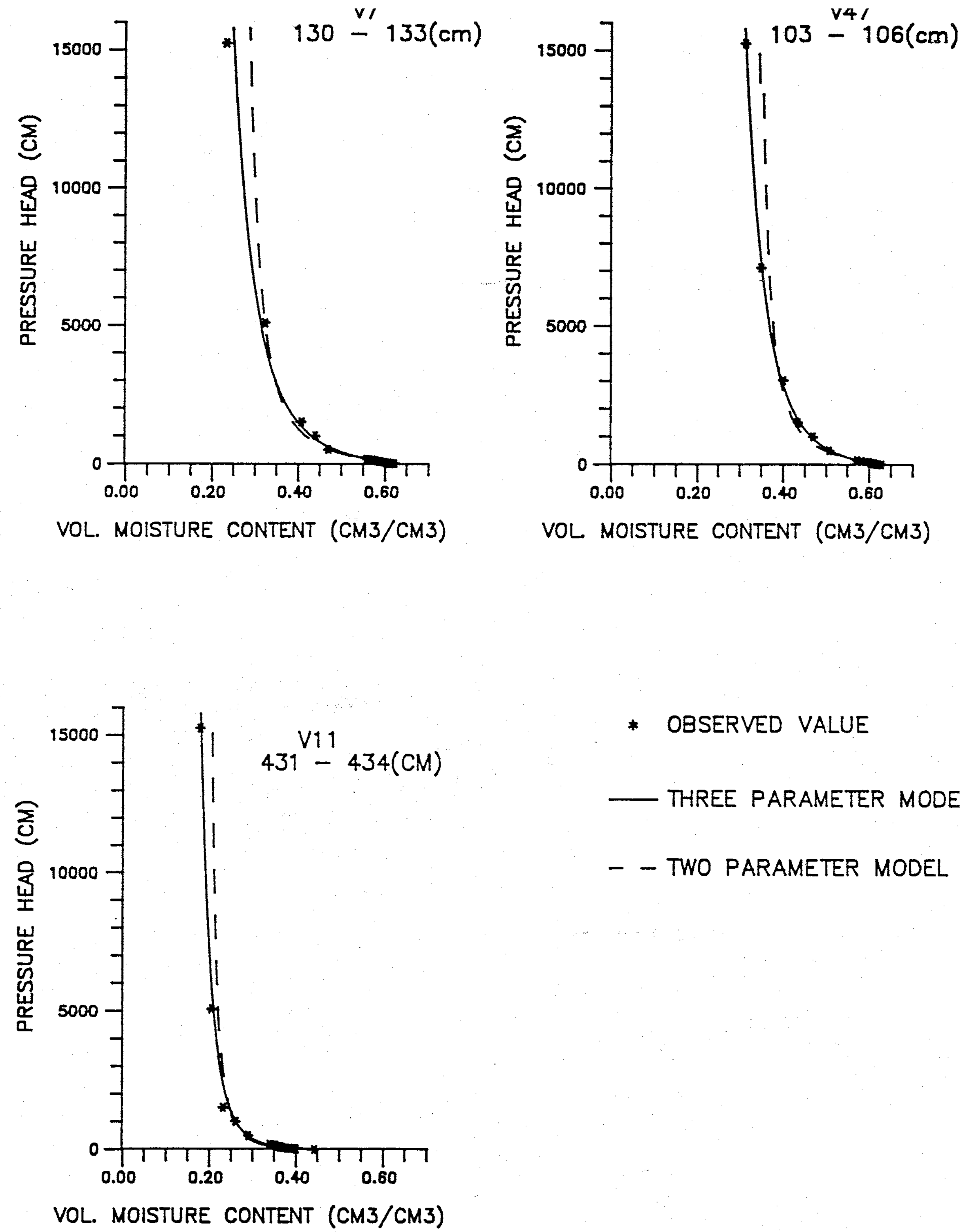


Fig. 21. Comparison of van Genuchten Two and Three Parameter Model Fit to Observed θ-ψ Data

or field testing. All unsaturated hydraulic conductivity values used in this work were estimated using the three-parameter model. A copy of van Genuchten's computer code and output from the program are included in Appendix C.

Sources of Error. The scale of the laboratory determinations of K_s and θ-ψ relationships may affect the accuracy of predicted K-ψ relationships from van Genuchten's code. For example, individual layers of sand and silt in some areas of the tailings impoundment may be only several millimeters thick, whereas the K_s values were determined over 13.3 cm intervals that contained numerous layers. Thus the laboratory procedure resulted in an arithmetic mean hydraulic conductivity. Moisture-retention relationships were determined from a 3.0 cm high sample taken from the bottom of each vertical transect tube. The material contained in the ring sample may not have been representative of the material over which K_s was determined in all cases. The equipment used to measure the parameters limited the degree to which spatial variability of the individual layers could be assessed.

Moisture Retention Relationships

The moisture content of a porous media is function of pressure head. The relationship between volumetric moisture content (θ), and the negative pressure head (ψ) of the liquid phase (relative to atmospheric) is represented graphically by a moisture characteristic or theta-psi curve. In this work moisture content was determined on a volumetric basis. Volumetric moisture content is determined by;

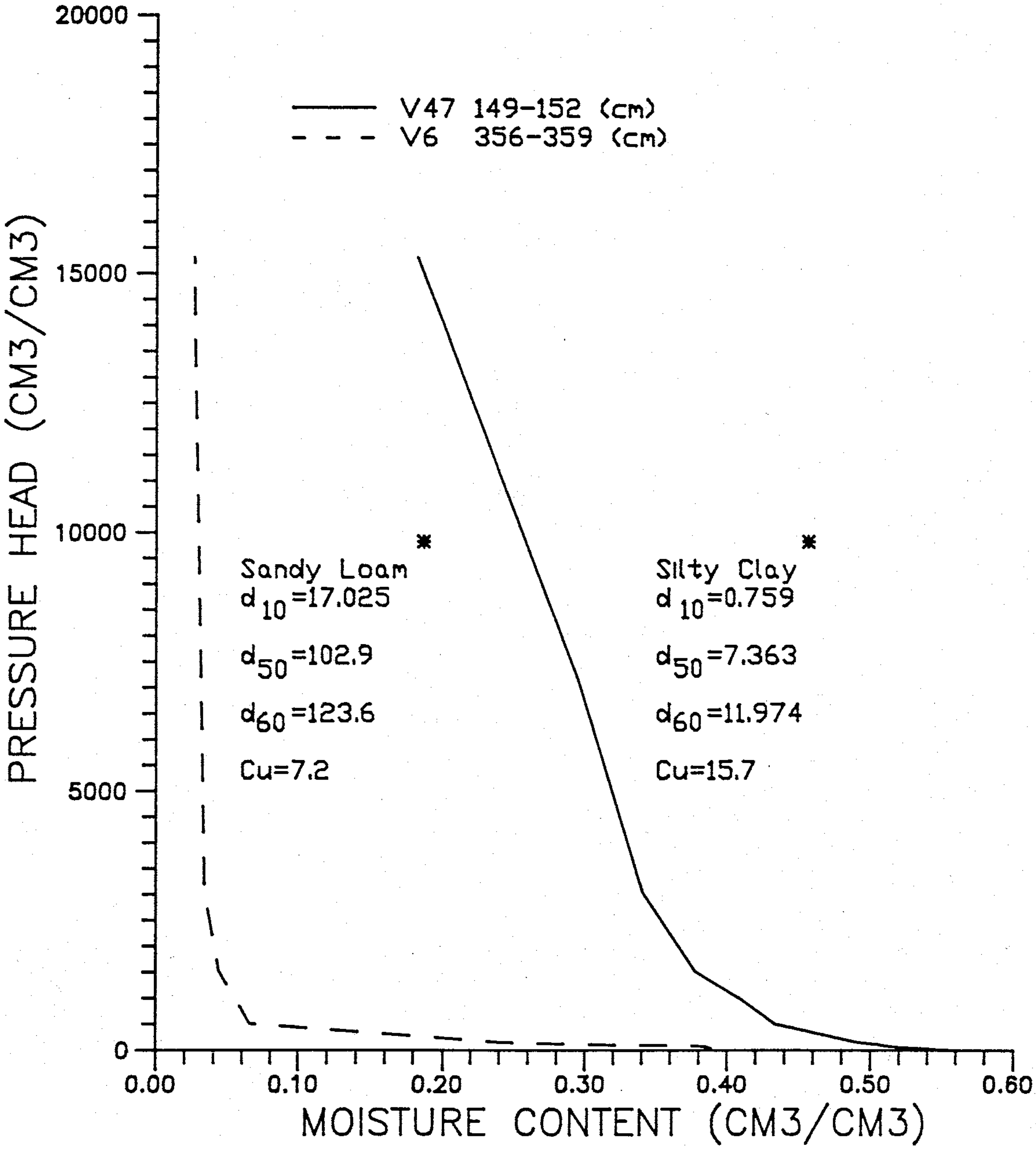
$$\theta = \frac{V_f}{V_t} \qquad (12)$$

where V_f equals the volume of fluid in a sample (cm^3), and V_t is total volume of the sample (cm^3). Theta has a maximum value equal to porosity of the porous media.

Structure and texture of a porous media determine the amount of water retained at a given pressure head. At low values of suction (<1.0 bar), moisture retention is most strongly influenced by the structure of the medium. At suctions greater than one bar, texture becomes increasingly important (Hillel, 1980).

The effect of texture on moisture retention is illustrated in figure 22. A fine-grained porous media has uniform pore size distribution which results in a gradual release of moisture as negative pressure increases. Conversely, in coarse-grained material most of the pores are relatively large. The predominance of large pores results in the release of most of the moisture present over a narrow range of low suction values.

The moisture characteristic curve for a given porous medium is a different shape during desorption (drying) than sorption (wetting). The sorption curve is displaced to the left of the desorption curve (figure 23). At a given pressure, the moisture content of a porous media will be greater if the sample is drying as opposed to wetting. This phenomena is termed hysteresis. The intermediate or scanning curves show the path that the θ-ψ relationship would follow if a porous media were partially dried, then rewetted, or vice versa. In this work,



*Particle diameters are in microns.

Fig. 22. Effect of Texture on Moisture Retention in Tailings Material

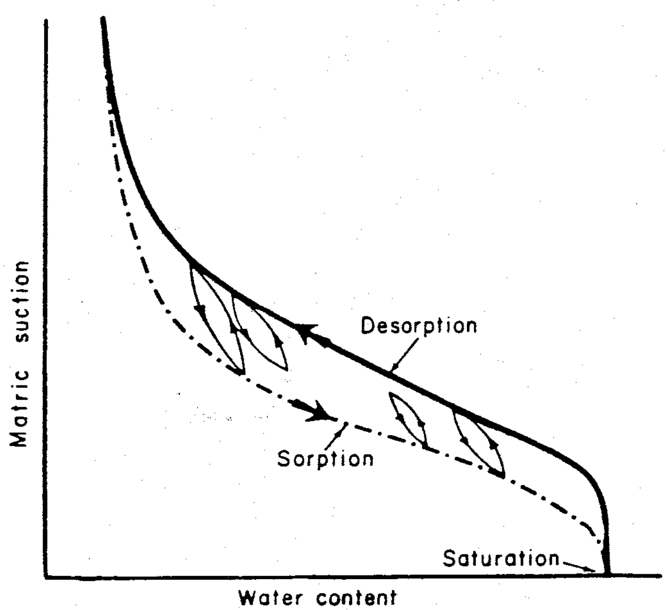


Fig. 23. Graphical Representation of Hysteresis

(Source: Hillel, 1980)

only primary drying curves were determined for tailings samples because the numerical model used is not capable of incorporating hysteresis.

Method. The hanging-water-column or tension plate apparatus similar to that described by Vomocil (1965) (figure 24) was used in the laboratory to determine theta-psi relationships. The apparatus used consisted of a Pyrex 350 ml buchner funnel (D) with a fritted ceramic disk (C). The funnel was hydraulically connected at the bottom via Tygon tubing (F) to a graduated 50 ml Pyrex buret (G) with a Rotoflo stopcock (H). To prevent moisture loss due to evaporation, the apparatus was made into a closed system by fitting a rubber stopper to the top of the funnel. The stopper was cored to accept a 7.6 cm length of copper tubing. The copper vent tube was connected to the buret via Tygon tubing.

The theta-psi relationship is determined using the hanging column by the application of successively increased suction with measurement of equilibrium wetness at each step. Suction was applied to the sample via the porous plate by maintaining the height of the meniscus in the buret below the porous plate. The porous plate is permeable only to water but not to air, at pressures less than the air-entry value of the porous ceramic plate. The air-entry value of the plate used was approximately 200 cm.

