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 incorporating the spatial variability of mill tailings impoundments' hydraulic properties into a numerical model of seepage. An extensive data base was generated to characterize the spatial variability of an abandoned lead-zinc mill tailings impoundment in South Central New Mexico. The data base was developed through laboratory analysis of tailings samples obtained with 60 cm thin wall samplers, and in-situ moisture measurements made with a neutron probe. Parameters measured include saturated hydraulic conductivity, K_{sat}, moisture content-positive pressure head relationships, θ-ψ, porosity, n, particle size distribution and in-situ volumetric moisture contents. Difficulties we encountered during sampling of the slime zone and foundation material Neutron probe calibration problems encountered prevented reliable measurements in moist (θ > 0.35 cm^3/cm^3) areas of the impoundment.

Characterization of the spatial variability of mill tailings hydraulic properties was performed by Gary Johnson (1987). The primary input from Johnson's analysis to this work is a two-dimension regression model of saturated hydraulic conductivity along the northerly sampling transect. The regression model is used to incorporate the spatial variability of the impoundment's hydraulic properties in the numerical model.

The numerical model used to study seepage is UNSAT2 (Davis & Neuman, 1983). Steady state simulations were conducted along the vertical cross section where samples were collected to characterize the mill tailings' hydraulic properties. Boundary conditions for the simulations were based on in-situ measurements of moisture at the impoundment surface and in the foundation material prior to and after ponding of water in the spring and fall of 1986. In homogeneous areas of the impoundment, the numerical model predictions of water content agree with observed values. In heterogeneous zones, numerical results are inconsistent with observed data. Results of the numerical simulation also indicate that the interior of the impoundment remains at great than 90 percent saturation, that movement of moisture is predominately downward except near the southern edge, and that an extended period of ponding produces saturated flow of limited extent immediately below the pond.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td></td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>1</td>
</tr>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>1</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>vii</td>
</tr>
<tr>
<td>I.  INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td>II. DESCRIPTION OF FIELD SITE</td>
<td></td>
</tr>
<tr>
<td>Geology</td>
<td></td>
</tr>
<tr>
<td>Hydrogeology</td>
<td></td>
</tr>
<tr>
<td>Soils</td>
<td></td>
</tr>
<tr>
<td>Description of Tailings Impoundment</td>
<td></td>
</tr>
<tr>
<td>III. TAILINGS CHARACTERIZATION</td>
<td></td>
</tr>
<tr>
<td>Heterogeneity</td>
<td>1</td>
</tr>
<tr>
<td>Origins of Spatial Variability of Mill Tailings</td>
<td>1</td>
</tr>
<tr>
<td>Hydraulic Properties</td>
<td></td>
</tr>
<tr>
<td>Preliminary Field Work</td>
<td>2</td>
</tr>
<tr>
<td>Base Map</td>
<td>2</td>
</tr>
<tr>
<td>Locations of Sampling Transects and Neutron Access Tube</td>
<td>2</td>
</tr>
<tr>
<td>Collection of Samples</td>
<td>2</td>
</tr>
<tr>
<td>Sampling Method</td>
<td>2</td>
</tr>
<tr>
<td>Sampling Problems</td>
<td>2</td>
</tr>
<tr>
<td>In-Situ Moisture Measurements</td>
<td>2</td>
</tr>
<tr>
<td>Installation of Access Tubes</td>
<td>2</td>
</tr>
<tr>
<td>Neutron Probe Calibration</td>
<td>3</td>
</tr>
<tr>
<td>Sources of Calibration Error</td>
<td>3</td>
</tr>
<tr>
<td>Laboratory Analysis</td>
<td>4</td>
</tr>
<tr>
<td>Saturated Hydraulic Conductivity</td>
<td>4</td>
</tr>
<tr>
<td>Method</td>
<td>4</td>
</tr>
<tr>
<td>Calculations</td>
<td>4</td>
</tr>
<tr>
<td>Sources of Error</td>
<td>4</td>
</tr>
<tr>
<td>Sample Removal from Shelby Tubes</td>
<td>5</td>
</tr>
<tr>
<td>Unsaturated Hydraulic Conductivity</td>
<td>5</td>
</tr>
<tr>
<td>Method</td>
<td>5</td>
</tr>
<tr>
<td>Sources of Error</td>
<td>5</td>
</tr>
<tr>
<td>Moisture Retention Relationships</td>
<td>5</td>
</tr>
<tr>
<td>Method</td>
<td>6</td>
</tr>
<tr>
<td>Sources of Error</td>
<td>6</td>
</tr>
<tr>
<td>Porosity</td>
<td>6</td>
</tr>
<tr>
<td>Particle Size Analysis</td>
<td>6</td>
</tr>
<tr>
<td>IV. NUMERICAL SIMULATIONS</td>
<td>6</td>
</tr>
<tr>
<td>Review of Numerical Simulation of Seepage in Tailings</td>
<td>7</td>
</tr>
<tr>
<td>Capability of UNSAT2</td>
<td>7</td>
</tr>
<tr>
<td>Model Verification</td>
<td>7</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS--Continued

Problem Definition ................................................................. 7
Results and Discussion ............................................................. 8
Method ....................................................................................... 8
   Assumptions and Limitations .................................................... 8
   Characterization of Spacial Variability ...................................... 8
   Boundary Conditions ............................................................... 8
   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 ............................................................... 12

