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Settlement of Uranium Mill Tailings Piles

A Comparison of Analysis Techniques

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ABSTRACT

Two empirical methods of settlement analysis (Terzaghi's theory and a simplified version of the Fredlund-Morgenstern two-stress-state approach) were compared to the computer code TRUNC, a modified version of the TRUST code for variably saturated flow in deformable porous media. The three methods were used to predict settlement of a 12.2-m-deep pile of tailings slimes with a drain at the bottom.

The simpler, empirical methods of settlement analysis were just as effective as TRUNC in predicting total settlement. For saturated tailings, predictions of total settlement by Terzaghi's theory and TRUNC were in close agreement (1.69 and 1.72 m, respectively). For partially saturated tailings, the simplified stress-state approach and TRUNC predicted similar total settlements (0.52 and 0.51 m, respectively).

Terzaghi's theory, as applied, overestimated the time of settlement under saturated conditions (170 days versus 140 days predicted by TRUNC) because it did not account for gravitational gradients. No empirical or analytical means were available to predict the time of settlement under partially saturated conditions. The TRUNC code, however, predicted 1500 days (4.1 years) for settlement under partially saturated conditions. If the magnitude of partially saturated settlement is considered significant, then the time over which it occurs will most likely be the deciding factor in determining when to place the cover on the tailings pile.

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FIGURES

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LIST OF SYMBOLS

Symbol	Description	Units[a]
$\vec{A}$	Vector normal to the surface	-
C_a	Compression index when the stress is constant	-
C_c	Compression index when the pore pressure is zero	-
cs	Integral limit over the surface of a control volume	L^2
C_v	Coefficient of consolidation	L^2/T
cv	Integral limit over a control volume	L^3
d	Derivative operator	-
e	Void ratio	L^3/L^3
e_z	Reference void ratio on the void ratio versus effective stress curve	-
f	Subscript denoting final condition	-
G	Fluid generation rate of a node	M/T
g	Gravity	L/T^2
H	Total thickness of the tailings pile	L
h	Length of the longest drainage path	L
i	Subscript denoting initial condition	-
K	Hydraulic conductivity	L/T
k	Intrinsic permeability	L^2
L	Length between two nodes	L
M_c	Fluid mass capacity of a node	M/L
$\vec{n}$	Unit outward normal vector	-
n	Porosity	L^3/L^3

(a) Units are L = length, M = mass, and T = time

S	Degree of saturation	-
T	Dimensionless time factor	-
t	Time	T
U	Excess pore water pressure	M/LT^2
u_a	Pore air pressure	M/LT^2
u_w	Pore water pressure	M/LT^2
V	Volume	L^3
V_{sol}	Volume of solids in a node	L^3
$\vec{v}$	Normal velocity vector relative to the surface of the control volume	L/T
W	Fluid mass content	M
z	Vertical dimension	L
β	Coefficient of compressibility of water	LT^2/M
Γ	Surface bounding a finite subregion	L^2
Δ	Increment operator	-
∂	Partial derivative operator	-
ε_v	Volumetric strain	L/L
γ_w	Specific weight of water	M/L^2T^2
μ	Coefficient of viscosity	M/LT
ρ_w	Density of water	M/L^3
ρ_{wo}	Density of water at atmospheric pressure	M/L^3
ρ_{slimes}	Density of slimes material	M/L^3
σ	Total stress	M/LT^2
σ'	Effective stress	M/LT^2
σ'_a	Average effective stress	M/LT^2
σ'_z	Reference effective stress on the void ratio versus effective stress curve	M/LT^2

ψ	Pore pressure	M/LT^2
ϕ	Total potential	L

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EXECUTIVE SUMMARY

Uranium mill tailings piles pose a number of environmental problems including the emission of radon gas to the atmosphere and the seepage of chemical contaminants to the ground water. These hazards have prompted government agencies to seek to have the piles covered and drained. In the process of covering and draining the piles, the piles may settle and cause the cover to crack, rendering it less effective as a radon gas barrier. To avoid this problem a method is needed to predict the amount of total settlement and the time of settlement so that the covers can be placed at the optimum time.

Several methods for analyzing the settlement of tailings piles exist today. Terzaghi's theory and the two-stress-state approach, both empirical, can be used to predict saturated and partially saturated total settlement, respectively, when pore water pressures are decreased or a cover is added. In some cases, Terzaghi's theory (Terzaghi 1948) can also be used to predict the time of saturated settlement. A third method for analyzing settlement is the computer code TRUNC (TRansient UNsaturated Consolidation), developed by Pacific Northwest Laboratory (PNL) with the support of the U.S. Nuclear Regulatory Commission (NRC). TRUNC is a modified version of the computer code TRUST, which was written for variably saturated flow in deformable porous media (Narasimhan 1975). TRUNC incorporates the two-stress-state approach to consolidation, which is considered an improvement over the χ-parameter approach used in TRUST because the χ-parameter is so difficult to define. TRUNC can thus be used to simulate the effect of cover placement on total settlement and time of settlement in both the saturated and partially saturated regions. To provide guidance, comparisons of the predictions of total settlement and time of settlement with the empirical analysis methods and TRUNC were made for a representative tailings pile.

As a test case, we considered a saturated tailings pile of slimes, 12.2 m deep, which was consolidated by a combination of drainage and loading. The settlement and time of settlement were predicted using the two empirical methods where applicable and the computer model TRUNC. Comparing the total settlement predicted using the three methods showed the predictions to be similar for both the saturated and partially saturated cases. The empirical analyses were performed in a more rigorous manner than usual and are detailed in the report.

Terzaghi's theory predicted a longer settlement time than TRUNC, in this case, 20% longer (170 days versus 140 days). Greater settlement time was predicted when using Terzaghi's theory because the theory does not account for gravitational gradients. Partially saturated settlement time could be predicted only with TRUNC, which predicted 1500 days for 92% consolidation. Because of the much greater length of settlement time, the final decision as to when to place the cover may depend on the estimate of the length of time for partially saturated settlement to occur. At this time, such an estimate can only be obtained with a comprehensive flow model such as TRUNC.

1.0 INTRODUCTION

Uranium mill tailings piles have created a number of environmental problems, including radon gas emission to the atmosphere and potential seepage of contaminants to the ground water (Landa 1980). To reduce the rate of radon gas emission, covers are placed on the piles. The integrity of these covers must be maintained throughout the life of the pile (i.e., no cracking should occur) to minimize radon escape. Tailings, however, are sluiced into pits so the piles by nature of their construction are unstable. If a cover load is applied, the tailings may consolidate and cause the pile to settle, which could fracture the cover. In addition, after mill operations have ceased, the piles either eventually dry out to some degree or are drained to prevent ground-water contamination. Either case may lead to further settling and possible cover disruption.

Mill operators and licensing agencies need a method to assess the potential settlement of a tailings pile and the time required for that settlement under both saturated and partially saturated conditions. With the proper analysis tools, they may be able to determine the best time to cover the tailings.

This report compares the results from using two empirical methods to predict settlement with results from a numerical model. Specifically, total settlement and time predicted under saturated conditions with the classical linear theory of Terzaghi (Terzaghi 1948) are compared with predictions from the computer code TRUNC (TRansient, UNsaturated Consolidation). The TRUNC code calculates saturated consolidation using Terzaghi's theory in conjunction with a fluid flow code. It is a modified version of the code TRUST, written by Narasimhan (1975) to analyze variably saturated flow in deformable media. The conceptual model that led to TRUST was described in a series of papers by Narasimhan (1975), Narasimhan and Witherspoon (1976, 1977, and 1978), and Narasimhan, Witherspoon and Edwards (1978). A portion of the TRUST code originated from a heat flow code called TRUMP (Edwards 1968).

The TRUST code described the consolidation of partially saturated soils by attempting to relate the pore pressure to the effective stress via the parameter χ (Bishop 1960). The parameter χ, however, has been found to be a highly nonlinear function of the degree of saturation and also dependent on the soil type and hysteresis (Gates 1982). Therefore, the TRUST code was modified to incorporate the two-stress-state description of consolidation under partially saturated conditions proposed by Fredlund and Morgenstern (1976).