Each sample taken from the bottom of the shelby tube was rewetted for 24 hours prior to placement in the hanging column. During disassembly of the permeameter, some drainage of the tailings occurred. After rewetting each sample was weighed to obtain a saturated weight, and then placed in the hanging-column. The meniscus in each buret was

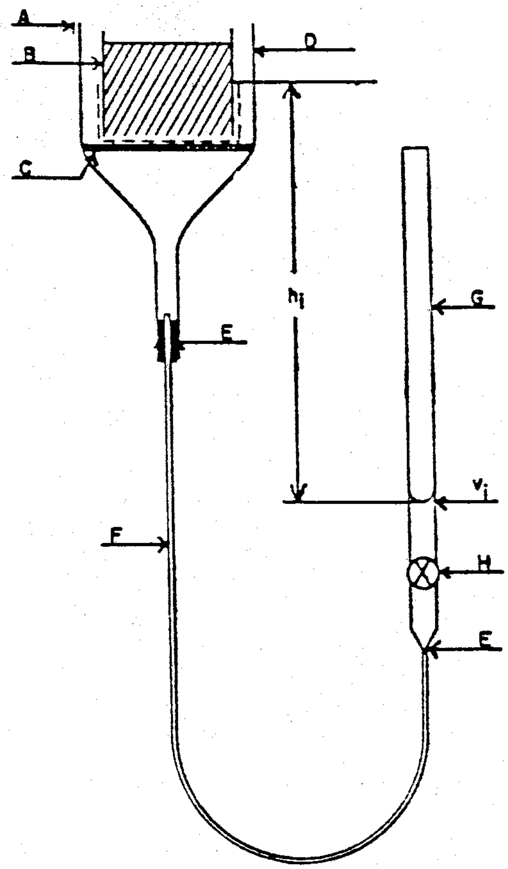


Fig. 24. Hanging-Water-Column Apparatus

(Source: Vomocil, 1965)

placed at the center of the sample, which is the zero pressure reference mark. After equilibrium was reached, the buret was quickly lowered 10-15 cm. The stopcock of the buret was then opened and the sample was again allowed to equilibrate for 24 hours. The amount of water forced from the sample was the difference in buret reading prior to and after the step change, in imposed negative pressure head. Negative pressure head, suction, imposed on the sample was the distance between the center of the sample and the meniscus in the buret at equilibrium. After equilibrium the buret was quickly lowered 10-15 cm and the sample allowed to equilibrate. The cycle was repeated until total suction applied was approximately 150 cm. Hanging-columns were read at the same time each day to minimize temperature related variations (Larson, 1984).

Moisture content at each equilibrium suction was calculated by dividing the total amount of water that flowed out of the sample in the remaining steps by the sample volume. After removal from the hanging-column each sample was weighed. Mass of the water loss was checked against volume measurements of water loss.

To obtain θ-ψ relationships above 150 cm of negative pressure head, a pressure plate apparatus (15-bar Ceramic Plate Extractor model A-140, Soil Test Inc., Evanston, Ill.) was used. Figure 25 is a schematic of a pressure plate apparatus. The upper part of the pressure plate cell was pressurized above atmospheric pressure using nitrogen gas. The water below the ceramic plate was maintained at atmospheric pressure via a tubular connection to the atmosphere. The pressure head difference across the sample drives water through the ceramic plate. Each plate has a designed air-entry value and will pass only water up to that value. Moisture contents at 1.5 and 15 bars of pressure were determined

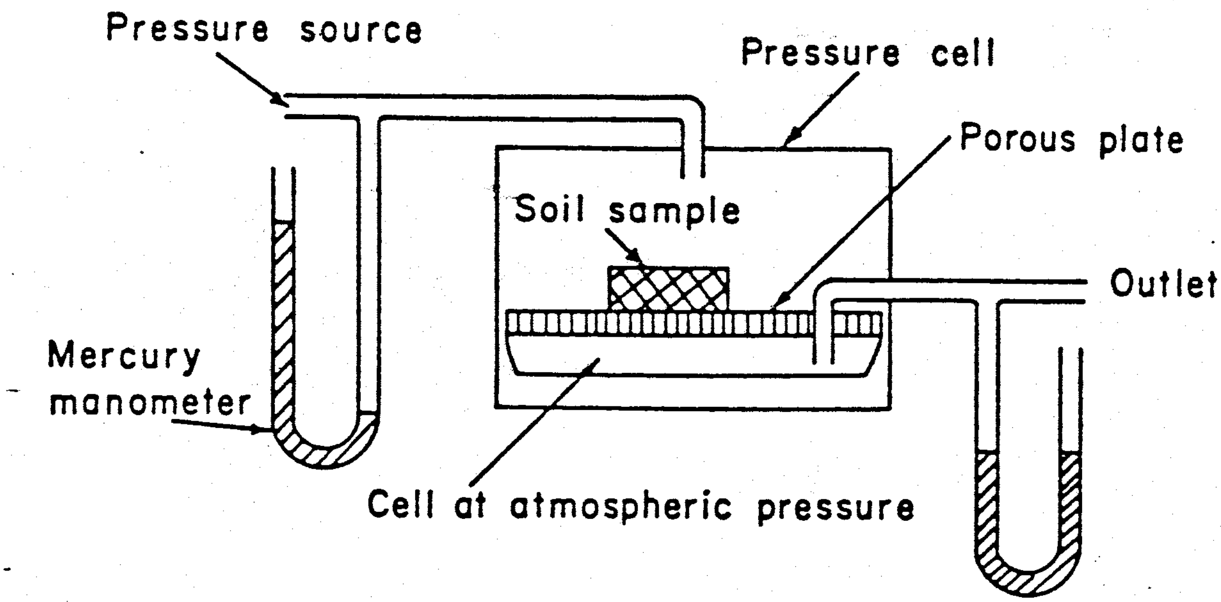


Fig. 25. Schematic of Pressure Plate Apparatus

(Source: Hillel, 1980)

for all samples from the horizontal transects. Samples taken from the vertical transects had moisture contents determined at 0.5, 1.0, 1.5, 3.0, 7.0, 15.0 bars. To shorten equilibrium times three different ceramic plates were used with 1.0, 3.0, and 15.0 bars air entry values. The lower the air-entry value of a plate the larger the pores, the faster the plate transmits water, and the quicker equilibrium is reached. After samples reached equilibrium they were removed from the pressure cell, weighed, and returned to the cell. The pressure was increased to the next step. Equilibrium times for tailings samples at different pressures were determined through a series of trial runs. Samples subjected to constant pressure were weighed on a daily basis until the weights remained constant. Laboratory determined θ-ψ data is included in Appendix C.

Sources of Error. Potential sources of error in using the pressure plate include loss of sample and hydraulic connection between the sample and ceramic plate. Each time a sample ring was removed from the cell to be weighed, the hydraulic connection between the plate and sample was broken. When replacing a sample, firm contact between sample and plate must be reestablished.

Porosity

Porosity is an index of the relative void volume of a porous media:

$$n = \frac{V_f}{V_t} \tag{13}$$

where n is porosity, V_f is the volume of the voids (L^3), V_t is volume of the sample (L^3). Porosity ranges from about 0.25 in gravels to 0.70 in clays (Freeze and Cherry, 1979, page 37). Porosity ranged from 0.38-0.72 in the tailings sampled. Porosity values determined from tailings samples are included in Appendix B.

In this work porosity was calculated on a volume basis using the equation;

$$n = \frac{V_{lost}}{V_t} \tag{14}$$

where V_{lost} is the volume (cm^3) of water lost from a saturated sample after oven drying, and V_t is the total volume of the sample. In using this method the density of water is assumed to be 1.0 gm/cm^3.

After samples were removed from the pressure plate and weighed, they were oven dried at 105 ^{0}C for 24 hours and then reweighed. The sample's oven-dried weight was subtracted from its saturated weight to determine the mass (gm) of water lost. Based on the assumption above, the mass of water lost is equal to the volume of water lost.

The greatest source of error was loss of sample during the transfer of samples between different apparatus. To the extent possible, material separated from a sample was recovered. During disassemblege of shelby tube apparatus, drainage of tailings samples occurred. To obtain a saturated weight, samples were allowed to rewet for 24 hours. In some instances samples considered saturated when weighed may have been slightly undersaturated or supersaturated.

Particle Size Analysis

Particle size analysis was performed using a standard technique outlined by Day (1965). Particle size parameters measured include d_{10}, d_{16}, d_{30}, d_{50}, d_{60}, d_{84}. The parameters indicate the percent of material by weight which is finer than the size given. Particle size distribution parameters calculated include uniformity coefficient (d_{60}/d_{10}), coefficient of curvature $((d_{30})^2/(d_{10})(d_{60}))$, trask sorting coefficient $((d_{84}/d_{10})^{1/2})$, trask skewness $((d_{84}\ d_{16})/(d_{50})^{1/2})$, and geometric mean particle diameter $((d_{16}\ d_{84})^{1/2})$. Results of particle size analysis are included in Appendix D. Refer to Johnson (1987) for a discussion of particle size analysis results.

IV. NUMERICAL SIMULATIONS

The spatial variability of hydraulic properties in an unsaturated porous media can have a significant effect on the movement of moisture (Yeh et. al, 1985; Heerman, 1985; Dirksen, 1978). Numerical models, such as UNSAT2 (Appendix E), can simulate seepage flow through impoundments; the accuracy of the results are limited in part by the quality of input data. To assess the potential impacts of seepage through tailings impoundments on ground-water quality, the spatial distribution of hydraulic properties must be characterized.

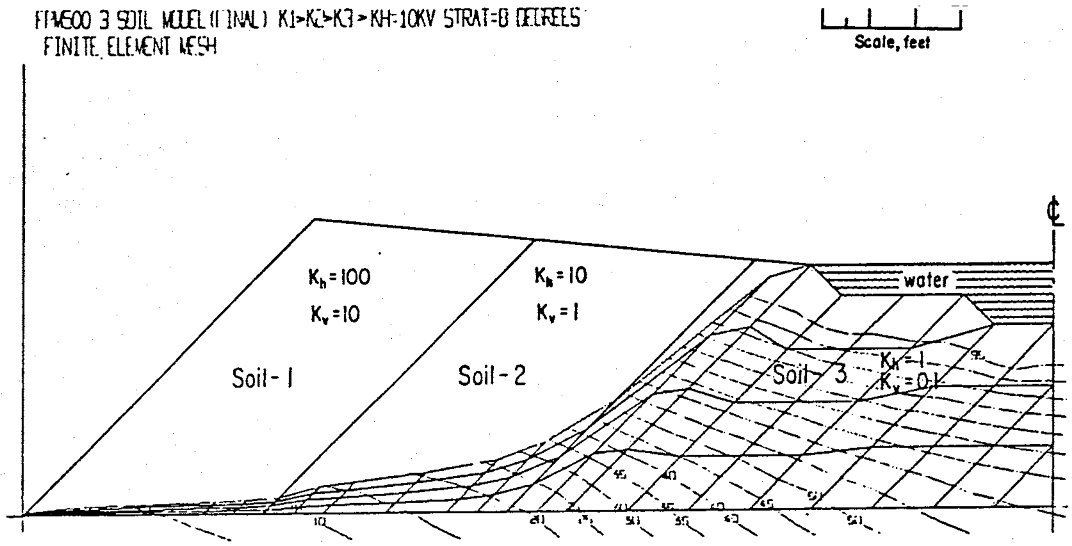
In this work the impact of the spatial distribution of hydraulic properties on moisture retention and movement are examined. Specifically examined is the extent to which saturated flow occurs in the Waldo Mine mill tailings impoundment under present field conditions. Johnson's (1987) geostatistical analysis of the impoundments' hydraulic properties is incorporated into the numerical simulations to the extent possible. Both one- and two- dimensional simulations are performed along the north trending sampling transect. One-dimensional simulations are conducted as a precursor to the two-dimensional simulations to examine the model's response to various input parameters including simulation times and finite element mesh density and to validate the model. In the two-dimensional cases both ponded and non-ponded surface conditions are examined. The purpose of the non-ponded conditions is to establish initial conditions for the pile in a dry quasi-equilibrium state as a starting point for the ponded simulations. In both cases, the impact of the tailings material defined as isotropic or anisotropic and various boundary conditions on model results are investigated.