APPENDIX B ............................................................................. 14
   Program to Calculate Saturated Hydraulic Conductivity from Permeameter Data ............................................. 14
   Example of Program Output ..................................................... 14
   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 $\theta$-$\phi$ Data ................................................................. 17

APPENDIX D ............................................................................. 22
   Particle Size Analysis Data ..................................................... 22

APPENDIX E ............................................................................. 31
   Computer Code for the Solution of Philip's Equations ............... 31
   UNSAT2 Computer Code ........................................................ 31
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Locations of Mining and Processing Wastes</td>
<td>2</td>
</tr>
<tr>
<td>2.</td>
<td>Location Map</td>
<td>5</td>
</tr>
<tr>
<td>3.</td>
<td>Water Table Map of Magdalena Mountains</td>
<td>7</td>
</tr>
<tr>
<td>4.</td>
<td>Soil Survey Map of the Magdalena Area</td>
<td>8</td>
</tr>
<tr>
<td>5.</td>
<td>Eastern View Across the Waldo Mine Mill Tailings Impoundment</td>
<td>10</td>
</tr>
<tr>
<td>6.</td>
<td>Cross Section of Tailings Impoundment Along N Trending Transect Line</td>
<td>12</td>
</tr>
<tr>
<td>7.</td>
<td>Schematic of Upstream Method of Tailings Dam Construction</td>
<td>17</td>
</tr>
<tr>
<td>8.</td>
<td>Least Squares Regression of Saturated Hydraulic Conductivity</td>
<td>18</td>
</tr>
<tr>
<td>9.</td>
<td>Base Map of Tailings Impoundment</td>
<td>22</td>
</tr>
<tr>
<td>10.</td>
<td>Location of Sampling Transects and Neutron Access Tubes</td>
<td>23</td>
</tr>
<tr>
<td>11.</td>
<td>Location of Neutron Access Tubes Along Sampling Transect Cross Section</td>
<td>30</td>
</tr>
<tr>
<td>12.</td>
<td>Neutron Probe Calibration Curve</td>
<td>34</td>
</tr>
<tr>
<td>13.</td>
<td>Aerial Extent of Ponding on Layer Two</td>
<td>35</td>
</tr>
<tr>
<td>14.</td>
<td>Shelby Tube Permeameter</td>
<td>43</td>
</tr>
<tr>
<td>15.</td>
<td>Schematic Diagram of Shelby Tube Permeameter</td>
<td>44</td>
</tr>
<tr>
<td>16.</td>
<td>Position of Samples for $K_s$ Measurements Along Horizontal Sampling Transects</td>
<td>47</td>
</tr>
<tr>
<td>17.</td>
<td>Position of Samples for $K_s$ Measurements Along Vertical Sampling Transects</td>
<td>48</td>
</tr>
<tr>
<td>18.</td>
<td>Fluctuation in Saturated Hydraulic Conductivity for a Tailings Sample</td>
<td>50</td>
</tr>
<tr>
<td>19.</td>
<td>Permeameter Apparatus for Quantifying Boundary Flow</td>
<td>52</td>
</tr>
<tr>
<td>Illustration Description</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>20. Effect of Texture on Hydraulic Conductivity with Changing Negative Pressure Head</td>
<td>.54</td>
<td></td>
</tr>
<tr>
<td>21. Comparison of van Genuchten Two and Three Parameter Model Fit to Observed θ-ψ Data</td>
<td>.57</td>
<td></td>
</tr>
<tr>
<td>22. Effect of Texture on Moisture Retention in Tailings Material</td>
<td>.60</td>
<td></td>
</tr>
<tr>
<td>23. Graphical Representation of Hysteresis</td>
<td>.61</td>
<td></td>
</tr>
<tr>
<td>24. Hanging-Water-Column Apparatus</td>
<td>.63</td>
<td></td>
</tr>
<tr>
<td>25. Schematic of Pressure Plate Apparatus</td>
<td>.65</td>
<td></td>
</tr>
<tr>
<td>26. Position of Free Surface for Different Profile Configurations</td>
<td>.71</td>
<td></td>
</tr>
<tr>
<td>27. Finite Element Grid and Column Used in Test Case</td>
<td>.76</td>
<td></td>
</tr>
<tr>
<td>28. Position of Wetting Front over Time</td>
<td>.79</td>
<td></td>
</tr>
<tr>
<td>29. Change in Infiltration over Time</td>
<td>.80</td>
<td></td>
</tr>
<tr>
<td>30. Cumulative Inflow Depth over Time</td>
<td>.81</td>
<td></td>
</tr>
<tr>
<td>31. Impoundment with Neutron Probe and Sampling Locations, Plane of Symmetry</td>
<td>.86</td>
<td></td>
</tr>
<tr>
<td>32. Cross Section of Impoundment Along North Trending Transect with Neutron Probe Tube Locations</td>
<td>.87</td>
<td></td>
</tr>
<tr>
<td>33. Contoured Cross Section of the Two-Dimensional Regression Fit to the Log K Data</td>
<td>.89</td>
<td></td>
</tr>
<tr>
<td>34. True-to-Scale Cross Section Along Sampling Transect</td>
<td>.91</td>
<td></td>
</tr>
<tr>
<td>35. Finite Element Grid for Two-Dimensional Simulations</td>
<td>.98</td>
<td></td>
</tr>
<tr>
<td>36. Comparison of the Effect of Foundation Material on Moisture Content Profiles</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>37. Comparison of the Effect of Simulation Time on Moisture Content Profiles</td>
<td>104</td>
<td></td>
</tr>
<tr>
<td>38. Simulation of Moisture Contents Along Vertical Transects</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>39. Hydraulic Head Distribution After Initial Drainage</td>
<td>111</td>
<td></td>
</tr>
<tr>
<td>40. Hydraulic Head Distribution After Ponding</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>Illustration Description</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>41. Percent Saturation After Initial Drainage</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>42. Percent Saturation After Ponding</td>
<td>114</td>
<td></td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table
1. Results of Analysis on Dry Tailings Samples
2. Results of Chemical Analysis on Shelby Tube Leachate and Impoundment Pond Water
3. Hydraulic Parameters for Two-Dimensional Simulations
4. Hydraulic Parameters for One-Dimensional Simulations
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I. INTRODUCTION