Predictions of settlement under partially saturated conditions using a simplified version of the two-stress-state approach are also compared with predictions of TRUNC. Throughout the rest of this report, the simplified version of the two-stress-state approach of Fredlund and Morgenstern is referred to simply as the stress-state approach. Through this analysis, we hope to determine those areas where the simpler solutions (i.e., Terzaghi's theory) provide acceptable results and areas where a more definitive model is needed (i.e., TRUNC).

The data used for our test cases are from uranium mill tailings slimes, which are fine materials with particle diameters less than 75 μm in size. Most of the data used were taken from experiments conducted by Sherry (1982) on samples from Shiprock, New Mexico. Supplemental data have been derived at PNL for samples from Grand Junction, Colorado. Using these two sources of data, we believe that we have the best data set currently available to test analysis techniques for predicting settlement. The development of the data set is discussed in detail in Appendix B.

2.0 CONCLUSIONS AND RECOMMENDATIONS

Thick earthen covers may be placed on uranium mill tailings piles sometime after the mill ceases operation to suppress the emission of radon gas. The covers will add to the overburden stress, thus causing the piles to settle, which may crack the cover and possibly affect fluid flow and contaminant transport.

The empirical methods for predicting settlement were compared with results from TRUNC, which incorporates the various aspects of consolidation and fluid flow. TRUNC accounts for changes in permeability during saturated consolidation, which represents an improvement over Terzaghi's original theory. TRUNC uses the two-stress-state approach in the partially saturated region. Although the increased capability and inherent complexity of TRUNC may not be warranted for prediction of total settlement, it is definitely needed for estimating settlement times. Specifically, we found the following.

- Predictions of total settlement under saturated conditions by both Terzaghi's theory and TRUNC were nearly identical.
- Terzaghi's theory, when applied to a large saturated tailings pile underlain with a drain, predicted a conservative (longer) settlement time because it did not account for the gravitational gradient.
- Given the necessary data, predictions of total settlement under partially saturated conditions by both the stress state approach (as used in this document) and TRUNC were nearly identical.
- TRUNC results indicated that settlement under partially saturated conditions can occur for several years after drainage is initiated.
- Predictions of settlement times under saturated conditions may be overshadowed by settlement times under partially saturated conditions.

Based on our results, we recommend that further investigation of this subject include the following:

- comparison of the analysis techniques for predicting settlement of materials other than slimes, such as sands and various sand/slime mixes
- comparison of predictions of total settlement and settlement times for layered systems by TRUNC, which can handle material layering, with predictions by Terzaghi's theory, which requires that the system be considered mixed and homogene us in order to calculate the settlement time
- an effort to gauge the importance of secondary consolidation in settlement and settlement time predictions.

3.0 SETTLEMENT ANALYSIS UNDER SATURATED CONDITIONS

Terzaghi's theory (Terzaghi 1948) is based on simple, one-dimensional consolidation in which the soil permeability is assumed constant over each loading increment. The computer code, TRUNC, simulates saturated consolidation in a manner similar to Terzaghi's, but does not make the assumption of constant permeability. Because consolidation, and thus settlement, will only occur as fast as the pore water pressure is dissipated, the lower permeability predicted by TRUNC should increase the predicted settlement time.

In the case of both analysis techniques, only primary consolidation is considered (i.e., that consolidation resulting from the dissipation of excess por pressure). Secondary consolidation, where soil particles are thought to fracture and/or undergo plastic deformation, is not considered because the effects are thought to be small in relation to primary consolidation.

3.1 TERZAGHI'S THEORY

The essence of Terzaghi's theory is that, for saturated systems, the effective stress on the soil grains is equal to the difference between the total stress resulting from the overburden and the pore water pressure. In equation form,

$$\sigma' = \sigma - u_w \tag{3.1}$$

where σ' = effective stress on the soil grains
σ = total stress
u_w = pore water pressure.

Numerous experiments have measured the void ratio as a function of effective stress. Figure 3.1 illustrates typical results. In many cases, these results are approximated with a straight line whose form is

$$e_f = e_i - C_c \log \left(\frac{\sigma'_f}{\sigma'_i}\right) \tag{3.2}$$

where i,f = subscripts indicating initial and final conditions
e = void ratio
C_c = compression index, which is the slope of the void ratio versus logarithm of effective stress relationship. The pore water pressure is assumed to be greater than atmospheric pressure.

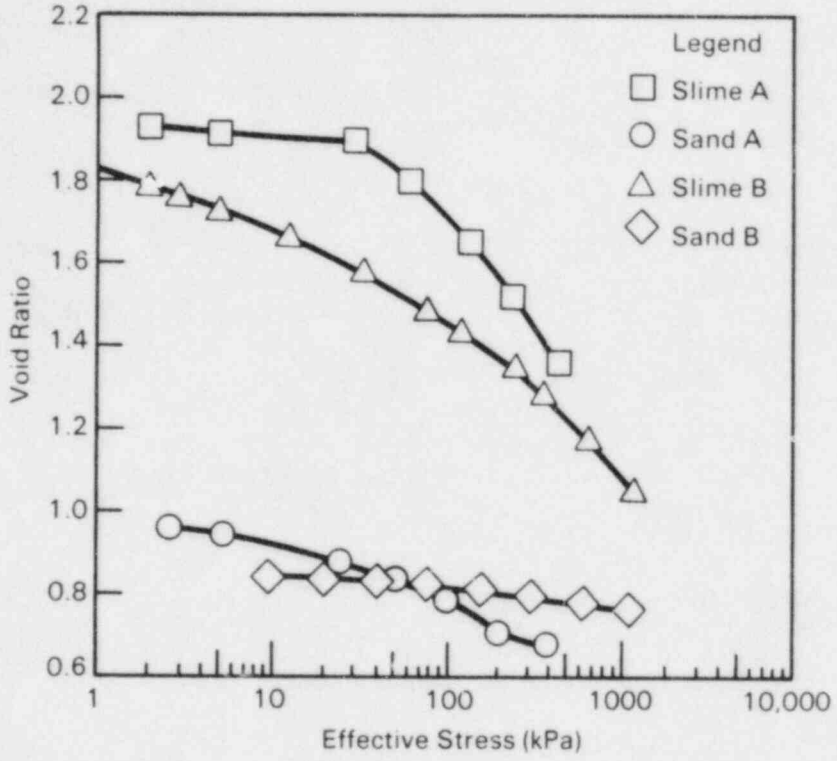

FIGURE 3.1. Typical Curves of Void Ratio Versus Effective Stress for Sands and Slimes [material (A) is from Nelson et al. (1983) and material (B) is from Schrauf (1984)]

3.1.1 Settlement

For a system consolidating in only one dimension (vertical), the volumetric strain of a soil stratum can be expressed as

$$\varepsilon_v = \frac{\Delta H}{H} = \frac{\Delta e}{1+e_i} \qquad (3.3)$$

where ε_v = volumetric strain
H = stratum thickness
ΔH = change in stratum thickness; settlement
Δe = change in void ratio.

Rearranging and combining Equations (3.2) and (3.3) yields an expression for the settlement of a given stratum.

$$\Delta H = \frac{HC_c}{1+e_i} \log \left(\frac{\sigma'_f}{\sigma'_i}\right) \qquad (3.4)$$

To use Equation 3.4 to predict the settlement of a tailings pile, we must first determine how many layers the pile must be broken into. The method is more accurate when thinner layers are analyzed, but the calculation effort can become prohibitive and the potential for error may increase. In our discussion, we do not mean to imply that layers are of different material, as the term 'layering' suggests. The term 'layers' is used here only to refer to sections of the tailings pile at specific depths for which consolidation is calculated separately.