Review of Numerical Simulation of Seepage in Tailings

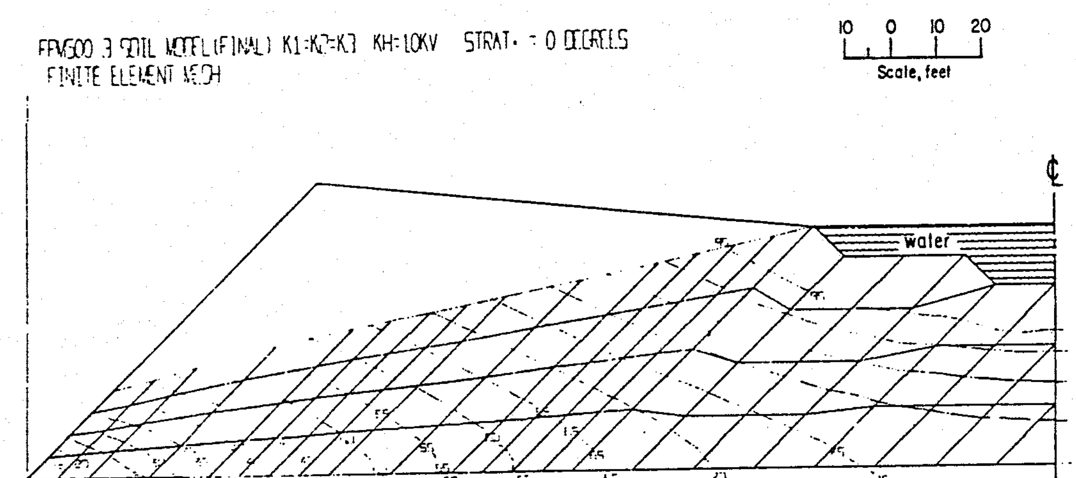
A number of researchers have used finite element models to analyze fluid movement through impoundments including Kealy (1970), Bloomsburg and Wells (1978), and Bartlett (1983). Although the researchers acknowledge the impact of field heterogeneities on fluid movement, characterization and incorporation of the spatial variability of hydraulic properties into their models are either greatly simplified or ignored.

Kealy (1970) used a finite element model for two-dimensional analysis of seepage in a zinc-lead-copper tailings impoundment. His primary objective was to locate the position of the free surface, and to study the accompanying development of seepage faces and implications on impoundment stability. Although incorporation of heterogeneities was limited to assigning different hydraulic conductivities to large blocks within the cross-sectional profile, Kealy did show that even a simplistic representation of the heterogeneities present in a tailings pile can have a significant effect on the position of the free surface (figure 26).

The mathematical model to be use in this work, UNSAT2, has been use by others to analyze seepage through waste impoundments. Bloomsburg and Wells (1982) used UNSAT2 to analyze one- and two-dimensional seepage through partially saturated retorted oil shale waste. In their work, results from UNSAT2 were compared to analytical and experimental results



Output From a Finite-Element Model of An Inhomogeneous, Anisotropic (8° Inclination to Horizontal) Embankment On An Impermeable Base.



Output From a Finite-Element Model of a Homogeneous, Anisotropic (0° Inclination) Embankment On An Impermeable Base.

Fig. 26. Position of Free Surface for Different Profile Configurations

(Source: Kealy, 1970)

for a variety of flow problems in order to assess the accuracy of the model. Overall results of UNSAT2 agreed with the analytical solutions and experimental data. The authors' attempt to incorporate heterogeneities into the modeling profiles was limited to a few large blocks with contrasting hydraulic properties. Again, as Kealy's (1970) work illustrated, even a simply heterogeneous pattern produced major changes in the movement and retention of moisture in a modeling profile.

More recently, Bartlett (1983) used UNSAT2 to analyze one-dimensional seepage and evaporation from recently deposited tailings. For the hypothetical homogenous, isotropic profiles, hydraulic parameters were obtained from the literature. Bartlett examined the effect of three variables, texture, evaporation, and time between deposition of new saturated layers, on the movement and redistribution of moisture in the profiles. Bartlett's results showed that initially saturated coarse- or medium-grained tailings with a water table at a depth of 300 centimeters and subject to evaporation, transmitted moisture to the surface from a maximum depth of 25 centimeters. Fine grain tailings, subject to the same conditions, maintained a steady upward flux of moisture from the water table for the duration of the simulation, 65 days. These results illustrate the greater ability of fine-grained material to transmit moisture under unsaturated conditions. After the original profiles drained for 65 days, moisture was input into the system in the form of a slurry layer. The wetting front passed through the coarse- and medium-grained tailings and eventually drained to the water table. The water content of the coarse- and medium-grained profiles was unchanged by passage of the wetting front. As the wetting front moved through the fine-grained tailings, the moisture was quickly redistributed and increased the profile's water content. Although Bartlett's work did not incorporate heterogeneities, his results have implications for tailings piles such as the Waldo Impoundment which is composed of sands, slimes, and areas of interfingering sands and slimes.

Capabilities of UNSAT2

The UNSAT2 model is an improved extension of UNSAT1 and was originally described by Neuman et al. (1973). Complete documentation and the user guide is available from the Nuclear Regulatory Commission (Davis and Neuman, 1983). A copy of the modified code used in this work is included in Appendix E. The model is a finite element code based on a lumped mass Galerkin method utilizing triangular elements. UNSAT2 can be used to investigate problems in unsaturated, partially saturated or fully saturated porous media. The model can simulate flow in one or two dimensions, and three-dimensional flow can be analyzed in situations where radial symmetry exists about the vertical coordinate. The flow domain can have irregular boundaries and can be composed of different soil materials, each having arbitrary degrees of anisotropy arranged in any desired pattern. Flow to a fully or partially penetrating well of finite radius, and pumping at an arbitrary rate from an unconfined aquifer can be simulated. The model can account for well bore storage and the tapping of several aquifer layers at the same time. UNSAT2 can also model water removed from the system by plants using atmospheric and soil conditions as well as plant growth to determine water uptake by the plants.

Time-dependent boundary conditions which can be used include conventional prescribed head and flux boundaries, and those controlled by atmospheric conditions such as seepage faces and evaporation or infiltration surfaces. The initial conditions are described by pressure or total heads. A restart feature built into the model allows the type and value of boundary conditions to be changed at any time during a simulation.

Model Verification

Problem Definition

Proper application of a numerical model requires that the accuracy of the numerical solution should be checked. The purpose of this test case was to compare the results obtained from UNSAT2 with the results obtained from an exact analytical solution for one specific problem. Comparison between the methods was made for one-dimensional vertical infiltration into a homogeneous, isotropic porous medium with an initially uniform moisture content. The analytical solution used was Philip's solution for one-dimensional vertical infiltration. Comparison of the two methods involved examining predictions of:

- the advancement of the wetting front with time,
- the cumulative infiltration with time, and
- the infiltration rate with time.

The boundary and initial conditions for the simulations were as follows. The top and bottom boundaries were designated as constant head boundaries. The top boundary was assigned a pressure head equal to zero. The bottom boundary was assigned a pressure head value which corresponded to the initial moisture content assigned to the profile, but with the option of becoming a seepage face at late time. The entire profile was assigned an initially uniform moisture content except at the surface nodes. Mathematically these conditions are stated as

Top boundary:

$$t \geq 0 \qquad z = 0 \qquad \psi = 0 \qquad \theta = \theta_S$$

Bottom boundary:

$$t \geq 0 \qquad z = 63 \qquad \psi = \psi(\theta_i) \qquad \theta = \theta_i$$

$$t \gg 0 \qquad z = 63 \qquad \psi = 0 \qquad \theta = \theta_s$$

Initial conditions:

$$t = 0 \qquad z > 0 \qquad \psi = \psi\,(\theta_i) \qquad \theta = \theta_i$$

The finite element grid use in the numerical solution was the same mesh used by Davis and Neuman (1983) in their one-dimensional infiltration example problem, figure 27. Use of their grid allowed this user to become familiar with generating an UNSAT2 data file, simplified running the test case, and allowed a quick verification to be done on the version of UNSAT2 in use at Tech. The UNSAT2 code currently in use at New Mexico Tech was modified by Dr. Jim Yeh to run steady state simulations.

The one-dimensional infiltration problem involved wetting an initially dry profile; however, wetting curves were not generated for samples taken from the Waldo Impoundment as part of our characterization effort. Therefore, the hydraulic properties of copper tailings samples were used for the simulations to test UNSAT2. These hydraulic

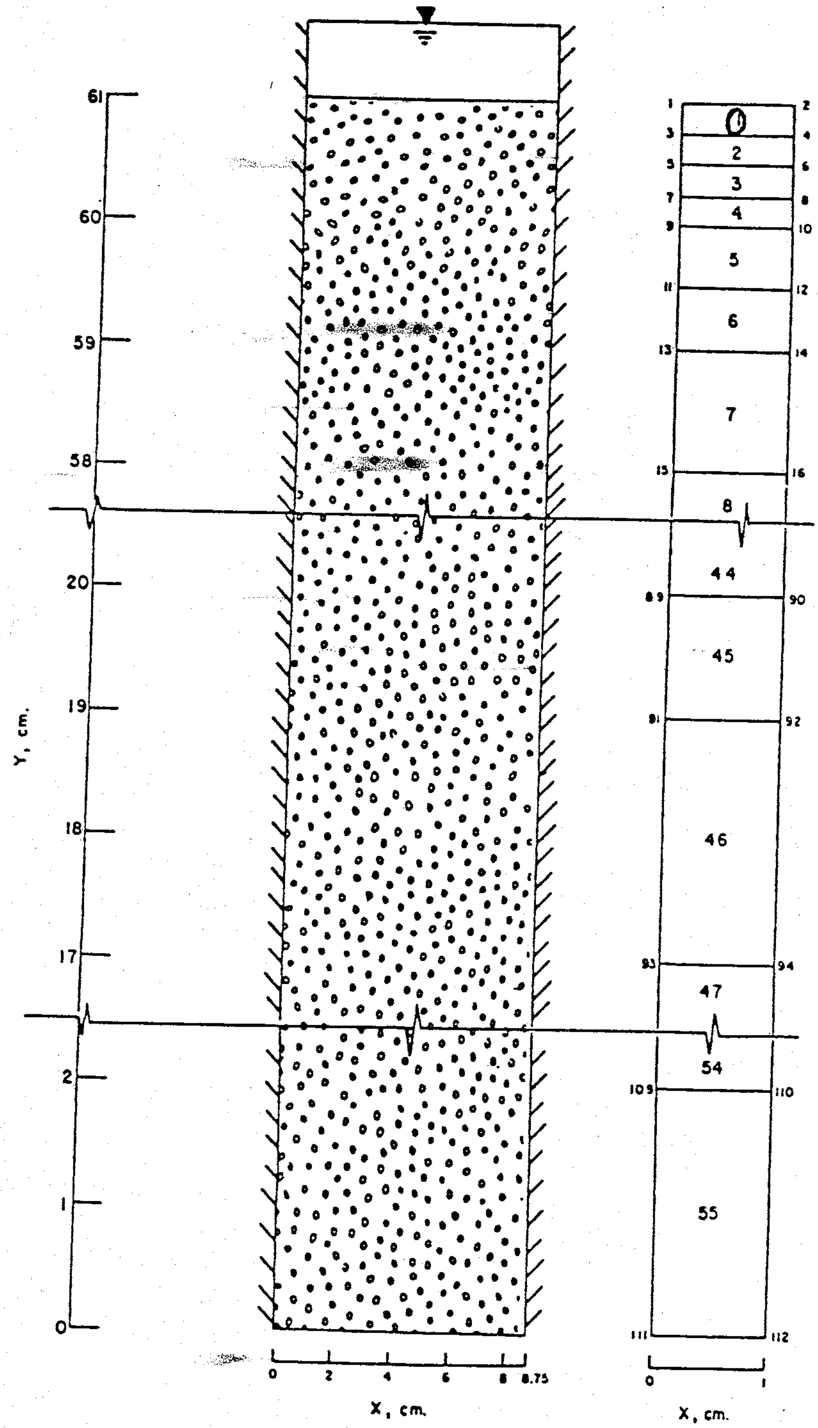


Fig. 27. Finite Element Grid and Column Used in Test Case

(Source: Davis and Neuman, 1983)

properties were previously measured by former graduate student Greg Lewis (1986). Lewis generated both wetting and drying theta-psi curves and also $K(\theta)$ relationships over a limited moisture content range. To expand the range of $K(\theta)$ relationships the appropriate hydraulic properties were input into the van Genuchten (1978) two parameter model.

Two forms of the Philip's solution were used in this analysis. A programmed version of Philip's solution, written by Dr. Peter Huyakorn (Huyakorn, unpublished) (Appendix E), was used to predict the advance of the wetting front with time. Cumulative infiltration depth and infiltration rate with time were determined using the two parameter equations from Hillel (1980) were used:

$$I = St^{1/2} + Kt \tag{15}$$

$$i = 1/2\ St^{-1/2} + K \tag{16}$$

where I is the cumulative infiltration depth (cm), i is infiltration rate (cm/sec), S is sorptivity (cm/sec$^{1/2}$), t is time (sec), and K is hydraulic conductivity (cm/sec). Sorptivity was determined using the equation given by Dirkson (1975):

$$S = \left[4(\theta_s - \theta_i)/\pi \int_{\theta_i}^{\theta_s} D(\theta)\ d\theta\right]^{1/2} \tag{17}$$

where θ_s is the moisture content behind the wetting front (cm^3/cm^3), θ_i is the intial moisture content, and $D(\theta)$ is hydraulic diffusivity (cm^2/sec). The integral was found using a program which numerically integrated the area under the $D(\theta)$-θ curve. The $D(\theta)$-θ curve was plotted using output from the van Genuchten model. A sorptivity value of 0.026 $cm/sec^{-1/2}$ was calculated. Hydraulic conductivity, K, was assumed to be equal to saturated hydraulic conductivity where K_s is equal to 0.0003 cm/sec. This was a reasonable assumption for a uniform soil under ponded conditions. A porosity value of 0.37 and an initial moisture content of 0.13 cm^3/cm^3 was used in the simulations.