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

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

One means of quantifying the seepage is the use of numerical models to elucidate flow dynamics through an impoundment. Although numerical models can provide useful flow analysis, accuracy of the results is 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 tailings
impoundment;

2) Characterize the spatial variability of the impor
t 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 &
retention.

The first phase of this study was conducted by myself and Gary
Johnson over a two year period (September 1984 to October, 1986). The
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 mill tailings impoundment located in South Central New Mexico, 2.4 kilometers south of the town of Magdalena (figure 2). The impoundment, owned by the American Smelting and Refining Company (ASARCO), is situated on the west side of the Magdalena mountains at an elevation of 2,088 meters above mean sea level. Vegetation in the surrounding area is juniper and pinon pine (Summers et al., 1972), although the tailings are completely devoid 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 mountain range in the Basin and Range physiographic province (Blakestad, 1978; Krewel, 1974). The area has undergone extensive uplift, erosion, and 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 Mississippian and Pennsylvanian limestone and Permian age sandstones. The sedimentary rocks are overlain by a thick sequence of silicic Tertiary volcanoclastic sediments, lavas and ash-flows. Quaternary deposits in the area of the field site include landslide deposits, alluvium, and talus.
Mineralization occurred by hydrothermal alteration, primarily alteration faults cutting limestones; the faults acted as conduits for hydrothermal fluids (Blakestad, 1978). The solutions formed limestone replacement deposits adjacent to the fault zones. Mineralization was also associated with dikes and sills. Metals mined in the area include zinc, lead, copper, gold, silver, manganese, tungsten, barium and vanadium (File, 1965).

**Hydrogeology**

Information regarding the hydrogeology of the area is limited and dated. Wells within two kilometers of the impoundment were completed in alluvium and volcanic sediments (Summers et al., 1972). Yields ranged from 0.08 to 0.20 m³/min. The two wells on ASARCO's property adjacent to the impoundment have collapsed and have been abandoned. The general direction of ground water flow beneath the impoundment is northwest towards Magdalena. Figure 3 illustrates the approximate configuration of the water table in the vicinity of the impoundment. Recent information from a well 0.8 km up gradient from the impoundment indicates that the depth to ground water is at 79-91 meters (Morgan, 1986). Based on available data, depth to the water table beneath the impoundment is estimated to be 80 meters.

**Soils**

The tailings impoundment overlays two soil mapping units, the Manzano silt loam (#424) and Lupdun-Datil association (#460) (figure 4 (Soil Survey of Socorro County, U.S. Dept. of Agriculture, Soil...
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 siloam is deep (> 152.0 centimeters), with moderately low permeability (0.5-1.5 centimeters per hour), and is formed in recent alluvium. Soils which make up the Lapdun-Datil association are deep (> 152 centimeters), and have moderate permeabilities (1.5-5.0 cm/hour). Both soils are formed in alluvium derived from volcanic rock. The location of the contact between the mapping units is approximate and has not been verified in the field.

**Description of Tailings Impoundment**

The tailings impoundment (figure 5) consists of a slag pile generated from a smelter and three distinct layers. These layers 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 well documented. The mill which produced the tailings was erected in 1940 and was operated intermittently until its closing and subsequent dismantling in 1950. The mill, a 181 metric ton/day capacity flotation plant, primarily processed zinc-lead sulfides and lead carbonates (Lus 1947). Peak production years centered around World War I and World War II. The depositional history of the pile was deduced from a series of U.S. Forest Service aerial photos, first-hand accounts of former mill employees and physical examinations of the site.

The first layer was deposited between the years 1913 (when the mill was constructed) and 1943. The lateral boundaries of this layer are most poorly contained of the three layers. Crude retaining walls were 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 topography. The second layer (which partially overlies the first layer, figure 6) was deposited in approximately 1943, with the third layer (which overlies a portion of the first and second layers) deposited sometime prior to the closing of the mill in 1950.

The upstream construction method was most likely used to construct the impoundment. Remains at the site imply that wooden retaining walls were built on the downhill sides of layer two and three to support the dikes. Tailings were delivered to the pile in elevated flumes which almost completely surrounded the pile. Chutes were spaced along the flumes to direct the flow of material to different areas. Excess water from the tailings was collected in central drains, pumped back to the 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 the direction of measurement at a point within a porous media. If hydraulic conductivity is independent of position within a porous media, then the media is homogenous, otherwise it is heterogeneous (Freeze and Cherry 1979; Bear, 1972). There are many types of heterogeneous configurations. Two types common to tailings impoundments are layers and trending heterogeneities, both of which can result from sedimentary depositional processes. Layered heterogeneity results from the 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 deltaic and alluvial fan deposits result from sedimentation of detrital material with gradual changes in fluid velocity. A trending heterogeneity can be described as a trend in the mean value of the probability distribution (Freeze and Cherry 1979).