A sample problem was set up to evaluate the effect of layer thickness on the calculation of settlement. The slimes data in Figure 3.2, taken from the data set in Appendix B, were used to describe the settlement of a pile of tailings slimes 12.2 m (40 ft) deep. In many engineering analyses, it is convenient to express the change in void ratio with effective stress with only one value for the slope, or C_c. In this case, a C_c value of 0.635 was used to represent the slope of the steepest part of the curve. Because the curve in the low effective stress range was much flatter, a second C_c value of 0.03 was calculated to fit the data more accurately and a second set of settlement

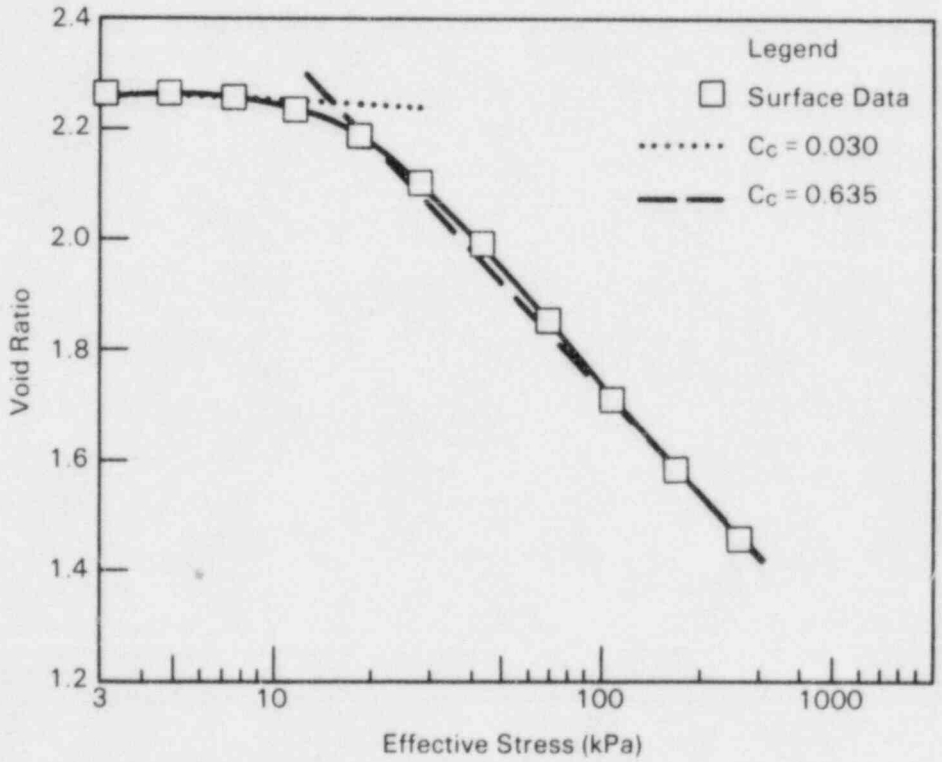

FIGURE 3.2. Void Ratio Versus Effective Stress for Tailings Slimes. Two C_c lines have been fit to data from the void ratio surface described in Appendix 3.

calculations were performed using both C_c values. The pile was divided into the desired number of layers of equal thickness and hydrostatic initial conditions were assumed. A cover load was applied that exerted a stress of 60 kPa. Drainage was then allowed to occur through the bottom until pore pressures throughout became zero. The results are plotted in Figure 3.3 as settlement versus the number of nodes (layers) used.

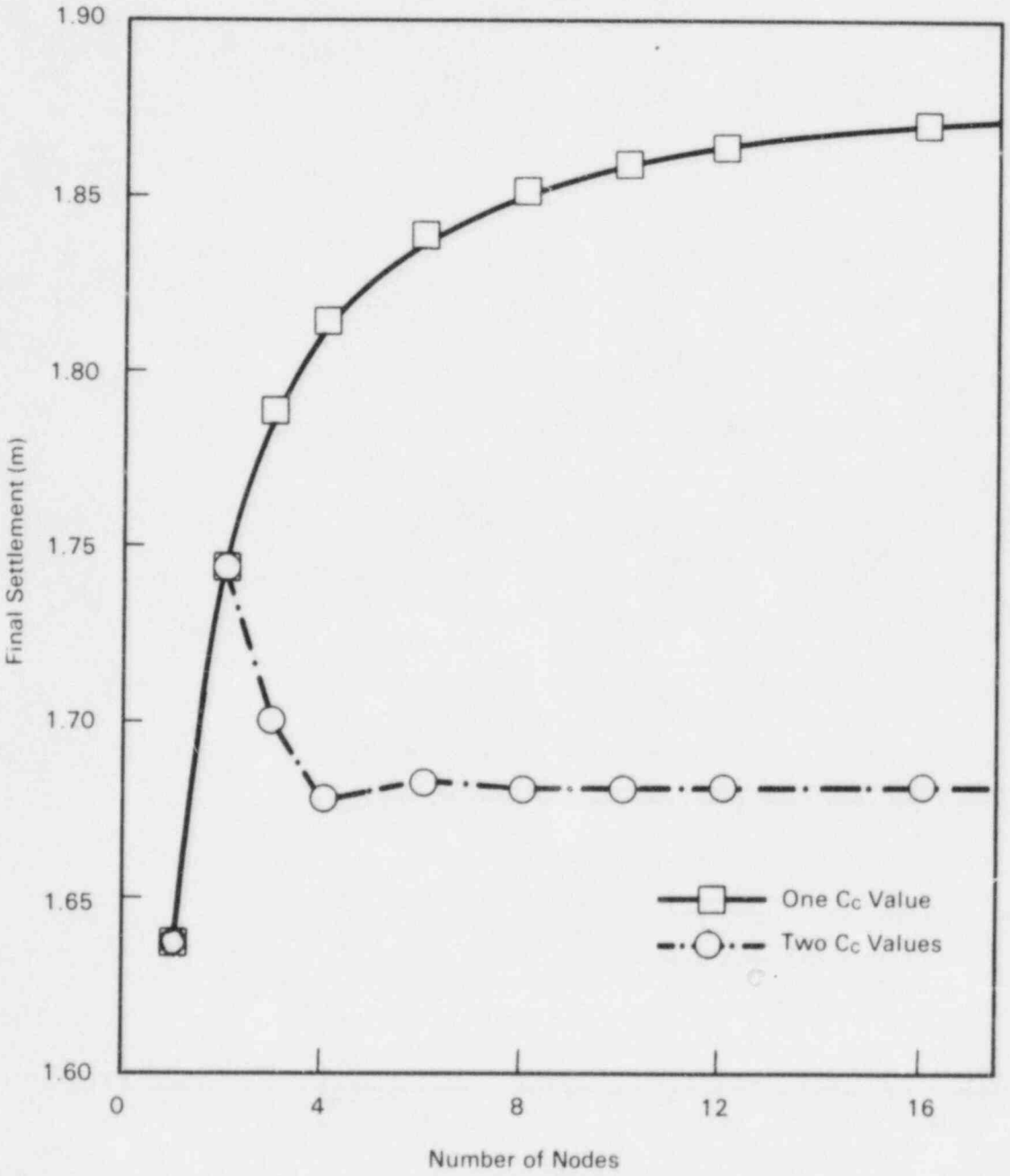

FIGURE 3.3. Effect of the Number of Nodes (layer thickness) in the Empirical Calculation on the Prediction of Settlement of a 12.2-m-Deep Pile of Slimes

When only the C_c value from the steep part of the curve was used, predicted settlement increased as the number of nodes was increased. A total settlement of about 1.87 m was approached asymptotically. The problem in using only one C_c value with these slimes data was that as layer thicknesses became smaller, the calculated effective stresses of the uppermost layers were small enough to be outside the range where the single C_c value (0.635) fit the measured data. Void ratios and thus settlement were overestimated, which caused the predicted settlement to increase as layer thicknesses were decreased. On the other hand, when both C_c values were used, the predicted settlement remained nearly constant after increasing to only four nodes. Note that the predicted settlements were the same for the one and two node cases. These values were similar because the calculated effective stresses were still in the range of the single C_c value of 0.635. After the pile is divided into three nodes, the effective stress of the top layer is small enough that it is in the range of the C_c value of 0.03.