Simulation times for the analytical and numerical solutions were 10, 100, 500, 1000, 3000, 5000, 7000 seconds. Plotted results showing the advance of the wetting front begin at t=500 seconds. Movement of the front at t=10 and 100 seconds was too small to incorporate into the plots. All other plots incorporated simulation results at all times.

Results and Discussion

Figure 28 illustrates the downward advance of the wetting front. The numerical simulation and analytical solution were in good agreement. At early time, the position of the front calculated by the Philip's solution was slightly ahead of the position predicted by UNSAT2. With increasing time, UNSAT2 predicted a slightly faster advancing front.

Results for infiltration rates versus time is shown in figure 29. At early time UNSAT2 predicted a considerably higher rate than the analytical solution. At later time both solutions were close, and correctly approached the saturated hydraulic conductivity value of the tailings material. At large values of time infiltration rate should nearly equal K_s.

Cumulative inflow as predicted by both solutions is illustrated in figure 30. At small values of time cumulative inflow calculated by

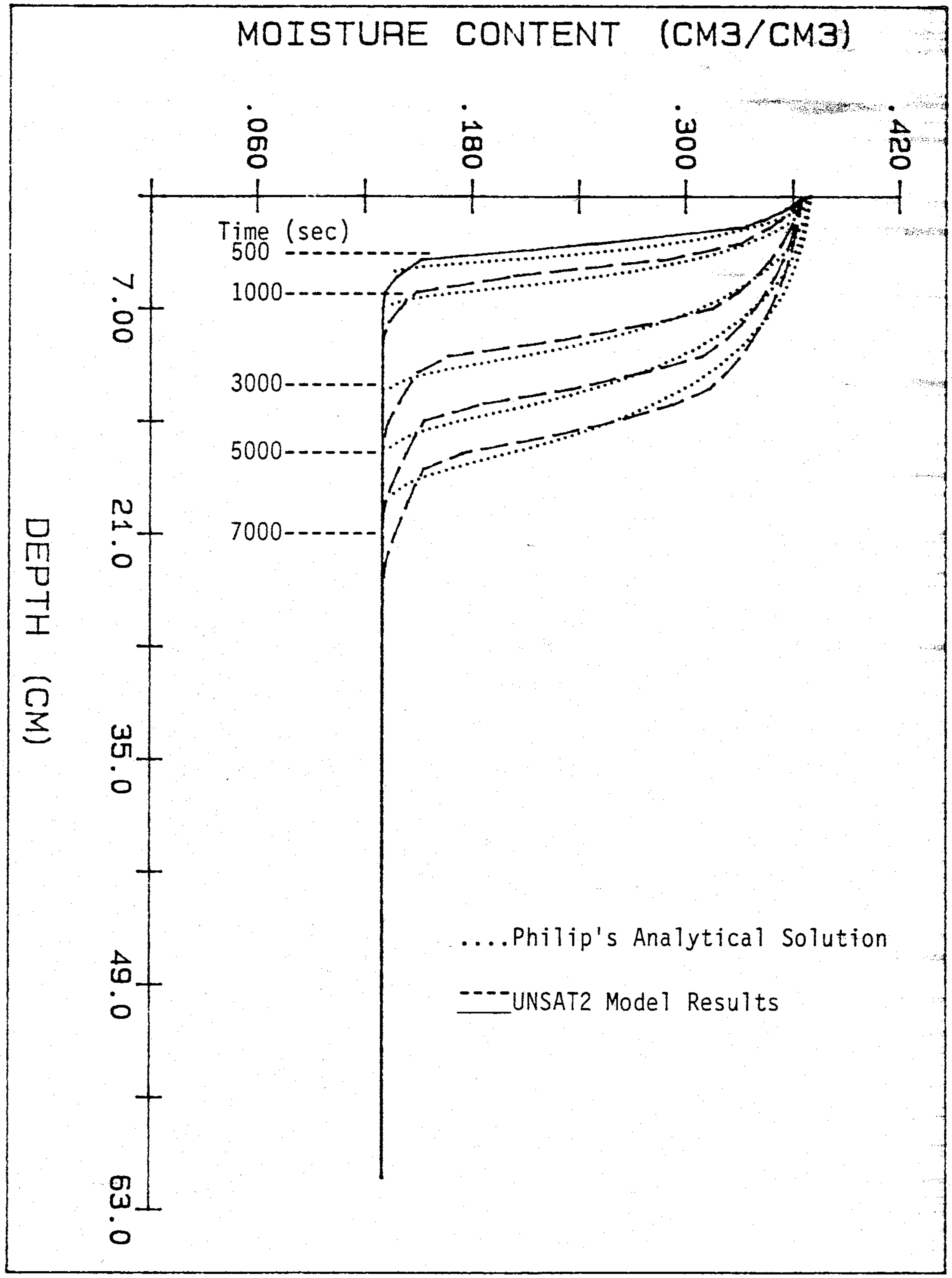


Fig. 28. Position of Wetting Front over Time

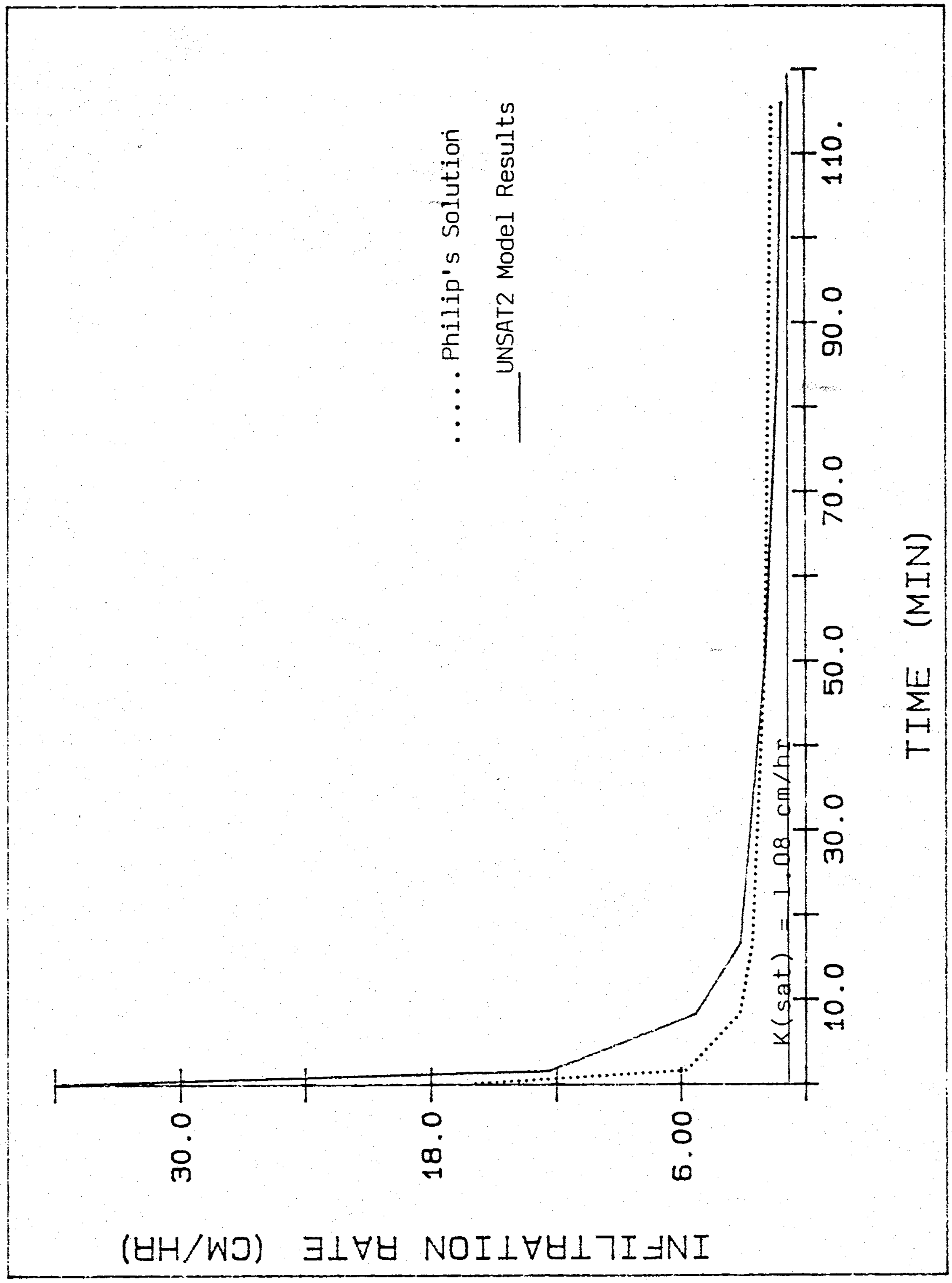


Fig. 29. Change in Infiltration Rate over Time

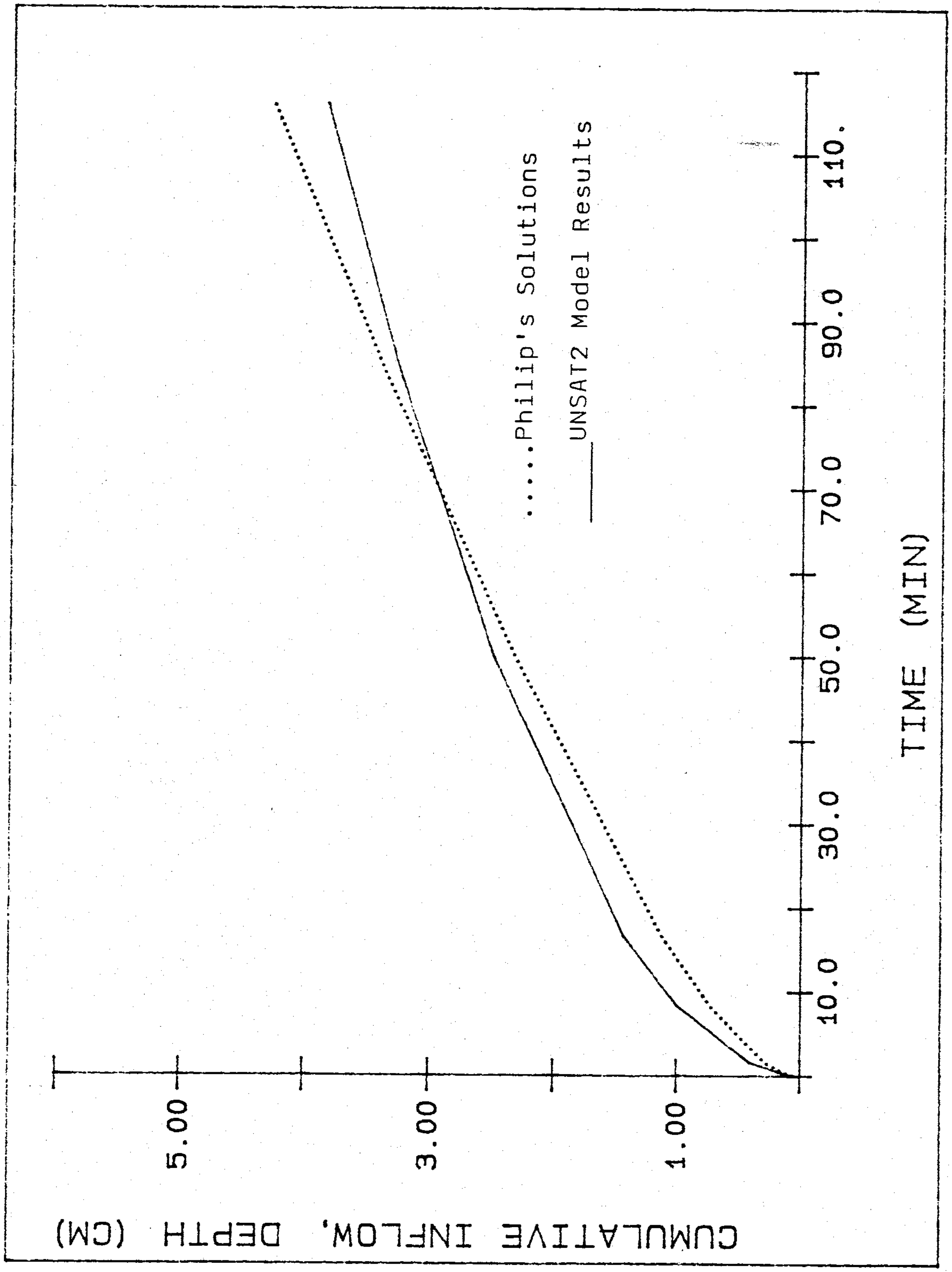


Fig. 30. Cumulative Inflow Depth over Time

UNSAT2 was much higher than values calculated by the Philip's solution. At later times the reverse is true.