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

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

Poulavassilis and Psychoyou (1985) studied the effect of layering in a soil profile on evaporation and reported findings similar to Martin et al. (1980). At the boundary between different materials, the soil water pressure head may exhibit a discontinuity. The characteristics of the break were a function of the type of layering and prevailing pressure head. The sequence of layering and pressure head at the boundary can have a significant impact on the evaporation rate. For water table at a constant depth, the evaporation rate attained a maximum value where the soil profile included a coarse layer underlying a finer layer. The evaporation rate was minimized with the opposite layering sequence.
Zaslavsky and Sinai (1981) found that in a layered media horizontal hydraulic conductivity, $K_h$, can be several times larger than vertical hydraulic conductivity, $K_v$. Kealy (1970) determined an average $K_h/K_v$ ratio of five to one in lead-zinc tailings. Laboratory studies of unsaturated flow through layered material by Heermann (1985) have also demonstrated this phenomenon.

The importance of incorporating the heterogeneous nature of porous media into a mathematical model of seepage flow was stressed by Siegel and Stephens (1980). Siegel and Stephens compared an analytical solution, developed by McWhorter and Nelson (1979), which predicts the advance of a wetting front beneath a lined pond, to a numerical solution. The analytical solution, which is for one-dimensional homogenous isotropic conditions, gave similar results to the numerical solution under isotropic conditions. However under anisotropic conditions the analytical solution over-estimated the advance of the 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 of the material being deposited are primary factors in determining whether a porous media will be homogenous or heterogeneous, isotropic or anisotropic. Tailings, a waste product of the mining and smelting industry, are finely ground rock (Rutherford et al., 1982) and are heterogeneous mixture ranging from sand to clay size particles. They are generally transported to a disposal site hydraulically at concentration of forty to fifty percent by weight (Klohn, 1979). The
watery slurries are contained in a tailings pond, or impoundment which allows solids to settle and water to be recycled. Deposition of tailings in an impoundment can be compared to depositional processes that occur in deltas.

Tailings impoundments are constructed using a variety of techniques. Upstream construction (figure 7) is the oldest and cheapest method (Klohn, 1979). From available evidence this method appears to have been used to construct layers two and three at the Waldo Mine tailings impoundment. In the upstream method a starter dike or dam is built to form the perimeter of the impoundment. Local material or the coarse fraction of the tailings are used to construct the dikes. The tailings slurry is discharged along the dike and flows towards the interior of the impoundment. As the fluid velocity decreases, material is sorted by size and density, with the smallest, lightest material deposited furthest from the discharge point. This type of deposition process, common to tailings disposal, combined with the particle size 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 impoundment samples taken at a depth of 192 centimeters.

Impoundments vary in the degree of uniformity, depending upon the mining and milling operations. The characteristics of ore produced from a mine and the volume rate of discharge from the mill house, can be quite variable during the lifetime of an operation. These variables in a mining and milling operation produce different degrees of layer heterogeneity unique to each impoundment. An impoundment may be uniform
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 mill tailings that is not considered by this work but may be important is the effect of chemical reactions on hydraulic properties such as permeability. In mine spoils that contain large amounts of pyrite, weathering (oxidation) of metal sulfides produces a low pH (2.3) (Burton et al., 1978). This leads to low infiltration rates into mine spoil with associated precipitation of salts near the zone of oxidation at the surface of the mine spoils (Burton et al., 1978). Pyrite (iron sulfide) occurs in ore taken from the Waldo Mine, from which the tailings were generated. Oxidation of the pyrite leads to acidification of water ponded on the surface of layer two. A pH of 2.25 was measured for pond precipitation in the interior area of layer two during this field 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 brought unweathered tailings material to the surface. Spatially variable accumulation of white precipitates and blistering of the top few millimeters of the tailings surface is evident following a rain or snow event. The chemical composition of the precipitates and mechanisms of blister formation was not studied. Other reactions occurring in the Waldo Mine tailings below the surface that may affect hydraulic 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 the
original tailings material both temporally and spatially. The influence of geochemistry on hydraulic properties should be characterized further.

One of the primary objectives of this research project, as outlined in the original proposal to the U.S. Bureau of Mines Generic Research Center, is the generation of an extensive data base of hydraulic properties for a mill tailings impoundment. The data base is to be used to characterize the spatial variability of the hydraulic properties of the impoundment. Decisions on which hydraulic parameters were to be measured, how to obtain the necessary samples, and how to analyze the 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 slimes.

   - 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/laboratory methods to use in tailings characterization refer to Larson (1984).
Preliminary Field Work

Base Map

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

Locations of Sampling Transects and Neutron Access Tube

Sampling of tailings material occurred along eight transects: two horizontal transects and six vertical transects (figure 10). The specific details of sampling and neutron logging methods are described 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 of tailings deposition which was similar to methods used today. Layer two is approximately two hectares in size, with a total surface relief of 1.8 meters. Thickness of the layer varies from 1.5 meters next to layer three to 7.6 meters at the northwest edge.

The two horizontal transects were in the same vertical plane which trends N 60° W, but each line of sampling was at a different depth. Placement of the horizontal transects was based on the interpretation of the impoundment structure. Transects were laid out perpendicular to th
Fig. 9. Base Map of Tailings Impoundment
plane of symmetry that divides the second layer into physically similar halves and parallel to the primary direction of tailings discharge. Across the upper horizontal transect 24 vertical samples were taken between the 15 to 69 cm interval. Sixty-nine vertical samples were taken along the lower transect over the 152 to 205 cm depth.