Two conclusions can be drawn:

1. If a fine mesh is to be used (more nodes, thinner layers), then care should be taken to ensure that the entire range of effective stress to be encountered will be adequately represented by the appropriate C_c values.

2. With adequate representation of the data (i.e., with more than one C_c value where appropriate), use of more than four nodes results in little change in the calculated settlement.

These points apply only to the slimes material used and a 12.2-m-deep tailings pile with bottom drainage.

3.1.2 Time of Settlement

Under saturated conditions, the time for a particular amount of settlement to occur is a function of the rate of dissipation of excess pore water pressure. The equations given by Terzaghi (1948) for excess pore water pressure dissipation are

$$\frac{\partial U}{\partial t} = C_v \frac{\partial^2 U}{\partial z^2} \tag{3.5}$$

$$t = \frac{T\, h^2}{C_v} \tag{3.6}$$

where ∂ = partial derivative operator
U = excess pore water pressure
t = time
C_v = coefficient of consolidation
z = elevation
T = dimensionless time factor
h = length of longest drainage path.

In deriving Equations (3.5) and (3.6), Terzaghi assumed that the material is initially in a state of hydrostatic equilibrium throughout. At hydrostatic equilibrium, no potential gradients exist within the material. Once a load is placed on the sample, the pore water pressure increases above the initial pressure; this increase in pore water pressure is considered the excess pressure. The drainage of water from the sample is thus driven only by the excess pore water pressure gradient.

The other major assumptions that were made by Terzaghi in deriving these equations were that

- the material is homogeneous and isotropic
- deformation is linear and small in relation to the total stratum thickness
- the coefficient of consolidation (C_v) is constant.

To some degree, laboratory experiments can be set up in which the material is homogeneous. In real world situations, however, this is rarely true. In tailings piles, for instance, the material is zoned according to particle size, ranging from sands, to sand-slime mixes, to slimes. For this study, we focused our analysis on the slimes material.

Deformation, in the case of tailings piles, is definitely not linear and may not be small. But as pointed out previously (Olson and Ladd 1979), the theory has been used because it is simple and because uncertainties in soil property definitions are likely to be a greater source of error.

The coefficient of consolidation, C_v, can be expressed as

$$C_v = \frac{(1+e_i)\ K\ 2.303\ \sigma'_a}{\gamma_w\ C_c} \qquad (3.7)$$

where K = hydraulic conductivity
σ'_a = average effective stress between the initial and final values
γ_w = unit weight of water.

C_v, being a function of the hydraulic conductivity, is not constant because hydraulic conductivity decreases with decreasing void ratio (as illustrated by Lambe and Whitman 1969). As a material consolidates and the conductivity decreases, the outflow should also decrease to some degree. In other words, the excess pore water pressure will dissipate more slowly, causing settlement to take longer. Because Terzaghi's theory assumes a constant conductivity, it may thus tend to predict a shorter time of settlement.

Under a given loading increment there will be a certain amount of primary consolidation. At any point in time, the percentage of that consolidation that has occurred is related to the amount of dissipated excess pore water pressure and can be plotted versus a dimensionless time factor, T (see Figure 3.4). For most purposes, settlement is considered complete when the consolidation has reached 92%, where the dimensionless time factor, T, (Equation 3.6) has a convenient value of 1.0.

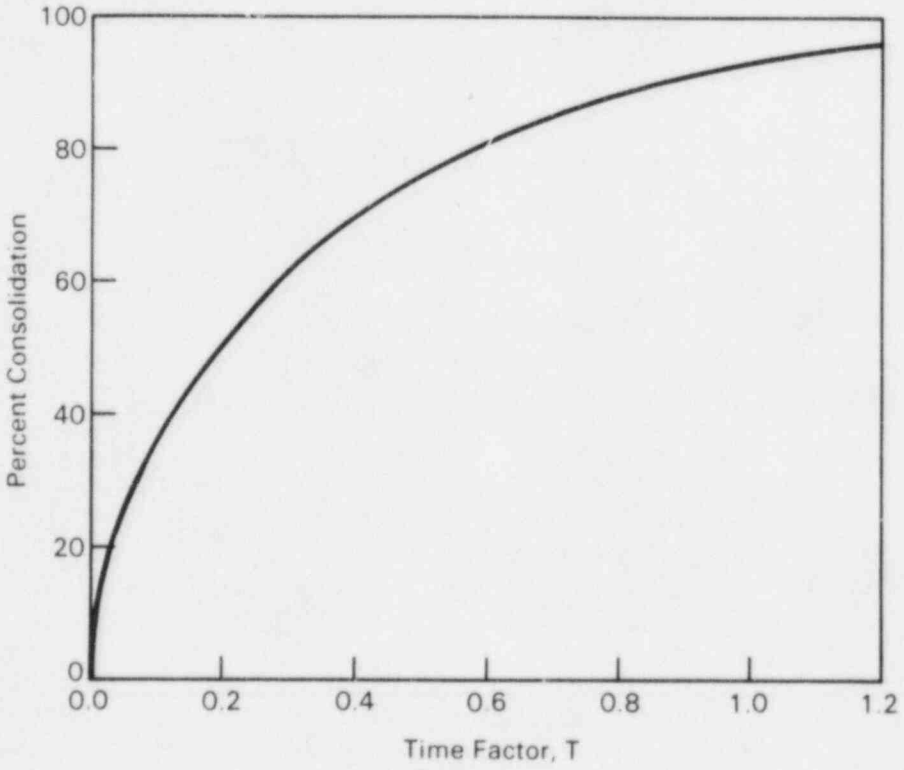

FIGURE 3.4. Percent Saturated Consolidation Versus the Dimensionless Time Factor, T

3.2 TRUNC

The purpose of this section is to describe how the TRUNC code calculates settlement of saturated soils. Also included are discussions of the necessary initial and final conditions for TRUNC and the inherent approximations in the methodology used by TRUNC.

3.2.1 Methods of Calculating Settlement

Two methods for calculating void ratio changes in the saturated zone are implemented in the TRUNC code. The first method uses the classical log-linear relationship between the effective stress and the void ratio, given by Equation 3.2. The data necessary for using this option in the TRUNC code are the compression index, C_c, and a reference point on the void ratio versus logarithm of effective stress curve delineated by e_z and σ'_z.

Two problems may occur when using this option. Depending on the data set, the first problem is manifested when the void ratios calculated using Equation (3.2) do not match those calculated from the void ratio surface. (The surface referred to here is the surface used to describe the void ratio as a function of two stress-state parameters. This surface is described in detail in Section 4.) This will only be a problem if the TRUNC code is being used to calculate settlement as the tailings pile goes from a saturated to a partially saturated state. If the void ratios calculated using Equation (3.2) match the void ratio surface for all stress levels when the pore pressure is zero, then this problem will not occur.

The other problem that can occur involves the use of nodes so small that the effective stresses of the uppermost nodes are in the nonlinear range of the void ratio versus logarithm of effective stress curve. The TRUNC code currently uses only one C_c coefficient, and using nodes approximately 1 m thick or less will create problems with this option (see Section 3.1 and Figure 3.3).

The second method for calculating void ratio changes in the saturated zone uses the edge of the void ratio surface corresponding to zero pore pressure. The shape of this edge, defined by a specific number of data points, is a curve similar to those plotted in Figure 3.2. This method uses the entire curve, both the linear and nonlinear sections, to linearly interpolate between pairs of data points. This method is not subject to the two problems previously discussed and is recommended over the method that uses a single C_c value. Care must be taken so that the void ratio surface is adequately described for low effective stresses, otherwise TRUNC may extrapolate unrealistic values.

3.2.2 Initial And Final Conditions

The initial conditions required to use the TRUNC code are the total potential (pore water pressure plus elevation) and total stress (sum of the stresses caused by the soil column and water column). A simple iterative scheme is provided within TRUNC to define the initial stress condition because the total stress is dependent on the void ratio and vice versa. This calculation generally requires three to four iterations to solve for the correct void ratio and corresponding stress for each node.