There are several of possible sources of errors to account for the discrepancies in predictions made by the two methods. These included:

1) The form of the analytical solution used- Philip's original solutions were in term of infinite series solutions. There are several simplified approximations to the series solutions which can be used to calculate I and i. For small and intermediate values of time the two parameter equations (Hillel, 1980) are considered sufficiently accurate:

$$I(t) = St^{1/2} + At \qquad (18)$$

$$i(t) = 1/2St^{-1/2} + A \qquad (19)$$

Although A is well defined mathematically it is not easily determined. For this reason equations (15) and (16) were used. However, equations (15) and (16) are only considered accurate at large values of time. As noted by Hillel (1980) A does not equal K particularly at small and intermediate times. Use of the late time approximations to the infinite series solution may have been the primary error responsible for differences in predictions of cumulative infiltration and infiltration rates versus time made by UNSAT2 and the analytical solutions.

2) Round-off error: the original UNSAT2 code was written to run on a CDC computer system which is a 64 bit machine. The DEC-20s in the computer center at New Mexico Tech are 36 bit machines. The computer code in use at Tech has not been converted to double precision to account for differences in machine precision.

3) Numerical techniques used in UNSAT2- according to Huyakorn (1986) the manner in which triangular elements are used in UNSAT2 to make up rectangular elements, and the diagonal interpolation scheme used may introduce slight errors in the numerical calculations.

Overall results from the two methods compared favorably. Use of a better approximation to the Philip's solution at early time would probably eliminate the single largest source of error. It is not practical to eliminate the other sources of error. However, the results of this test verify that UNSAT2 produced reasonably accurate results when compare to an analytical solution.

Method

Assumptions and Limitations

In order to simplify the numerical simulations with UNSAT2, a number of assumptions have been made. These assumptions, which limit to some degree the accuracy of the results, are summarized as follows;

-conditions are isothermal and flow is in the liquid phase only;

-compression of the porous media does not occur. For the Waldo Tailings Impoundment which has been undisturbed for thirty-six years this assumption may not be critical;

-for two-dimensional simulations in a vertical cross-section, no flow occurs orthogonal to the cross-sectional plane;

-principal directions of hydraulic conductivity are perpendicular and parallel to the stratifications in the tailings pile, and stratification is assumed to be similar to that of another lead-zinc-copper tailings impoundment which was inclined eight degrees from horizontal toward the center (Kealy, 1970);

-an anisotropy ratio, K_h/K_v, of two to four is used, these are values determined by Kealy (1970),

-hysteresis is ignored in the soil-moisture characteristic relationship and the unsaturated hydraulic conductivity-pressure head relationship and;

-unsaturated hydraulic conductivity relationships can be derived from soil-moisture characteristics. In this work van Genuchten's (1978) closed-form analytical model is used to determine these relationships.

To further simplify the modeling task and minimize CPU time, only the southern half of layer two along the north-trending sampling transect was modeled. The transect was divided in half by a vertical west-trending plane of approximate symmetry (figure 31). The plane of symmetry divides the second layer roughly at the point where the measured saturated hydraulic conductivity reaches a minimum. The southern half of the transect is used because it contains a maximum number of sampling points, including four vertical sampling transects as compared with two on the northern half (figure 32). In addition, the southern half of the transect overlies only a small area of layer one. The finite element grid, time step size, and total simulations times are kept constant for all runs in order to compare the different simulations.

Characterization of Spatial Variability of Hydraulic Properties

The characterization and interpretation of the spatial variability of hydraulic properties at the Waldo Mine Tailings Impoundment was conducted by Gary Johnson (Johnson, 1987). A variety of geostatistical techniques including trend surface analysis and kriging were applied to quantify the spatial distribution of hydraulic properties such as

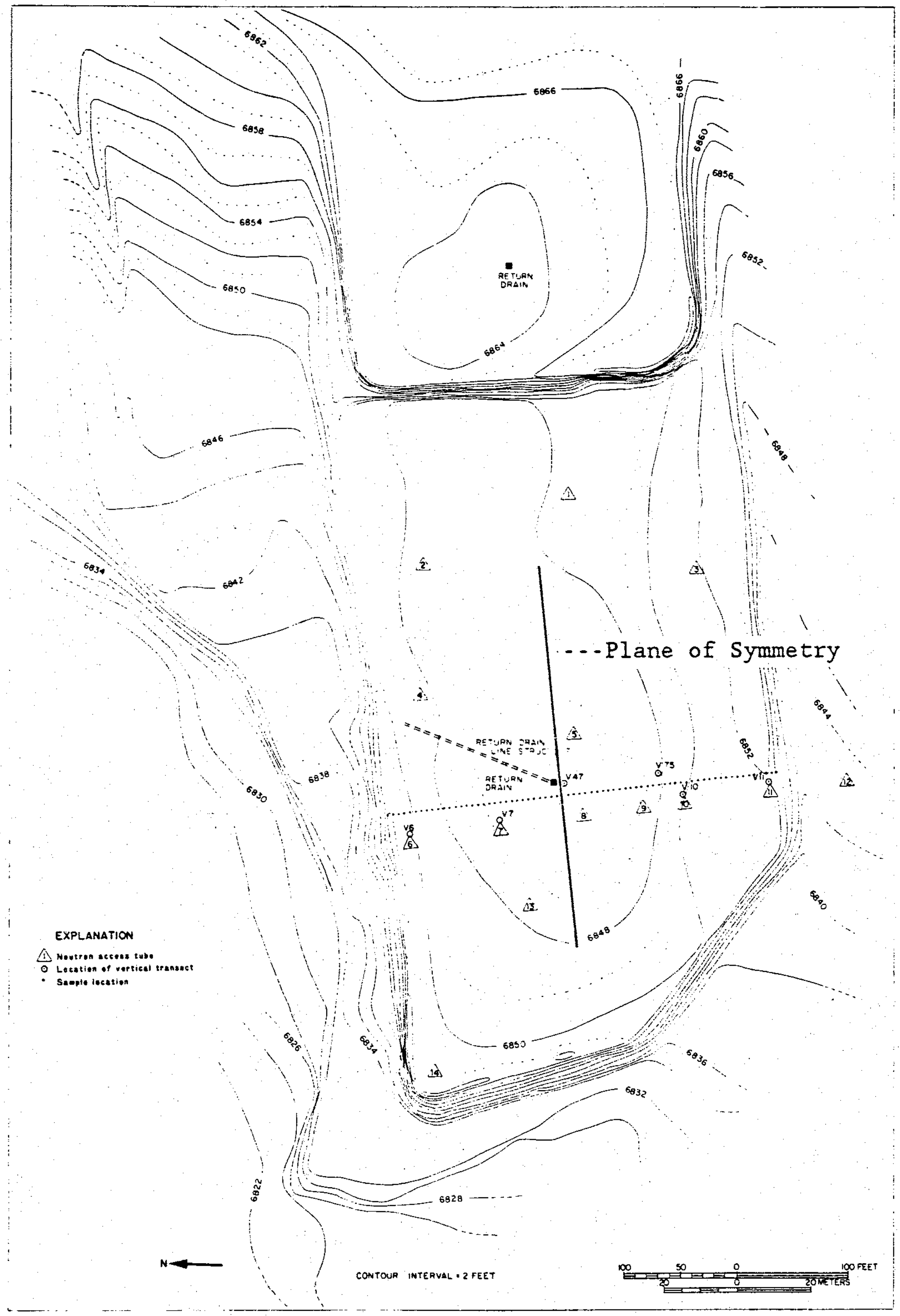


Fig. 31. Impoundment with Neutron Probe Sampling Locations and Plane of Symmetry

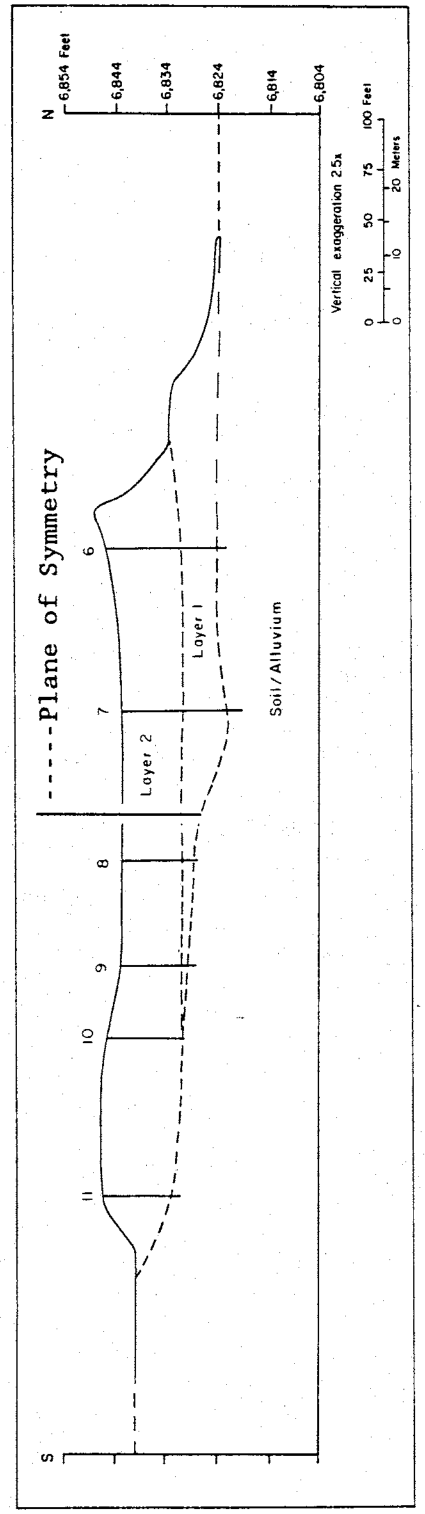
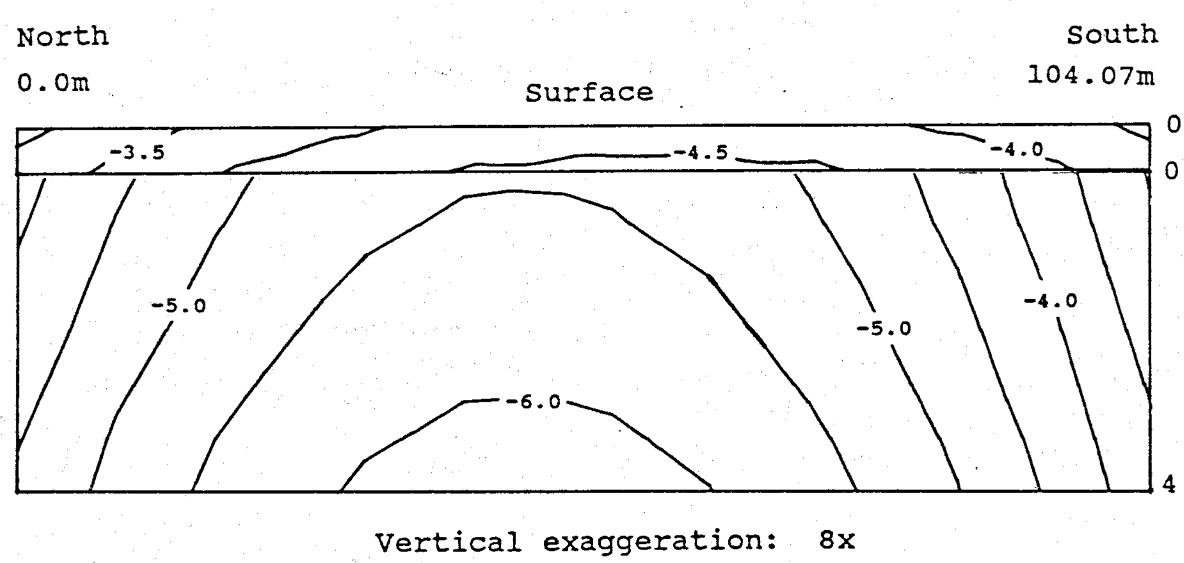


Fig. 32. Cross Sections of Impoundment Along North-Trending Transect with Neutron Probe Tube Locations

porosity, saturated hydraulic conductivity, grain size, and moisture content at specific suctions.

The primary input from Johnson's (1987) work to this modeling effort is two-dimensional regression (trend surface) analysis of saturated hydraulic conductivities along the sampling transect (figure 33). Saturated hydraulic conductivities across the cross sectional profile range from 10^{-7} to 10^{-4} cm /sec). Johnson's interpretation of the spatial variability of K_s across the cross section is similar to the conceptual model developed by Kealy (1970). Unique to Johnson's model in comparison to Kealy's work is a 50 centimeter surface zone (figure 33). The presence of this upper zone is due to surface erosion since abandonment of the site in 1950 and in-situ formation of calcium carbonate- and iron-cemented hardpans in the oxidation zone that has been subject to repeated cycles of wetting and drying. The in-situ development of carbonate cements is supported by the presence of rhombehedral calcite crystals (≈ 5 mm long) in a fine-grained tailings matrix. Beneath this surface layer, are zones common to tailings impoundments, that include an interior fine-grained moist slime zone, a transitional area containing interfingering of slimes and tailings sand, and the outer area consisting of tailings sands.