The vertical transects were located adjacent to the horizontal transects. Vertical transects V47 and V75 were located east of the horizontal transect, (figure 10). Both were located in the tailings slime zone. Samples from this zone required use of a backhoe to obtain complete recovery. Placing V47 and V75 on the west side of the horizontal transects would have caused significant disturbance near neutron tubes 8, 9, and 10 due to the use of a backhoe to retrieve samples. The remaining vertical transects V6, V7, V10, and V11 were all located two meters east of neutron tubes 6, 7, 10, and 11, respectively, along a line trending N 7.5° W (figure 10). With few exceptions, each vertical transect consisted of a continuous set of vertical samples from the impoundment surface to 100 centimeters into the underlying native soil.

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

**Collection of Samples**

**Sampling Method**

Thin wall samplers (shelby tubes) pushed with a Mobile B-30 drill rig were used to extract tailings samples for laboratory analysis. Different sampling equipment, such as 100 cm³ ring samplers, were evaluated in the field. However, thickness of the impoundment and the presence of hardpans made them impractical. The thin-wall samplers used (model DR-164C, Soil Test, Evanston, IL) were 60.9 cm long, 7.6 cm diameter (O.D.), and were made of galvanized steel. Galvanized steel tubes were chosen over standard steel units because of their corrosive nature of the tailings. The inside of each tube was sprayed with a clear lacquer before use to further inhibit corrosion.

A coupling device (model DR-164W, Soil Test, Evanston, IL) was used to attach each tube to the extension rod. A check valve in the coupling device allowed air to escape as the tube filled with sample. As the tube was extracted the check valve would seat, creating a partial vacuum above the sample, helping to retain the sample.

Taking a sample along the horizontal transect consisted of the following steps. At the sampling point a 10.2 cm diameter auger bit was used to drill a pilot hole to within approximately 10 cm of the desired sampling depth. Following retraction of the auger a spare shelby tub was lowered into the hole to clean the sides and complete the hole to the desired depth. The spare tube was removed from the hole, and the 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 tut 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 to prevent loss of moisture and sample during transport back to the laboratory.

The procedure used in vertical sampling was similar to the outlined above for the horizontal transects. However, it was not necessary to drill and ream the hole prior to taking a sample because sampling was continuous from the surface of the impoundment into the underlying native soil (approximately 100 cm).

Sampling Problems

Several problem areas were encountered in sampling the tailings which in some instances prevented collecting a sample, or require alternate sampling technique. Sampling problems occurred in the interior portion of the pile which contained slime, along the perimeter of the impoundment where extremely hard layers were encountered, or 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 material consistently at a high moisture content. The topography of the pile 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 sufficient frictional forces between the sample and tube wall, and the vacuum created by the check valve to break the sample at the tubes cutting edge. The high moisture content of the slime increased the cohesive
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 encountered along the perimeter of the impoundment. Exact origin of these layers is not known, but one theory is that cyclical wetting and drying has resulted in dissolution and precipitation of calcium and iron deposit at specific depths. In some instances the indurated layer(s) prevented sampling with a Shelby tube. The layer(s) had to be removed by drillin before sampling could continue. Fortunately, the aerial extent of the hard pans was small, so that there are only a few gaps in sampling data.

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

**In-Situ Moisture Measurements**

Measurement of moisture content with a neutron moisture meter was the only hydraulic parameter measured in-situ. The neutron probe 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 was to determine indirectly the in-situ pressure head distribution across
the sample transect cross section to use as initial conditions for the numerical model. Pressure heads were to be determined from moisture contents measured in the six access tubes along the sampling transect and from the moisture-retention relationships (water content versus pressure head) determined from vertical transect samples. Further, the moisture content measurements along the profile were to have been statistically analyzed in the companion research effort (Johnson, 1987). Additionally, results of neutron logging in the thirteen access tubes installed in layer two were to be analyzed to clarify the effect of the impoundment's structure on three-dimensional moisture distribution and movement of moisture across the tailings-native soil interface. Results of neutron moisture measurements are included in Appendix A.

Installation of Access Tubes

Using a neutron probe usually requires the installation of access tubes, although use of uncased holes in well indurated material has been reported by Hammermeister et al (1985). Access tubes installed in the impoundment penetrated the entire thickness of the tailings and extended 50-100 cm into the underlying native soil (figure 11). Five cm (0.2 in), 4.9 cm (I.D.), aluminum irrigation pipe was used as access tubing. The bottom of each tube was sealed with a #10 rubber stopper and nut-bolt-washer assembly (Schwankl, 1986). A hole was cored through each rubber stopper, and the bolt was placed through the hole. A large washer was placed on each end of the bolt and a nut threaded onto the bolt. This stopper assembly was recessed into the access tube approximately 1.3 centimeters. Tightening the bolt compressed the stopper to form a water-tight seal. The remaining space between the
Fig. 11. Location of Neutron Access Tubes Along Sampling Transect Cross Section
stopper and end of the tube was filled with silicone to insure the integrity of the seal and protect the nut-bolt assembly from corrosion. To prevent vandalism, the tops of the tubes were installed five centimeters below grade. Prior to burial, a #10 rubber stopper was installed into the top of each tube, and a three inch PVC slip cap was placed over each tube.