To compare the results of the different analysis techniques, we had to distinguish between settlement under saturated versus partially saturated conditions for the TRUNC results. For the empirical calculations, the final pore water pressure at the end of saturated settlement was set to zero for every node. Because of the dynamic nature of TRUNC, however, pore water pressures

vary with depth. There is no time when pore water pressures are zero throughout the column. The criterion we chose to separate settlement under saturated conditions from partially saturated conditions was the point in time when the pore water pressure of the node in the middle of the column became zero. Figure 3.5 shows the pore water pressure distribution from TRUNC and the empirical results.

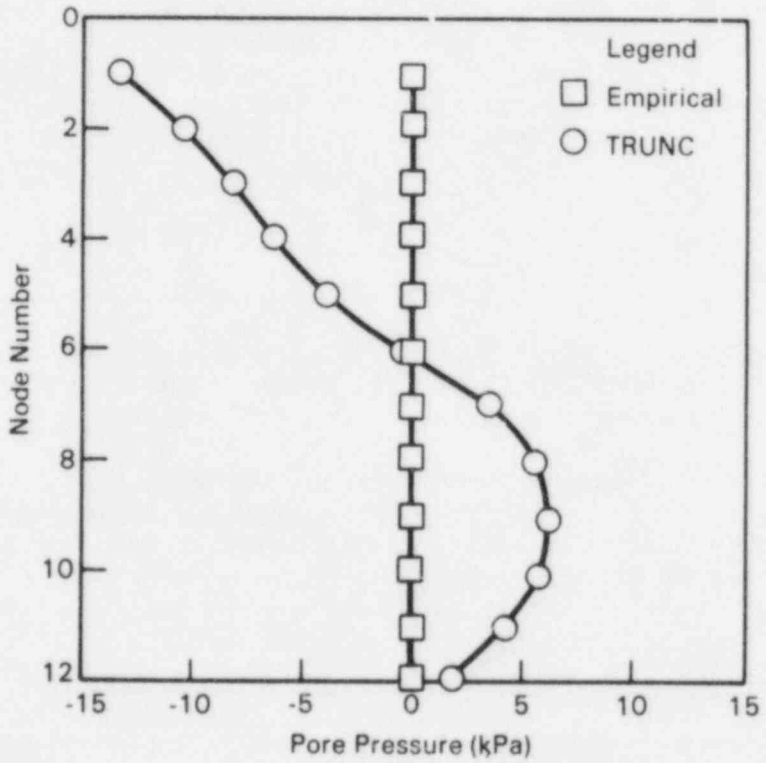

FIGURE 3.5. Pore Pressure Profiles Versus Depth for Two Analysis Methods at the Point in Time When Saturated Consolidation is Distinguished From Partially Saturated Consolidation

3.2.3 Inherent Approximations

The TRUNC code has two inherent approximations when used to evaluate settlement under saturated as well as partially saturated conditions. The first approximation is that material properties are averaged over each node. When used to evaluate settlement, this means the void ratio, stress, saturation, and pore water pressure are assumed to be constant over each node. The effect of this approximation is easily evaluated by comparing results using different node sizes. For one-dimensional comparisons, sufficiently small nodes can be chosen so that this approximation has little effect. For two- or three-dimensional evaluations of mill tailings piles, it may be impossible to use the very small node sizes because of computational time and costs.

The second approximation in the TRUNC code is that an Eulerian coordinate system is used which fixes the nodal locations and distances between nodes in space. In reality, the nodal locations actually move as the soil matrix deforms. This approximation limits the applicability of TRUNC to systems where the deformation is small. The effect of this approximation on both the flow calculations and on the stress calculations is explained below.

When used to simulate flow in consolidating porous media, the fixed coordinate system creates an error in the fluid flux calculations. The error in the flux calculations consists of two components, the gradient and the permeability. The gradient used to calculate the flux across the interface between any two nodes is based on the potential head difference and the original undeformed node lengths.

$$\text{Gradient} = \frac{\Delta\phi}{L}$$

where $\Delta\phi$ is the potential head difference between two nodes and L is the length between two nodes. The undeformed node lengths are longer than the consolidated node lengths; hence, the gradient is underestimated.

The effect of consolidation is to decrease the void ratio, which effectively decreases the permeability. The permeability used in TRUNC to calculate the flux across the interface between any two nodes is based on a harmonic mean of the permeabilities of the two nodes, using the undeformed node lengths as the weights. The permeability calculated for the interface is thus overestimated because the undeformed node lengths essentially bias the harmonic mean calculation to the node with less deformation (i.e., higher void ratios and higher permeability). If the true consolidated node lengths were used, the node having undergone more consolidation (lower void ratio and lower permeability) would be closer to the interface between the nodes and would have a greater influence in the harmonic mean calculation.

The fixed nodes for water flow calculations in TRUNC also produce errors in stress calculations. The stress calculation consists of two components, the weight of the soil matrix and the weight of the water above a node. The stress caused by the soil matrix is calculated on the first iteration and is not updated. Consequently, the volume of solids and the corresponding stress resulting from the soil matrix are not affected by the approximation of a fixed coordinate system. The stress component from the weight of water above a node is, however, affected by the fixed coordinate system. The original undeformed node lengths are used throughout the simulation to calculate the weight of the water above a node. Hence, the calculated component of stress from the water is greater than actually exists.

The net effect of the errors introduced by the fixed coordinate system depends on the amount of consolidation. The magnitude of this error was calculated by evaluating the mass of water at each node and comparing it with the mass of water predicted by TRUNC. The mass of water at each node can be calculated by the following equation:

$$W = e\, V_{sol}\, \rho_w\, S \tag{3.8}$$

where W = fluid mass content
V_{sol} = volume of solids
ρ_w = density of water
S = degree of saturation

The water content at each node in the TRUNC code is based on a control-volume form of the continuity equation, where errors in the flux calculations affect the water content at each time step. The control-volume form of the continuity equation (Fox and McDonald 1973) can be written as

$$0 = \int_{cv} \rho_w \frac{\partial V}{\partial t} + \int_{cs} \rho_w \vec{v}\, d\vec{A} \tag{3.9}$$

where ∂ = partial derivative operator
V = volume
cv = limits of the integral over the control volume
$\vec{v}$ = normal velocity vector relative to the surface of the control volume
d = derivative operator
$\vec{A}$ = vector normal to the surface
cs = limits of integral over the surfaces of the control volume.

The TRUNC code uses a discretized form of Equation (3.9). Comparing the calculated water content estimated by TRUNC with the water content calculated using Equation (3.8) indicated that TRUNC overpredicted the cumulative flux out the bottom of the column by 5% at 140 days for our example case.

3.3 COMPARISON OF SETTLEMENT ANALYSIS TECHNIQUES UNDER SATURATED CONDITIONS

To compare Terzaghi's theory with TRUNC, we set up a problem involving a tailings pile. Each analysis method was used to predict the settlement of the saturated tailings pile as well as the time to complete settlement. Differences and/or similarities in predictions were used to assess the methods.

3.3.1 Problem Description

The slimes tailings material used for this comparison was chosen for several reasons. First, it is one of the few materials for which we could construct a satisfactory data set (see Appendix B). Second, slimes generally exhibit the greatest amount of consolidation of any tailings materials. Slimes also have the lowest permeability values, so drainage and settlement of the pile take longer. Therefore, slimes may have the most potential to affect settlement. Finally, we wanted to deal with only one material, rather than a mixture. Tailings piles are usually a mixture of sand and slimes, but our

focus was on the differences in settlement predicted by the two methods and not on the errors introduced by heterogeneity.

As in the previous example, we considered a 12.2-m-deep pile of saturated slimes with initial hydrostatic equilibrium throughout. A cover load exerting a stress of 60 kPa was applied to the surface. Drainage of the pile was allowed to occur through the bottom of the pile until the pore pressures at all depths were zero, or in the case of TRUNC, until the pore pressure of the middle node became zero.

Twelve nodes (i.e., layers) were used in each analysis. As indicated previously, use of more than four nodes with Terzaghi's theory is unnecessary. TRUNC, however, requires more than four nodes to operate efficiently, especially when used to simulate partially saturated flow and consolidation. Therefore, both methods were used with twelve nodes to be consistent.