Johnson found from two-dimensional regression analyses of hydraulic parameters, that only the detrended θ_{15} data contained sufficient correlation to justify additional analysis using kriging techniques. Johnson developed regression equations for various parameters including saturated hydraulic conductivity and porosity. However, these equations are not used in this work because these relationships can not be



Log K_s (cm/sec)

Vertical Exageration: 8x

Fig. 33. Contoured Cross Section of the Two-Dimensional Regression Fit to the Log K_s Data

(Source: Johnson, 1987)

incorporated into the current version of UNSAT2. In addition, the regression equations only provide estimates of K_s and n; moisture retention data (θ-ψ) and unsaturated hydraulic conductivities also are relationships required by UNSAT2 to define the porous media.

Although the entire impoundment is not a true rectangle, Johnson's representation of the impoundment in cross-section as a rectangle is a reasonable assumption for the southern half modeled in this work (figure 33). As can be seen in figure 34 which is true to scale, the southern half of the impoundment does approximate a rectangle.

Different methodologies are used in choosing hydraulic parameters for the one-dimensional and two-dimensional simulations. In the one-dimensional simulations of vertical transects V47, V10 and V11, observations from each transect are directly incorporated into each numerical model. Direct incorporation is possible because each vertical transect contains a limited number of observations. For the two-dimensional simulations, the large number of observations and complexity of correlating observations between different transects made direct incorporation of hydraulic data infeasible. The data base of mill tailings' hydraulic properties, Figure 33 and field observations were used to delineate specific zones of tailings material across the impoundment. A zone is defined as an area within one order of magnitude of hydraulic conductivity for these modeling purposes. This definition of the zones, each with a unique set of hydraulic parameters, simplifies the formulation of spatial relationships between different material in a very heterogeneous environment.

To select the most appropriate hydraulic properties for each zone in the two-dimensional simulations vertical transect data were used to

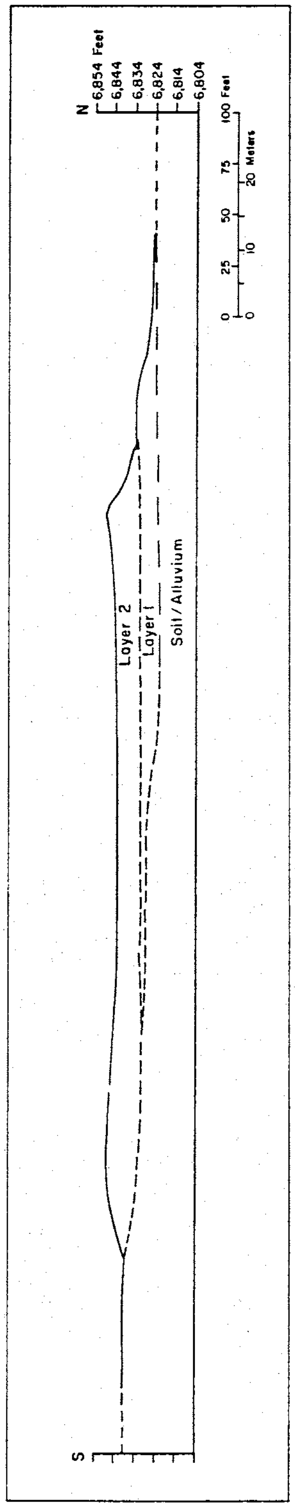


Fig. 34. True-to-Scale Cross Section Along Sampling Transect

generate parameters for the zones of permeability. Only the vertical transect data contain complete data sets; horizontal transects lack both θ-ψ and K_r-ψ relationships. To select parameters, only observations located within a particular zone have been considered.

Each complete set of hydraulic parameters developed from an individual tailings sample was evaluated using criteria based primarily on K_s, and secondarily on porosity and theta-psi relationships. This criteria is consistent with the use of Johnson's saturated hydraulic conductivity regression model as the primary tool for incorporating the spatial variability of tailings hydraulic properties in the numerical models. Saturated hydraulic conductivity as the primary parameter must fall within the range defining a zone. Hydraulic conductivity values approaching the median value of a zone were preferred.

Porosity and theta-psi relationships were evaluated to ensure that they were consistent with tailings material correlated with a particular zone. An extreme example of a discarded data set is one which has a K_s typical of interior slime material, and porosity and theta-psi relationship typical of tailings sands found along the perimeter of the impoundment. Parameters used in the two-dimensional simulations are listed in Table 3.

Boundary Conditions

Boundary conditions common to the one- and two-dimensional simulations consist of a prescribed flux (Neumann type) boundary, an evaporation surface along the tailings/atmosphere interface and a prescribed head (Dirichlet) boundary along the tailings/natural soil

TABLE 3. Hydraulic Parameters For Two-Dimensional Simulations

Zone	K_{sat} *	Stratification ⊙	K_h/K_v †	n*	Parameter Source*
1	7.42 E-07	8.0°	2	0.520	V47 293-306 cm
2	4.21 E-06	8.0°	2	0.536	V47 148-152 cm
3	1.02 E-05	8.0°	2	0.427	V6 300-314 cm
4	4.76 E-04	8.0°	4	0.508	V11 342-345 cm
5	5.27 E-07	8.0°	1	0.491	V47 412-425 cm
6	1.40 E-03	8.0°	1	0.441	V11 419-434 cm

Node #	Zone	Negative Prescribed Pressure Head (cm)	
1-11		Impermeable Boundary (line of Symmetry)	
Tailings/Atmosphere Interface			
22-242	3	355.0	
252-459	3,4	211.0	
469-638	4	15800.0	
Tailings/Soil Interface			
		Draining Case	Ponded Case
12-419	5a	211.0	53.0
430-549	5b	178.0	63.0
559-619	6	668.0	168.0

* see Hydraulic Properties & θ/ψ Data Sheets for vertical transects.
⊙ Angle between principle conductivities and x coordinate (Kealy, 1970).
† Source Kealy (1970).

interface. Except along the evaporation surface, all boundary and initial conditions are input as pressure heads; the model calculates total head. For nodes along the evaporation surface a maximum potential rate of evaporation is prescribed as are the minimum allowable pressure heads. The model calculates fluid flux across the boundary based on the ability of porous media to transmit moisture. Parameters used in the one-dimensional simulations are listed in Table 4.

To determine minimum allowable pressure heads along the evaporation boundary, in-situ pressure head was calculated from neutron probe moisture measurements at 61 cm depth (made in March, 1986) and θ-ψ relationships developed from samples taken at the 51 cm depth in the vertical transects (V47, V10 and V11). Neutron probe readings made at the 30 cm depth were not used because near-surface measurements can be inaccurate due to loss of fast and thermalized neutrons to the atmosphere. Also, the closest tailings sample with developed θ-ψ relationships is the 51 cm sample.

Samples with developed θ-ψ relationships used to develop minimum allowable pressure heads were different for the one- and two-dimensional simulations. Field and laboratory evidence indicates hydraulic properties of the upper 50 centimeters of the impoundment are inconsistent with the material below 50 centimeters. Johnson (1987) found the two-dimensional regression model that treated the upper 50 centimeters separately most accurately predicted the K_s values. In one-dimensional simulations, in which Johnson's model is not used, hydraulic parameters for the 50 centimeter surface zones are developed from samples taken at 51 centimeters in each of the three vertical transects. The same samples could not be used in the two-dimensional simulation

TABLE 4. Hydraulic Parameters For One-Dimensional Simulations

VERTICAL TRANSECT V47

Boundary Conditions: Lower ψ = 211.0 Upper ψ = 355.0

θ used to estimate B.C., Tube 8*: Lower θ = 0.331 @ 426.72 cm (3/86) Upper θ = 0.449 @ 60.96 cm (3/86)

Grid Spacing: Vertical = 25.0 cm Horizontal = 1.0 cm

Total Simulation Time: 2.0 & 36 years; profile drained only

Material	Elevation (cm)	K_{sat} ⊙ (cm/sec)	n⊙	Sample transect position† (cm)
1	375-425	8.33 E-07	0.534	50-53
2	325-375	3.93 E-08	0.628	103-106
3	25-325	4.21 E-06	0.536	207-210
4	0-25	5.27 E-07	0.491	426-429

VERTICAL TRANSECT V10

Boundary Conditions: Lower ψ = 178.0 (soil below V47)
ψ = 126.0 (soil below V11)
Upper min ψ = 211.0

θ used to estimate B.C., Tube 10*: Lower θ = 0.345 @ 426.72 cm (3/86) Upper θ = 0.265 @ 60.96 cm (3/86)

Grid Spacing: Vertical = 25.0 cm Horizontal = 1.0 cm

Total Simulation Time: 2.0 & 36 years; profile drained only

Material	Elevation (cm)	K_{sat} ⊙ (cm/sec)	n⊙	Sample transect position † (cm)
1	375-425	1.73 E-4	0.571	48-51
2	325-375	3.43 E-05	0.375	99-102
3	275-325	4.66 E-06	0.471	149-152
4	225-275	4.70 E-05	0.405	200-203
5	175-225	4.77 E-04	0.387	249-252
6	125-175	1.02 E-04	0.439	296-299
7	25-125	1.02 E-05	0.422	348-351
8	0-25	(see Layer 4-V47 or 6-V11)		

VERTICAL TRANSECT V11

Boundary Conditions: Lower ψ = 668.0 Upper ψ = 15800.0

θ used to estimate B.C., Tube 11*: Lower θ = 0.199 @ 426.72 cm (3/86) Upper θ = 0.110 @ 60.96 cm (3/86)

Grid Spacing: Vertical = 25.0 cm Horizontal = 1.0 cm

Total Simulation Time: 2.0 years; profile drained only

Material	Elevation (cm)	K_{sat} ⊙ (cm/sec)	n⊙	Sample transect position† (cm)
1	425-375	4.25 E-04	0.518	48-51
2	375-325	1.61 E-03	0.578	99-102
3	325-275	7.18 E-03	0.557	149-152
4	275-175	1.81 E-05	0.452	243-246
5	175-25	4.76 E-04	0.508	342-345
6	25-0	1.40 E-03	0.441	431-434

* see Neutron Probe Data Sheet (appendix A)
⊙ see Vertical Transect Hydraulic Properties Data Sheet (appendix B)
† see Vertical Transect Theta/Psi Data Sheet (appendix C)

because the measured K_s are not within the range predicted by the regression model (10^{-4} to 10^{-5} cm/sec). For the one-dimensional case, measured in-situ theta values are correlated to theta-psi relationships to estimate the in-situ psi. However in the two-dimensional case this approach could not be used because the in-situ theta values exceed the saturated theta determined for the 50 cm surface zone. Therefore, the same minimum allowable pressures heads are applied in both the one- and two-dimensional cases.

The in-situ pressure head values for the natural soil beneath the tailings pile were estimated from in-situ moisture contents and representative moisture characteristic curves from vertical transect samples. Although the vadose zone beneath the pile is 46-61 meters thick, the tendency of the natural soils to readily transmit or impede drainage from the tailings is a function of the contrast in hydraulic conductivities between the tailings and soil.

The north edge of the flow domain is delineated by a plane of symmetry and is assigned a prescribed flux of zero, a no flow boundary. Ponding of water to a depth of approximately 15 centimeters in the interior portion of the pile occurs several times a year. Prescribed head values of 15 cm are assigned to the nodes along the impoundment surface which is subject to ponding.

Initial Conditions

The initial conditions for UNSAT2 are input either as pressure or total heads. Originally, an actual field pressure head distribution was to be used in the model from values determined using volumetric moisture contents. Moisture contents were to be calculated from measurements made using a neutron probe in the six access tubes along the sampling transect and from theta-psi relationships determined from samples taken in vertical transects near the access tubes. Attempts to calibrate the neutron probe in the high moisture range (theta > 35%) were not successful. The interior portion of the pile subject to ponding frequently had volumetric moisture contents greater than 35 percent. To circumvent the calibration problem, all simulations start with saturated conditions, and a prescribed pressure head equal to zero is assigned to all interior nodes.

Time Step Size and Total Simulation Time

The time step size to use with UNSAT2 is unique to each modeling problem and is affected by the hydraulic properties of the porous media, boundary and initial conditions, and the coarseness of the finite element grid. Determination of the proper time step size is a trial and error process. To expedite the process and gain insight into how UNSAT2 would handle the boundary conditions as outlined above, a series of one-dimensional simulations were run. These runs were used to estimate the total simulation time needed to achieve an equilibrium state. Three different runs were made in which the hydraulic properties of the tailings measured from vertical sampling transects V47, V75, and V11 were used to simulate vertical flow in the slime, transitional, and sand areas, respectively.