Normally short, 1.5 to 3.0 meter, lengths of access tube were installed in soils or unconsolidated sediments using a five centimeter diameter hand auger to form a tight fit between the outside of the tube 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 drill stem consisting of 1.5 meter lengths of five centimeter diameter auger drill. The manner in which the lengths were joined produced a nonrigid stem which wandered during drilling, producing a hole 5.7 to 6.0 centimeters in diameter. Following completion of the hole and setting the tube in place, dry surface tailings material was used to backfill the annular space between the access tube and hole. Only with approximately 0.3 meter of the surface was it possible to directly compact the backfill.

Neutron Probe Calibration

Although each neutron probe is factory calibrated, usually calibration curve for each application must be produced. Initial sampling and neutron probe readings were made for calibration during tube installation on March 19, 1986. In an effort to generate calibration curve in the high moisture range (θ > 0.35), additions
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-held sampling equipment limited sampling depths to less than three meters. An access tube was installed following completion of each hole and readings were taken at depths corresponding to sample locations. The undisturbed samples were immediately weighed in the field to determine wet mass, sealed to prevent moisture loss and returned to the laboratory. Samples were reweighed to insure accuracy of the field scale and placed in an oven for 24 hours at 105° C. After removal from the oven, samples were weighed to determine the dry mass. The volumetric moisture content of a sample was determined using the following equation:

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

(1)

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

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

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

The correlation coefficient for regression analysis was 0.858. However, the high correlation coefficient is deceiving; the neutron probe did not provide uniform precision throughout the entire range of soil moisture. Attempts to use the probe to measure moisture contents above 0.35 produced poor results. Although the design range of the probe is 0.0 to 0.32 cm$^3$/cm$^3$ (C.P.N., 1983), calibration of the probe at higher moisture contents should be possible (Mr. John Mancuso, Campbell Nuclear, Pacheco, CA, 1986, personal communication). Attempts to calibrate the probe to moisture contents greater than 0.35 (using 2 data sets in the $\theta > 35 \%$ range) produced a poor correlation coefficient of 0.006.

Sources of Calibration Error

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

Late May through October of 1986 was unusually wet, producing a period 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 of ponding. Under conditions of piping, high moisture contents should have been recorded not only near the surface but at depth. Examination of the logs from access tubes 5, 7, 8, 9, 13 (located within the area subject to ponding) gave no indication of piping. During this period measured increases in moisture content with depth occurred gradually, if at all. The annulus may have been a zone of enhanced permeability as result of the low bulk density of backfilled material below the compacted zone. Neutron probe measurements were taken during calibration work below the compacted zone in tubes located within the slime zone prior to the onset of ponding. Volumetric moisture content readings, $\theta$, were 0.15 to 0.20 (cm$^3$/cm$^3$) lower than values observed in corresponding calibration samples. These observations indicate movement of moisture down the annular space was not a significant error in calibrating the neutron probe in the high moisture ranges.

The backfilled annulus with a lower bulk density was also considered as a possible source of error. Maximum width of the annulus was 0.6 cm. Hammermeister (1985) reported, that the USGS working a Yucca Mountain, Nevada, achieved good calibration results, (correlation coefficient of 0.94 for laboratory calibration in the moisture content 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 cm 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 and 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):

\[ \text{FeS}_2(s) + 7/2\text{O}_2 + \text{H}_2\text{O} = \text{Fe}^{2+} + 2\text{SO}_4^{2-} + 2\text{H}^+ \]  \hspace{1cm} (3)

\[ \text{Fe}^{2+} + 1/4\text{O}_2 + \text{H}^+ = \text{Fe}^{3+} + 1/2\text{H}_2\text{O} \]  \hspace{1cm} (4)
\[
\begin{align*}
\text{Fe}^{3+} + 3\text{H}_2\text{O} & \rightarrow \text{Fe(OH)}_3(\text{s}) + 3\text{H}^+ \\
\text{FeS}_2(\text{s}) + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} & \rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 16\text{H}^+ 
\end{align*}
\]

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, \( \theta \geq 0.35 \text{ cm/cm}^3 \), 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:

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

(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:
\[ K_s = \frac{k \rho g}{\mu} \] (8)

where \( k \) is intrinsic permeability or simply the permeability \( (L^2) \). The important fluid properties are density, \( \rho \), \( (M/L^3) \) and dynamic viscosity, \( \mu \), \( (M/LT) \). 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).

**Method.** 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, CO₂ 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 desired 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° C to account for changes in hydraulic conductivity due to changes in the viscosity of water by the relationship (Klute, 1965);

$$ K_{20} = K_T (\frac{\eta_T}{\eta_{20}}) $$

where $K_T$ is conductivity at the measured temperature (cm/sec), $\eta_T$ is viscosity (cp) of water at the measured temperature and $\eta_{20}$ is the viscosity (cp) of water at 20° 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. Position 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 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, Ill.). 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, Ill.) 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/slimate 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 Quantifying 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 $K-\theta_w$ 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 Pressure Head

(Source: Hillel, 1980)
was used to estimate unsaturated hydraulic conductivities. Input requirements included parameters measured in the laboratory (moisture content at saturation, $\theta_s$, saturated hydraulic conductivity, $K_{sat}$, and residual moisture content, $\theta_r$). 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:

$$K_r(S_e) = S_e^{1/2} \left( \frac{\int_0^{S_e} \frac{dS_e}{\psi}}{\int_0^1 \frac{dS_e}{\psi}} \right)$$ \hspace{1cm} (10)

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

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

$$K_r(\psi) = \left( 1 - (\alpha \psi)^{n-1} \right)^2 \left( 1 + (\alpha \psi)^n \right)^m$$ \hspace{1cm} (11)

where $m = 1-n$, and $n$ and $\alpha$ are independent parameters determined by non linear least squares curve fitting to the observed $\theta-\psi$ 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 $\alpha$ are estimated, and $\theta_r$ is fixed at the input value of $\theta_r$.