In Section 3.1.2, we mentioned that TRUNC iteratively calculates the initial total stress and hydraulic potential at each node using measured stress-strain data at zero pore water pressure. In the case of the Terzaghi method, we wrote a similar computer program which uses the two C_c values from Figure 3.2 to calculate initial conditions.

The assumption of no initial hydraulic gradient, inherent in Terzaghi's theory of the time dependence of settlement, is not fully met in our problem description. A drain is at the bottom of the column, which sets up a gravitational gradient immediately after simulation begins. The theory can, however, be used to give rough estimates of settlement time. These estimates may be useful for planning because they will tend to err on the conservative side by predicting longer settlement times.

Terzaghi's theory of settlement time can be applied to our problem in two ways. First, the theory can be used to calculate the time of settlement for the case where a cover is added to a saturated pile initially in hydrostatic equilibrium. This approach satisfies Terzaghi's assumptions, but the final state of the tailings pile at re-establishment of hydrostatic conditions is not zero pore pressure throughout. The zero pore pressure condition is necessary to separate the analysis into saturated and partially saturated settlement.

The second way to apply Terzaghi's theory, used for this analysis, is to assume that the profile has been drained to the point where pore pressures are zero throughout, and then do the analysis (Nelson et al. 1983). This does not satisfy the conditions in Terzaghi's derivation, and it necessitates neglecting the time taken to get from the initial hydrostatic condition to zero pore pressures at all depths. However, the final conditions more closely represent condition chosen to distinguish between saturated and partially saturated settlement.

3.3.2 Results

Looking at the predictions under saturated conditions in Table 3.1, we see that settlements predicted by the two methods are very close, within 0.03 m.

Consequently, in this test case, Terzaghi's theory is more than adequate for predicting total settlement under saturated conditions.

Predictions of the time of settlement by TRUNC and Terzaghi's theory are somewhat different. Terzaghi's theory predicts a longer time, which is in accord with our previous discussion of initial hydrostatic equilibrium. The error caused by the assumption of initial hydrostatic equilibrium appears to have been greater than that caused by Terzaghi's assumption of constant

TABLE 3.1. Comparison of Settlement and Time of Settlement Under Saturated Conditions Predicted by Two Analysis Techniques Using 12 Nodes.

Analysis Technique	Settlement, m	Time of Settlement, d
Terzaghi's Method	1.69	170
TRUNC	1.72	140

permeability. Also, note that for the time estimate from Terzaghi's theory, we ignored the time it takes to get from hydrostatic conditions to zero pore pressures throughout. Thus, the predicted settlement time would be even longer than the reported 170 days.

Settlement times using Terzaghi's theory are also subject to the inadequacies of the C_v calculation. The theory uses single values for the void ratio, effective stress, and hydraulic conductivity to calculate a C_v value that is uniform over the profile. In a tailings pile that is 12.2 m deep, the variations in these parameters are large, at least by a factor of two, which affects the calculated C_v value.

Although we assumed a 12.2-m-deep pile of slimes for our test case, tailings piles actually consist of many zones of differing particle sizes that affect predicted settlement time. Layers of coarser materials, such as sands, would aid in drainage because of their high permeability, and consequently, settlement times would be much shorter than predicted when assuming only slimes. The disparity in settlement time reported here between Terzaghi's theory and TRUNC might be smaller than the 30 days shown in Table 3.1 when using a profile with different material layers. TRUNC can be used to model a layered pile, but Terzaghi's theory cannot unless an average C_v value for the pile can be obtained by averaging the C_v values of the different materials.

If settlement under partially saturated conditions proves to be significant for a particular tailings site, then it would not matter how long saturated consolidation takes. Partially saturated consolidation is a much slower process and may possibly be the governing factor in timing the placement of the final cover.

4.0 SETTLEMENT ANALYSIS UNDER PARTIALLY SATURATED CONDITIONS

The two-stress-state approach to calculating settlement under partially saturated conditions relies on knowledge of the void ratio as a function of effective stress and pore pressure, a function which can best be described as a void ratio surface. Approximations of the void ratio surface can be made so that the simplified stress-state approach to consolidation can be used to predict settlement under partially saturated conditions. TRUNC uses the same void ratio surface to predict settlement, but does not have to make the same simplifying approximations of the void ratio surface. Of these two methods, only the TRUNC code can be used to predict partially saturated settlement times. Throughout this document, the term 'pore pressure' refers to the stress-state parameter (u_a-u_w), which is the difference between the pore air pressure and pore water pressure. Increasing pore pressure is indicative of a drying soil.

4.1 STRESS-STATE APPROACH

In the past, a number of effective stress equations were proposed for partially saturated soils. These equations were an attempt to couple together more than one stress variable. However, as pointed out by Gates (1982) "the stress-state should consist of independent stress variables."

Fredlund and Morgenstern (1976) proposed two stress-state parameters for partially saturated soil, $(\sigma-u_a)$ and (u_a-u_w), which can each be measured independently of the other. Void ratios and degree of saturation can be measured as functions of the two stress-state parameters and plotted as three-dimensional surfaces. The surfaces generated may or may not be unique, depending on the stress paths (Bishop and Blight 1963; Barden, Madedor and Sides 1969; Fredlund and Morgenstern 1976). However, given the stress path taken and the corresponding material property surfaces, one can calculate the amount of settlement to expect under partially saturated conditions.

4.1.1 Settlement

In the original equation proposed by Fredlund and Morgenstern (1976), the partially saturated term, rewritten in a slightly different form, is

$$\varepsilon_v = \frac{\Delta H}{H} = \frac{C_a}{1+e_i} \log \frac{(u_a-u_w)_f}{(u_a-u_w)_i} \qquad (4.1)$$

where C_a is the compression index when $d(\sigma-u_a)$ is constant.

The C_a term is essentially the change in the void ratio with respect to the change in (u_a-u_w) when the stress is held constant. Figure 4.1 contains plots of void ratio versus (u_a-u_w) for a number of different stress levels (see Appendix B for the data set). The data are not exactly log-linear, but we assumed so and fit lines between each pair of endpoints. The slope of each line becomes the C_a value for that stress level.

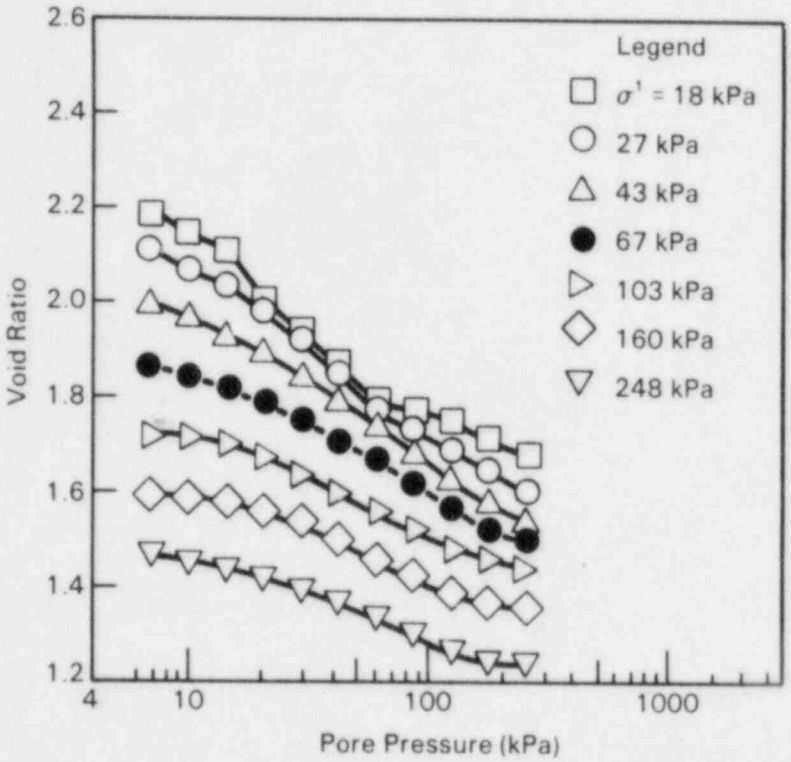

FIGURE 4.1. Void Ratio Versus Pore Pressure at Selected Levels of Effective Stress. The data are from the void ratio surface described in Appendix B.