Model Discretization

The finite element grid used in the two-dimensional simulations (figure 35) consists of 638 nodes and 626 elements. Rectangular elements

are divided into triangles during execution of UNSAT2. The minimum nodal spacing is 0.25 meters and maximum nodal spacing is 1.6 meters. The mesh was made finer along the contact between materials having large contrasts in hydraulic properties and along boundaries where steep hydraulic gradients may develop.

The mesh shown in figure 35 overlays figure 33, in Johnson (1987). The bold lines delineate four zones of differing saturated hydraulic conductivity permeability within the impoundment and two different foundation materials. The difference in appearance between figure 33 (Johnson, 1987) and figure 35 is due to vertical exaggeration. Curvature of the lines in figure 33 is due primarily to the large vertical exaggeration of 8x. Another difference between the figures is that 25 centimeters has been added to the base of figure 35 to include foundation material beneath the tailings impoundment.

Model Calibration and Validation

Historical records of hydraulic observations used for model calibration and validation do not typically exist for tailings impoundments as they do for other subsurface hydrologic systems. Vandalism of previously installed instruments at the Waldo mill tailings Impoundment precluded employment of equipment such as tensiometers and piezometers to measure hydraulic conditions within the impoundment. The only in-situ data available for model validation are neutron probe measurements of moisture content. Throughout this discussion, the accuracy of model input parameters and the suitability of UNSAT2 to simulate movement and retention of moisture within the impoundment are evaluated using neutron logs of moisture contents and field observations during drilling and trench operations over a two-year period.

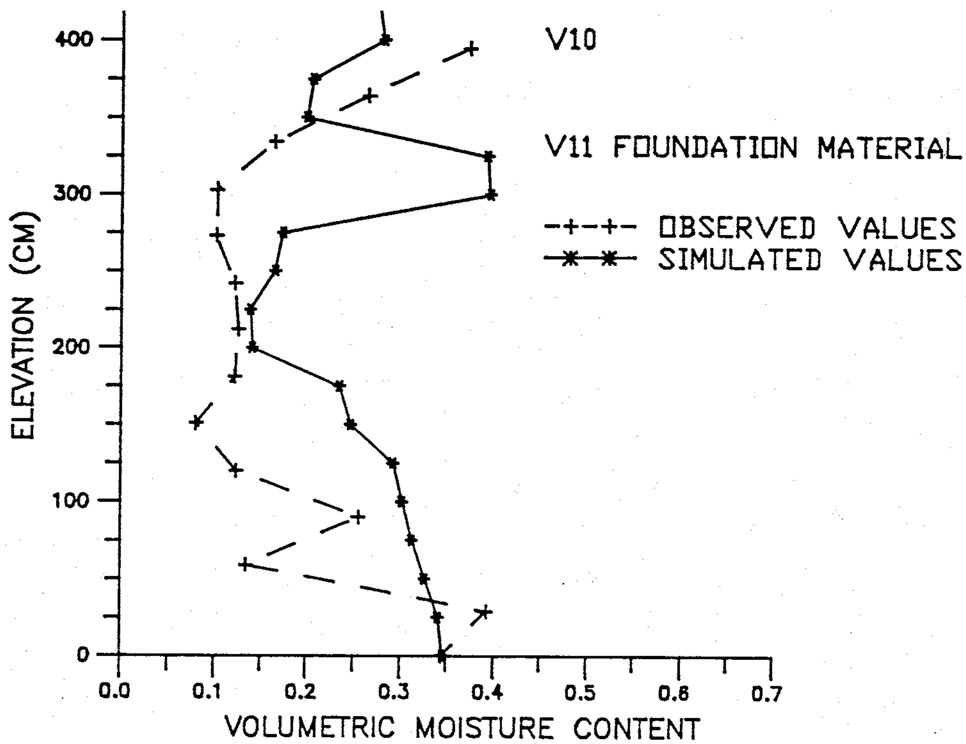
Results and Discussion

The results for the various numerical simulations for the Waldo Mine mill tailings impoundment are presented below. Included is a discussion on the simulation to quantify model input parameters, simulation times and appropriate foundation materials for areas beneath the impoundment for which no data exist. Additionally, a series of one- and two-dimensional simulations were performed to determine how well UNSAT2 reproduced observed moisture content profiles along vertical transects. The simulation results are compared against in-situ measurements made with a neutron probe. This comparison is the only method available by which to validate the model.

Two different cases of two-dimensional simulations along the modeling cross-sections were made. The first case without ponding was designed to estimate moisture content and total head profiles along the cross-section as existed in the Spring of 1986 prior to the onset of heavy rains. The second case simulates the effect of extreme ponding in the interior of the impoundment on moisture content and total hydraulic head profiles. In each case tailings material was defined as 1) homogeneous and isotropic, 2) homogeneous and anisotropic and 3) same as in 2) but with the southern edge changed from an evaporation to impermeable boundary. The results of numerical simulation, using boundary conditions determined from in-situ moisture content measurements, represent hydraulic conditions within the impoundment on the date that the in-situ measurements were made. They do not necessarily represent true equilibrium conditions.

Foundation Material

Hydraulic parameters for the foundation material beneath the transition zone were estimated because the native material could not be characterized from the field sampling program. Only two samples of the foundation material were obtained because of difficulties encountered during sampling, as described in the Methods section. The two usable samples that were obtained included a complete sample from V47 at a depth of 425 cm and a partial sample from V11 at a depth of 434 cm. The hydraulic conductivities measured for these two samples differed substantially; 10^{-7} cm/sec was measured for the V47 sample and 10^{-3} cm/sec was measured for the V11 sample. No soil sample was obtained for the transition zone, vertical transect V10, which lies in between the zones for which soil samples were obtained. To determine which of the two samples best represented the foundation material beneath the transition zone, two one-dimensional simulations were conducted. Hydraulic properties of the tailings material for the one-dimensional simulations were taken from the V10, while using the hydraulic properties for the foundation material from either V47 or V11. The results of the these two simulations were compared to in-situ water contents as measured by the neutron probe (figure 36). An appropriate prescribed pressure head for calculation of the lower boundary condition in the two simulations was determined using the in-situ theta of the V10 soil and the θ-ψ relationship developed for the foundation material beneath V47 and V11. The upper graph illustrates the results using the



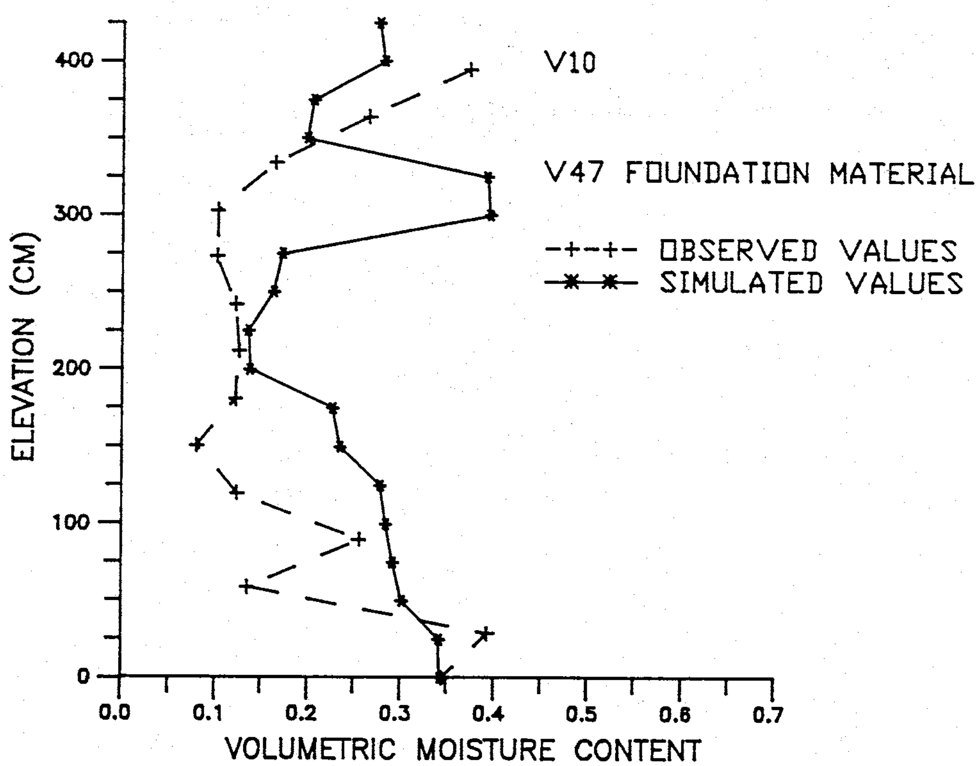
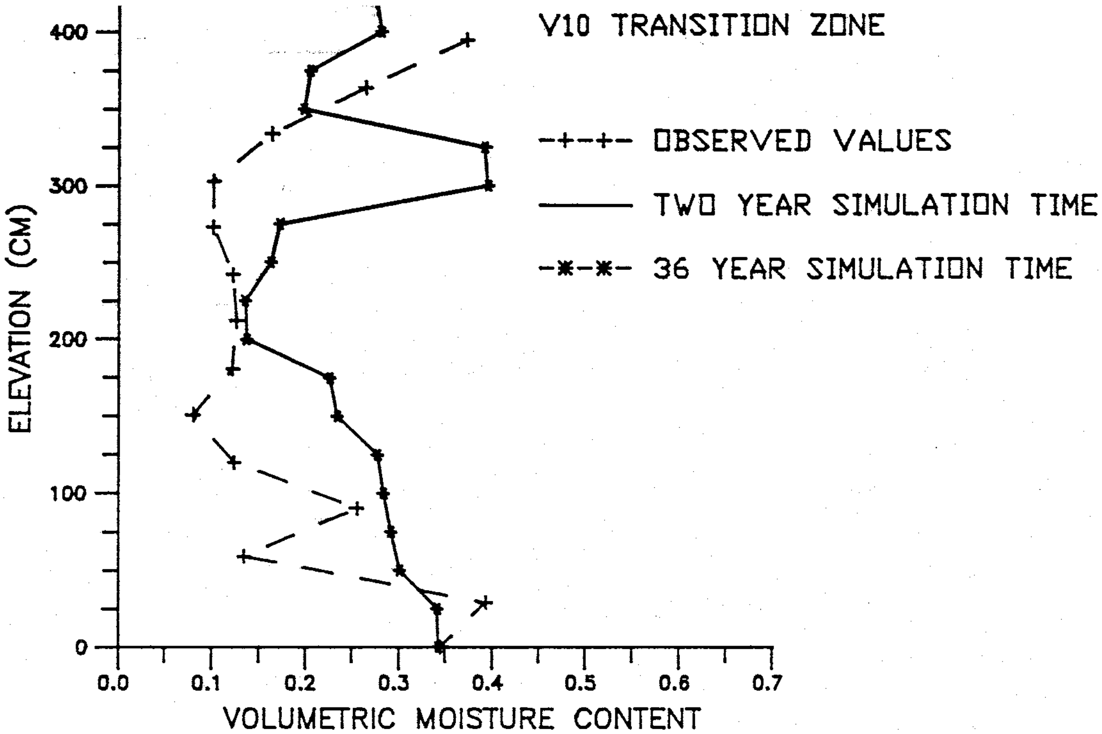


Fig. 36. Comparison of the Effect of Foundation Material on Moisture Content Profiles

V11 soil sample, and results based on the foundation material beneath V47 are presented in the lower graph of figure 36. The V47 soil produced a slightly dryer profile below 100 cm with predicted values closer to the observed moisture contents for V10. Based on this analysis, the numerical results appear to be insensitive to the foundation material. For these simulations, native soil found beneath the slime zone (V47) was used for the foundation material beneath the transition zone (V10).