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 $\theta - \psi$ data. Also, they concluded that a good fit to the $\theta - \psi$ 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 $\theta - \psi$ drainage data indicated that the three-parameter model produced a better fit to observed $\theta - \psi$ data (figure 21). Using the two-parameter model and a $\theta^r$ 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 $\theta - \psi$ 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 $\theta-\psi$ 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 $\theta$-$\psi$ relationships may affect the accuracy of predicted $K$-$\psi$ 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 ($\theta$), and the negative pressure head ($\psi$) 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;
\[ \theta = \frac{V_f}{V_t} \]  

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 \( \theta - \psi \) relationship would follow if a porous media were partially dried, then rewetted, or vice versa. In this work,
Fig. 22. Effect of Texture on Moisture Retention in Tailings Material

*Particle diameters are in microns.
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 $\theta - \psi$ 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:

$$n = \frac{V_f}{V_t}$$  \hspace{1cm} (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:

\[
\frac{V_{\text{lost}}}{V_t} = n
\]

(14)

where \( V_{\text{lost}} \) 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/cm³.

After samples were removed from the pressure plate and weighed, they were oven dried at 105°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 $d_{10}$, $d_{16}$, $d_{30}$, $d_{50}$, $d_{80}$, $d_{84}$. The parameters indicate the percent of material by weight which is finer than the size given. Particle size distribution parameters calculated include uniformity coefficient $(d_{80}/d_{10})$, coefficient of curvature $((d_{30})^2/(d_{10})(d_{80}))$, trask sorting coefficient $((d_{84}/d_{10})^{1/2})$, trask skewness $((d_{84}d_{16})/(d_{80})^{1/2})$, and geometric mean particle diameter $((d_{14}d_{84})^{1/2})$. 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:
\[ t \geq 0 \quad z = 0 \quad \psi = 0 \quad \theta = \theta_s \]

Bottom boundary:
\[ t \geq 0 \quad z = 63 \quad \psi = \psi_1 \quad \theta = \theta_i \]
\[ t >> 0 \quad z = 63 \quad \psi = 0 \quad \theta = \theta_s \]

Initial conditions:
\[ t = 0 \quad z > 0 \quad \psi = \psi_1 \quad \theta = \theta_i \]

The finite element grid used 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(θ) relationships over a limited moisture content range. To expand the range of K(θ) 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:

\[
I = St^{1/2} + Kt
\]  
(15)

\[
i = \frac{1}{2} St^{-1/2} + K
\]  
(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):

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

where \(\theta_s\) is the moisture content behind the wetting front (cm\(^3\)/cm\(^3\)), \(\theta_i\) is the initial 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 \(D(\theta) - \theta\) curve. The \(D(\theta) - \theta\) 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

Infiltration Rate (cm/hr)

K(sat) = 1.08 cm/hr

...Philip's Solution

UNSAT2 Model Results
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:

\[
I(t) = St^{1/2} + At \quad (18)
\]

\[
i(t) = \frac{1}{2}St^{-1/2} + A \quad (19)
\]

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, $K_r/K_v$, 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 suction.

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 rhomboidal calcite crystals ($\approx 5$ 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 $\theta_{15}$ 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
Vertical exaggeration: 8x

Log $K_s$ (cm/sec)

Vertical Exaggeration: 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 (\( \theta - \psi \)) 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
generate parameters for the zones of permeability. Only the vertical transect data contain complete data sets; horizontal transects lack both $\theta$-$\psi$ and $K_r$-$\psi$ 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

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

Node # | Zone | Negative Prescribed Pressure Head (cm) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1-11</td>
<td></td>
<td>Impermeable Boundary (line of Symmetry)</td>
</tr>
</tbody>
</table>

#### Tailings/Atmosphere Interface

<table>
<thead>
<tr>
<th>Node</th>
<th>Zone</th>
<th>Negative Pressure Head (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22-242</td>
<td>3</td>
<td>355.0</td>
</tr>
<tr>
<td>252-459</td>
<td>3, 4</td>
<td>211.0</td>
</tr>
<tr>
<td>469-638</td>
<td>4</td>
<td>15800.0</td>
</tr>
</tbody>
</table>

#### Tailings/Soil Interface

<table>
<thead>
<tr>
<th>Node</th>
<th>Zone</th>
<th>Draining Case</th>
<th>Ponded Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-419</td>
<td>5a</td>
<td>211.0</td>
<td>53.0</td>
</tr>
<tr>
<td>430-549</td>
<td>5b</td>
<td>178.0</td>
<td>63.0</td>
</tr>
<tr>
<td>559-619</td>
<td>6</td>
<td>668.0</td>
<td>168.0</td>
</tr>
</tbody>
</table>

* see Hydraulic Properties & $\theta/\psi$ 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 $\theta-\psi$ 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 $\theta-\psi$ relationships is the 51 cm sample.