In a settlement analysis, the question arises as to what value of C_a to use. One crude approach that gives conservative estimates of settlement is to use the C_a value for the lowest stress level of the data. A second and more rigorous approach is to represent C_a as a linear function of the effective stress. Figure 4.2 is a plot of the C_a values (calculated from Figure 4.1) versus the effective stress. A line was plotted through the two endpoints and its equation is given. The fit is not perfect, but can be done rather easily.

A third approach is to fit a curve to the data. The computer program HAVERFIT (McKeon et al. 1983), normally used to fit saturation data to pore pressure, was used to fit a curve to the C_a data. The resulting curve fit is shown in Figure 4.2 along with the equation for the curve. Whichever representation of C_a is used, it can be substituted for the C_a term in Equation (4.1).

A sample problem, similar to the one used in the saturated analysis, was set up to judge the appropriateness of each method of representing C_a. Settlement and drainage were simulated for 12.2-m-deep pile of saturated tailings slimes until pore water pressures were zero throughout. Then the pile was consolidated under a load stress of 60 kPa. Using the consolidated state as the starting point for this example, the pile was allowed to drain and desaturate with concurrent partially saturated consolidation. The pile was drained to

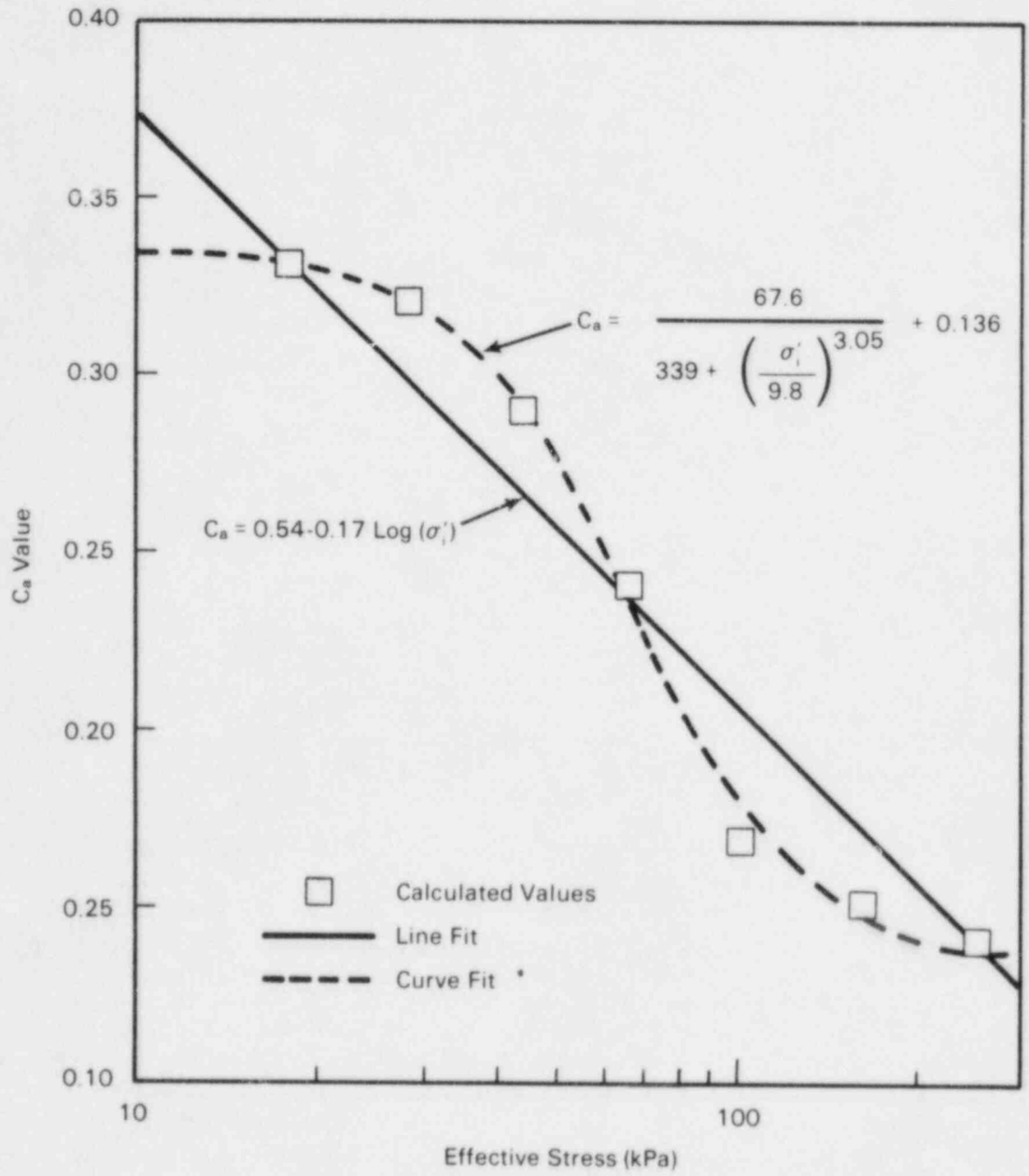

FIGURE 4.2. Values of C_a Calculated from Figure 4.1 Versus Effective Stress. A line and a curve have been fit to the data.

hydrostatic equilibrium with a drain at the bottom, such that the pore pressure, (u_a-u_w), at any depth equalled the elevation above the drain. The magnitude of the settlement was then calculated using each method of estimating C_a.

The results in Table 4.1 indicate that when using a single value of C_a (from the lowest stress level), the predicted settlement was nearly twice that obtained using the curve-fit form of C_a (1.00 m versus 0.52 m). Use of the linear C_a function resulted in a prediction of about 12% more settlement (0.58 m versus 0.52 m).

TABLE 4.1. Comparison of Predicted Settlement Under Partially Saturated Conditions Using Several Methods of Obtaining C_a (a)

Method of C_a Calculation	Settlement, m
Single C_a value	1.00
Line Fit of C_a data	0.58
Curve Fit of C_a data	0.52

(a) The initial pile depth was 12.2 m and 12 nodes were used.

Clearly, use of only the C_a value at the lowest stress level of the data was inappropriate. After the pile started to become partially saturated, the effective stresses at all depths were much higher (68 to 243 kPa) than the lowest stress level of the data (18 kPa). The linear and curved fits of C_a took into account the change in C_a with stress. The linear fit to the data was not as exact as the curved fit. However, fitting a line to data is fairly easy, whereas a little more effort is required to obtain a curved fit. Because predictions of settlement by the two methods are quite similar, a linear data fit may be adequate for most purposes.

4.1.2 Time To Settlement

At the present time, no analytical or empirical equation exists for predicting the time to total settlement under partially saturated conditions because of the highly nonlinear nature of unsaturated water movement.

4.2 CALCULATION OF SETTLEMENT USING TRUNC

To use the TRUNC code to evaluate settlement of soils in partially saturated flow systems, three properties of the soil matrix must be defined: void ratio, saturation, and intrinsic permeability. These properties must be defined as three-dimensional surfaces, with the two stress-state parameters, $(\sigma-u_a)$ and (u_a-u_w), as the axes in the horizontal plane. Examples of these surfaces are included in Appendix B.

The TRUNC code calculates settlement of partially saturated soils by first solving the fluid flow problem at a given time step using estimates of permeability and saturation. The estimates of permeability and saturation are bilinearly interpolated from the permeability and saturation surfaces. After fluid fluxes between nodes are calculated and convergence criteria are satisfied, new pore pressure values are calculated. With the new pore pressure and saturation values, the stress at each node is calculated. The air pressure, u_a, in the stress-state parameters, $(\sigma-u_a)$ and (u_a-u_w), is assumed to be zero. Using the new stress-state parameters, the corresponding void ratio at each node is bilinearly interpolated from the void ratio surface. The change in void ratio corresponds to the volume change at each node. For the one-dimensional columns reported in this document, the change in volume corresponds to the amount of settlement.