Simulation Time

One objective in running the one-dimensional simulations was to establish total simulation time needed to reach quasi-equilibrium conditions for the boundary conditions based on the March 1986 field data, before running intensive computer-time two-dimensional simulations. Simulations were conducted for the slime zone, V47, and the transition zone V10. Variable simulation time increments of up to two years and finally out to 36 years were completed. The 36 years corresponds to the time that the impoundment has been undisturbed. Figure 37 presents percent saturation profiles for V10 and V47 transects, at two and at 36 years. After two years moisture contents stabilize in the V10 profile, but the V47 profile continues to drain. The additional drainage that occurs between two and 36 years is small. However, the additional cost in CPU time to achieve the additional increment of drainage for a full two-dimensional model would not be small. Therefore, based on simulation results of V10 which is located between the extremely dry zone (V11) and the wet slime zone (V47), a



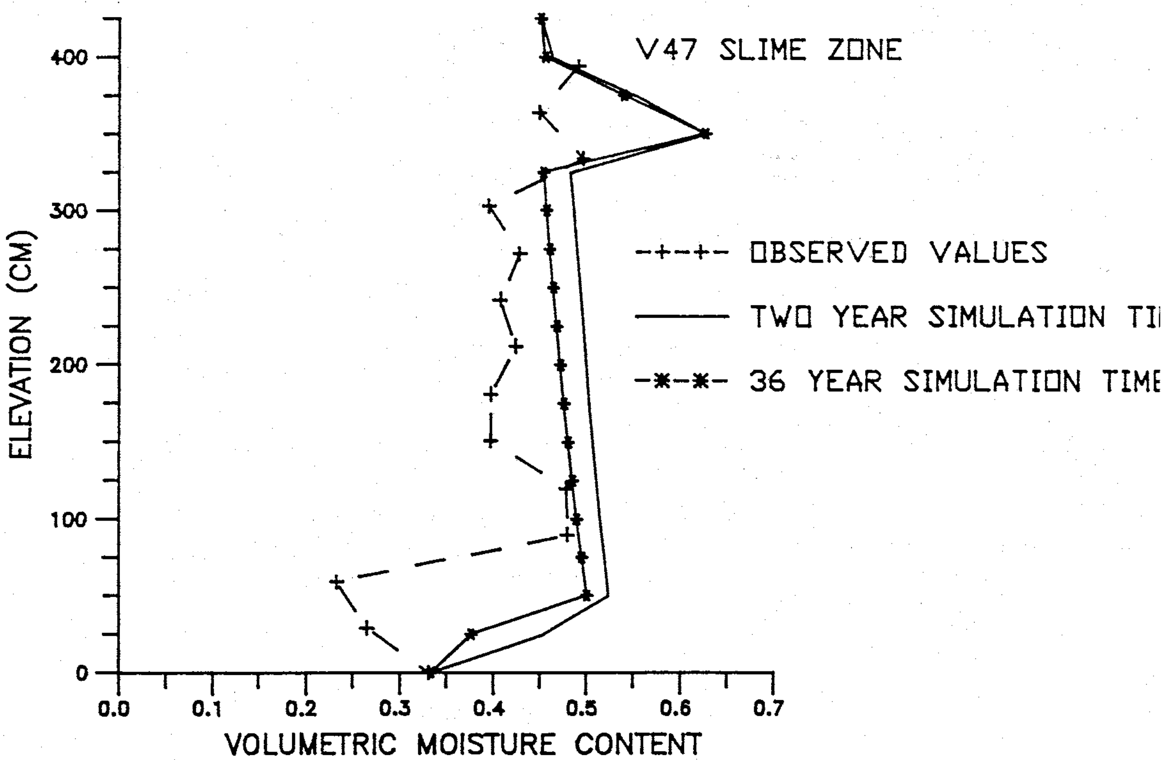


Fig. 37. Comparison of the Effect of Simulation Time

on Moisture Content Profiles

simulation time of three years was used for the draining period of the simulations.

Numerical Simulation of Moisture Content Along Vertical Transects

Figure 38 illustrates the capability of UNSAT2 to reproduce moisture profiles in various areas of the impoundment using hydraulic parameters determined along the vertical transects and the use of figure 33 to describe the spatial relationship of hydraulic properties of the tailings impoundment. One- and two-dimensional simulation results are plotted against in-situ moisture content data for each vertical transect. In the dry areas of the impoundment, the transition and sand zones, UNSAT2 predicts more moist conditions than measured in-situ. As discussed above, the neutron probe readings in areas where the moisture content exceeds 0.35 cm^3/cm^3 may be in error, with measured moisture contents lower than actual in-situ values. The accuracy of the UNSAT2 results in the moist interior of the impoundment is difficult to evaluate because of the problems with the neutron probe measurements in the slime zone.

Agreement between one- and two-dimensional simulations is best in the slime zone (V47) and the dam area (V11), two sections of the impoundments that are fairly homogeneous (Johnson, 1987). Johnson showed that all hydraulic properties determined for the V47 transect exhibited the smallest standard deviation about the mean. In the absence of heterogeneity in the hydraulic properties the results of the two-dimensional simulations are expected to resemble the one-dimensional simulations.

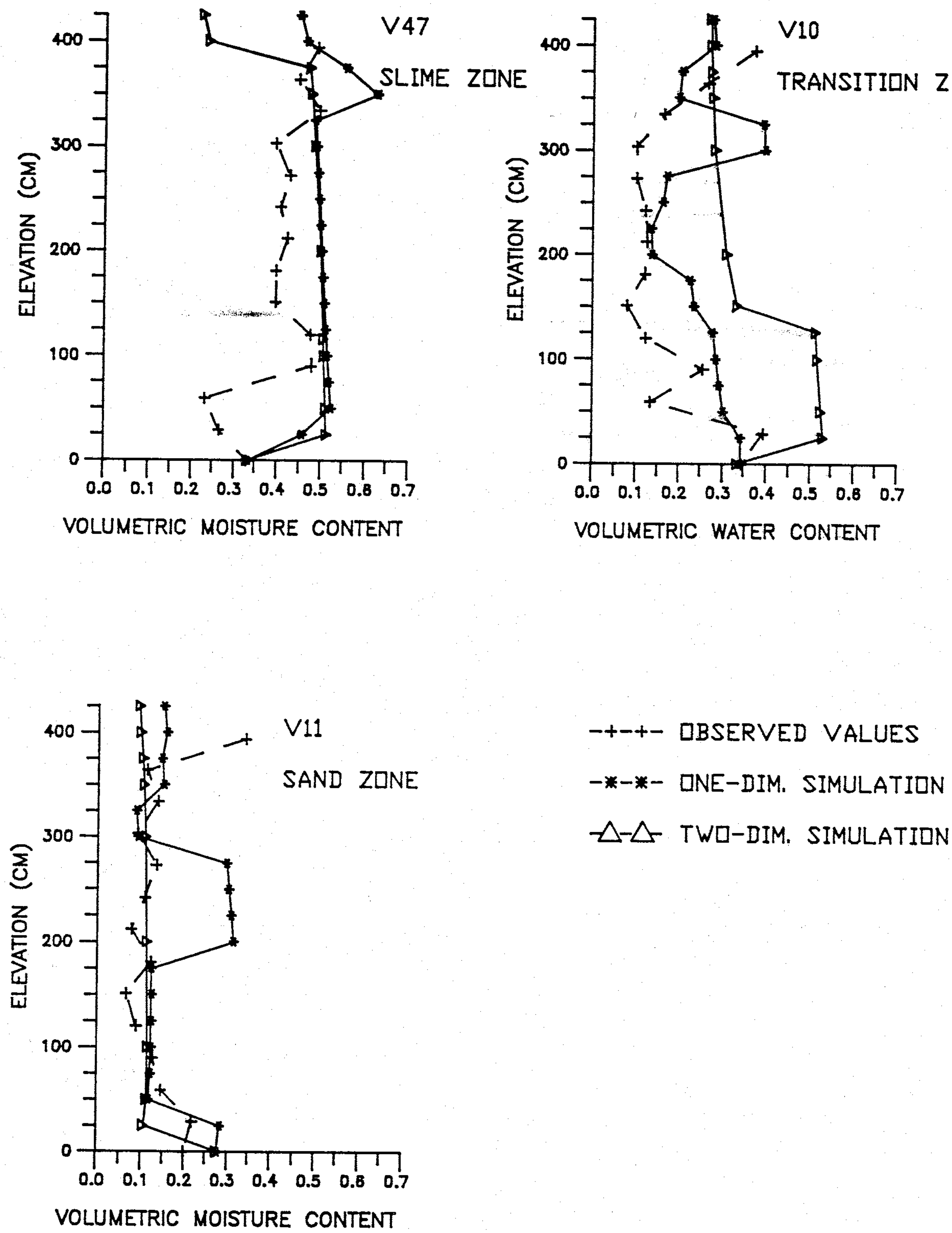


Fig. 38. Comparison of Moisture Content Along Vertical Transects

Although not as homogeneous as the slime zone, sandy material along the perimeter of the impoundment remains dry, near θ_r , approximately 0.10 cm^3/cm^3 (Appendix A). Output from van Genuchten's (1978) model indicates that decreases in moisture content above 15.0 bars are slight for perimeter material. Therefore, $\theta_{15.0} \approx \theta_r$ is a reasonable assumption. The homogenous nature of material used to establish hydraulic parameters also influences the similarity of results of the one- and two-dimensional simulations for V11. Most samples taken from V11 which were used in the simulations have similar values for porosity and θ_r. The moisture retention curves indicate that the sandy material drains quickly at low suction. The hydraulic characteristics of the material and boundary conditions used in the simulations produce moisture contents near θ_r, similar to field values. In this type of hydraulic setting and with very homogeneous material, choice of a representative set of hydraulic parameters for the regression model is shown not to be critical as long as θ_r is accurately represented.

For the V10 profile in figure 38, there is poor agreement of results between one- and two-dimensional simulations as well as with the observed values. V10 is located in the most heterogeneous area of the impoundment, as observed during trenching operations when alternating layers of wet and dry material were clearly evident. This heterogeneity affects the scale relationship between the sample size used to hydraulically characterize the vertical profile and the neutron probe measurements made in the field. Tailings samples used to generate θ-ψ relationships and other hydraulic parameters were 5.5 cm in diameter and 3 cm in height. These parameters from the point samples were then used in the one-dimensional simulations to represent 50 cm thick layers. However, the neutron probe measures moisture over a given volume of porous material (approximately 15-30 cm) that varies as a function of moisture content. Thus, the observed moisture contents in figure 38 represent average values in a spatially variable environment. The heterogeneity of the profile and its effect on the resolution of the scale problem between sample size and neutron probe measurements may be the primary causes for disagreement between observed and simulated theta values. Additionally, in the two-dimensional simulations the use of discrete zones yields inaccurate results in such a spatially variable area of the impoundment.

Discrepancies between the one- and two-dimensional simulations for V10 is due to the choice of hydraulic parameters representing zone 3. Sample statistics (Johnson, 1987) indicate that the sample chosen to represent zone 3 is more intermediate in hydraulic properties between V47 and V11 than the other available samples. Although both borings V6 and V10 lie entirely within the designated 10^{-5} cm/sec hydraulic conductivity zone, the material chosen may not accurately represent the V10 transect.

In all three graphs of figure 38, the effect of using hydraulic properties obtained from a point sample to represent a larger(50 cm or more) layer in the one dimensional models is evident as abrupt changes in moisture contents. Abrupt increases in moisture contents correspond to the presence of fine-grained, lower permeable layers. The actual effect that these layers have on moisture retention may be exaggerated in model results. Variables which are not considered in the one-dimensional simulations include true layer thickness, aerial extent of layers and lateral distribution of moisture.

The accuracy of model predictions can be severely effected when layered heterogeneities with such sharply contrasting hydraulic properties are not included in the model. In figure 38, Transect V47, a large discrepancy exists between observed and simulated moisture content values below 86 cm. Neutron probe readings show a large decrease in moisture content which delineates the interface between layers 2 and 1 located in vertical transect V47 samples. Hydraulic conductivities at the base of zone 2 are 10^{-7} cm/sec and in layer 1 range from 10^{-5} to 10^{-4} cm/sec. Complete sets of hydraulic parameters do not exist for layer 1 in the area of V47. Therefore predictions for the one-dimensional simulations are expected to be less accurate in this area. These results illustrate the need to accurately describe layered heterogeneities in a numerical model in order to assess seepage flow.

Results from the two-dimensional simulations in the area of V47 (figure 38) show a large discrepancy in moisture content in the upper 50 cm region as compared to the values measured and from one-dimensional simulations. The poor predictions are the result of using tailings material with a saturated hydraulic conductivity value consistent with Johnson's regression model (Johnson, 1987). The hydraulic properties of the material used in zone 3 in the two-dimensional simulation do not match the hydraulic properties of the tailings material. The regression model predicts the presence of a material with a hydraulic conductivity of 10^{-5} cm/sec over the slime zone instead of the actual measured hydraulic conductivity of 10^{-7} cm/sec. Along vertical transects V11 and

V10 model predictions above 375 centimeters do appear to be reliable. In these two cases the regression model predicts hydraulic properties similar to those measured in field samples.

Two-Dimensional Profiles

Results of two-dimensional simulations are presented in this section. For conditions before and after ponding three different scenarios are evaluated. Material within each zone is defined for the three scenarios as 1) homogeneous and isotropic, 2) homogeneous and anisotropic (table 3) and c) same conditions as in 2) but with the southern edge defined as impermeable. The results are presented as contours of total hydraulic head and saturation percentages. All plots presenting the results are true-to-scale to prevent distortion of the contours.

Several general observations can be made from the plots in figures 39 through 42. Although located in a semi-arid climatic zone, the Waldo Mine mill tailings impoundment retains a significant amount of moisture. The model predicts that approximately three-fourths of the impoundment is at a saturation level greater than 60 percent. The slime zone is predicted to be at a 90 percent or greater saturation level. The percent saturation profiles are consistent with field observations made during trench and sampling operations. The anisotropy ratio used in this work had little effect on the hydraulic head and moisture content distributions which is consistent with the findings of Kealy (1970). Under the ponded case, only in the dryer areas of the impoundment (less than 60 percent saturation, 40 meters south of the line of symmetry) was there any noticeable change in the position of the saturation level