Samples with developed $\theta-\psi$ 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>
<thead>
<tr>
<th>TABLE 4. Hydraulic Parameters For One-Dimensional Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VERTICAL TRANSECT V67</strong></td>
</tr>
<tr>
<td>Boundary Conditions: Lower $\psi = 211.0$ Upper $\psi = 355.0$</td>
</tr>
<tr>
<td>$\theta$ used to estimate B.C., Tube 1*: Lower $\theta = 0.331$ Upper $\theta = 0.449$</td>
</tr>
<tr>
<td>@ 426.72 cm (3/8) @ 60.96 cm (3/8)</td>
</tr>
<tr>
<td>Grid Spacing: Vertical = 25.0 cm Horizontal = 1.0 cm</td>
</tr>
<tr>
<td>Total Simulation Time: 2.0 &amp; 36 years; profile drained only</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Elevation (cm)</th>
<th>$K_\text{sat}$ (cm/sec)</th>
<th>$n\circ$</th>
<th>Sample transect position (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>375-425</td>
<td>8.33 E-07</td>
<td>0.534</td>
<td>50-53</td>
</tr>
<tr>
<td>2</td>
<td>325-375</td>
<td>3.93 E-08</td>
<td>0.628</td>
<td>103-106</td>
</tr>
<tr>
<td>3</td>
<td>25-325</td>
<td>4.21 E-06</td>
<td>0.536</td>
<td>207-210</td>
</tr>
<tr>
<td>4</td>
<td>0-25</td>
<td>5.27 E-07</td>
<td>0.491</td>
<td>426-429</td>
</tr>
</tbody>
</table>

| **VERTICAL TRANSECT V10**                                     |
| Boundary Conditions: Lower $\psi = 178.0$ (soil below V47)    |
| Upper $\psi = 126.0$ (soil below V11)                         |
| $\theta$ used to estimate B.C., Tube 10*: Lower $\theta = 0.345$ Upper $\theta = 0.265$ |
| @ 426.72 cm (3/8) @ 60.96 cm (3/8)                           |
| Grid Spacing: Vertical = 25.0 cm Horizontal = 1.0 cm           |
| Total Simulation Time: 2.0 & 36 years; profile drained only    |

<table>
<thead>
<tr>
<th>Material</th>
<th>Elevation (cm)</th>
<th>$K_\text{sat}$ (cm/sec)</th>
<th>$n\circ$</th>
<th>Sample transect position (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>375-425</td>
<td>1.73 E-04</td>
<td>0.571</td>
<td>48-51</td>
</tr>
<tr>
<td>2</td>
<td>325-375</td>
<td>3.43 E-05</td>
<td>0.375</td>
<td>99-102</td>
</tr>
<tr>
<td>3</td>
<td>275-325</td>
<td>4.66 E-06</td>
<td>0.671</td>
<td>149-152</td>
</tr>
<tr>
<td>4</td>
<td>225-275</td>
<td>4.70 E-05</td>
<td>0.605</td>
<td>200-203</td>
</tr>
<tr>
<td>5</td>
<td>175-225</td>
<td>4.77 E-04</td>
<td>0.387</td>
<td>249-252</td>
</tr>
<tr>
<td>6</td>
<td>125-175</td>
<td>1.02 E-04</td>
<td>0.439</td>
<td>296-299</td>
</tr>
<tr>
<td>7</td>
<td>25-125</td>
<td>1.02 E-05</td>
<td>0.422</td>
<td>348-351</td>
</tr>
<tr>
<td>8</td>
<td>0-25</td>
<td>(see Layer 4-V47 or 5-V11)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| **VERTICAL TRANSECT V11**                                     |
| Boundary Conditions: Lower $\psi = 668.0$ Upper $\psi = 15800.0$ |
| $\theta$ used to estimate B.C., Tube 11*: Lower $\theta = 0.199$ Upper $\theta = 0.110$ |
| @ 426.72 cm (3/8) @ 60.96 cm (3/8)                           |
| Grid Spacing: Vertical = 25.0 cm Horizontal = 1.0 cm           |
| Total Simulation Time: 2.0 years; profile drained only         |

<table>
<thead>
<tr>
<th>Material</th>
<th>Elevation (cm)</th>
<th>$K_\text{sat}$ (cm/sec)</th>
<th>$n\circ$</th>
<th>Sample transect position (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>425-375</td>
<td>4.25 E-04</td>
<td>0.518</td>
<td>48-51</td>
</tr>
<tr>
<td>2</td>
<td>375-325</td>
<td>1.61 E-03</td>
<td>0.578</td>
<td>99-102</td>
</tr>
<tr>
<td>3</td>
<td>325-275</td>
<td>7.18 E-03</td>
<td>0.557</td>
<td>149-152</td>
</tr>
<tr>
<td>4</td>
<td>275-225</td>
<td>1.81 E-05</td>
<td>0.652</td>
<td>243-246</td>
</tr>
<tr>
<td>5</td>
<td>175-25</td>
<td>4.76 E-04</td>
<td>0.508</td>
<td>342-345</td>
</tr>
<tr>
<td>6</td>
<td>25-0</td>
<td>1.40 E-03</td>
<td>0.641</td>
<td>431-434</td>
</tr>
</tbody>
</table>

* see Neutron Probe Data Sheet (appendix A)  
$\circ$ 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 $\theta$-$\psi$ 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 $0.35 \text{ cm}^3/\text{cm}^3$ 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 (VII), 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 \( \theta_r \), approximately 0.10 \( \frac{cm^3}{cm^3} \) (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, \( \theta_{15.0} = \theta_r \) 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 \( \theta_r \). 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 \( \theta_r \), 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 \( \theta_r \) 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 \( \theta-\phi \) 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 $10^{-8}$ 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 affected 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