4.2.1 Initial And Final Conditions (TRUNC)

To properly define initial conditions when applying a load, the TRUNC simulation must be started under saturated conditions. The necessary initial conditions for saturated consolidation are the total stress and the total potential. If a load is applied to a partially saturated soil system, the void ratio would decrease, thereby increasing the degree of saturation and causing hysteretic effects. The TRUNC code is not capable of analyzing these hysteretic effects. However, if the load is applied to a saturated soil system, the load will initially be carried by an increase in pore water pressure. The load will then be gradually transferred to the soil matrix as the excess pore water pressure dissipates because of drainage. The soil system will remain saturated (until all excess pore water pressure dissipates) and no hysteresis will occur.

The final condition reached with the TRUNC simulation is hydrostatic equilibrium, where the pore pressure at each node equals the elevation above the drain located at the bottom of the pile. This is about as dry as the tailings pile will become under conditions of drainage. Although evaporation could remove more water, the amount of water removed may be negligible if a cover is placed on the tailings pile surface.

4.2.2 Inherent Approximations (TRUNC)

The errors introduced by the Eulerian (fixed) coordinate system for partially saturated settlement are the same as those discussed in Section 3.2 for saturated settlement. Briefly reiterating those errors, the original undeformed node lengths are used in the calculation of the stress and the fluid flux. This approximation (fixed coordinates) limits the applicability of TRUNC to systems where the deformation is small. The magnitude of the error introduced by the Eulerian coordinate system in the partially saturated case is 5.7% of the flux out the bottom of the column at 5000 days. This error was calculated in the same manner as described in Section 3.2. The fact that the error increases only 0.7% from 140 days to 5000 days is probably the result of the relatively smaller amount of consolidation occurring in the partially saturated system after 140 days.

4.3 COMPARISON OF SETTLEMENT ANALYSIS TECHNIQUES UNDER PARTIALLY SATURATED CONDITIONS

We set up a test problem to predict the settlement of a partially saturated tailings pile using both the simplified stress-state approach and TRUNC. TRUNC was also used to predict the settlement time. As previously stated, no empirical or analytical solution exists, to our knowledge, that can be used to predict the time of settlement for the partially saturated case.

4.3.1 Problem Description

A pile of saturated tailings slimes 12.2 m deep was allowed to consolidate under a load stress of 60 kPa and drain until the pore pressures of all nodes were zero. For the TRUNC simulation, this was assumed to be the case when the pore pressure of the middle node was zero. After this point in time, we considered the system to be consolidating under partially saturated conditions. In the case of the stress-state approach, Equation (4.1) was used with the C_a term described as a function of the effective stress (curve-fit function in Figure 4.2). In the simulation with TRUNC, the void ratio, saturation, and permeability surfaces in Appendix B were used.

4.3.2 Results

The results in Table 4.2 indicate that the two methods predicted essentially the same total settlement, within 0.01 m of each other. Thus, if the data were available to yield the C_a function, partially saturated consolidation could be predicted rather easily with the simplified stress-state approach.

TABLE 4.2. Comparison of Predicted Settlement and Time Under Partially Saturated Conditions for Two Methods of Analysis Using 12 Nodes.

Analysis Technique	Settlement, m	Time for Settlement, d
Stress-State Approach	0.52	-
TRUNC	0.51	1500(a)

(a) Corresponds to 92% consolidation.

TRUNC predicted that 92% of the partially saturated settlement would take place in 1500 days. In Figure 4.3, the percentage of settlement under partially saturated conditions is plotted versus time. If a certain amount of settlement were determined to be acceptable, the curve could be used to determine the amount of time required to reach that point. For instance, if 0.25 m of settlement (out of a total of 0.5 m) could be tolerated without significant

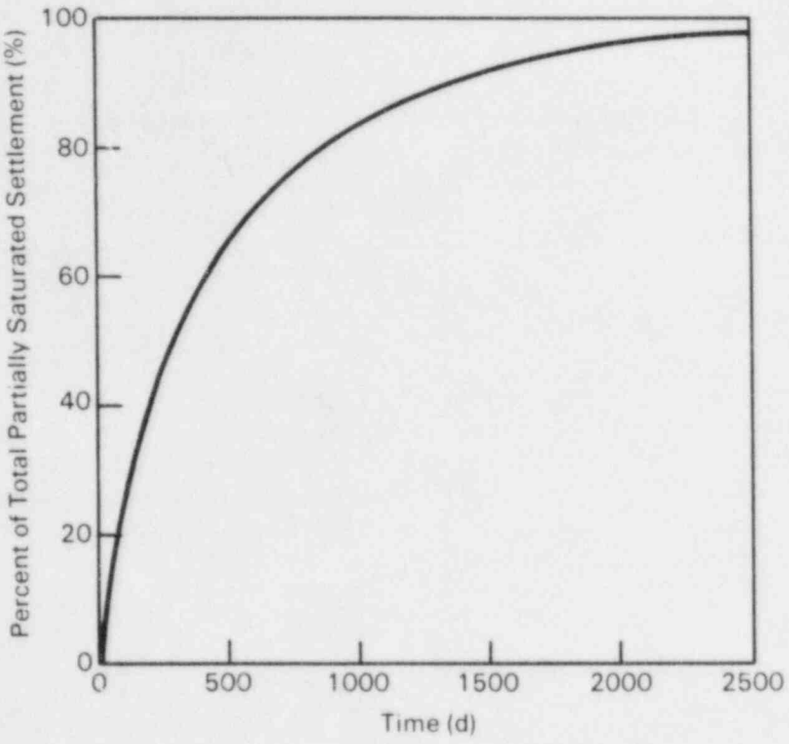

FIGURE 4.3. Percentage of Partially Saturated Settlement Versus Time as Calculated by TRUNC

structural damage to the cover, then this 50% settlement would be reached at about 430 days. In this manner, a plot similar to that in Figure 4.3 could be used as a planning tool to determine the best time for placement of a cover.

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APPENDIX A

EXAMPLE CALCULATIONS

APPENDIX A

EXAMPLE CALCULATIONS

Two examples are presented here to illustrate the methods of settlement analysis discussed within the main text. The first example deals with the calculation of settlement and time of settlement under saturated conditions using Terzaghi's theory. The second example shows the calculations of settlement under partially saturated conditions using the two stress-state approach.

SATURATED SOILS

The problem considered was that of a 12.2-m-deep uranium mill tailings pile that is saturated and must be drained and covered. The material was assumed to consist entirely of slimes for which the stress-strain properties are illustrated in Figure 3.2. Initial pore water pressures were assumed hydrostatic, which means that the pile is in equilibrium and that there is no flow. The pile was then dewatered by allowing water to drain out the bottom of the pile. No flow was allowed through the top of the pile. Only the calculations for a one-node problem are shown.

Settlement

In this analysis, the pile was allowed to consolidate by 1) decreasing pore water pressure from the initial hydrostatic equilibrium condition to zero pore pressure and 2) adding a cover load. The initial void ratio and total stress can be iteratively calculated assuming that the pile is completely saturated.

For a one-node problem, the effective stress will always be in the linear range of the void ratio curve, so a single value of the compression index, Cc, can be used. Some of the soil properties, calculated initial conditions, and final conditions were

$$\rho_{slimes} = 2820 \text{ kg/m}^3$$

$$C_c = 0.635$$

$$\sigma = 96 \text{ kPa}$$

$$e_i = 2.0$$

$$u_{wi} = 60 \text{ kPa}$$

$$\sigma'_i = \sigma - u_{wi} = 96 - 60 = 36 \text{ kPa}$$

$$u_{wf} = 0 \text{ kPa}$$

$$\sigma'_f = \sigma - u_{wf} = 96 - 0 = 96 \text{ kPa}$$

The final void ratio was computed using the following expression. (Equations in this appendix are numbered as they appear in the corresponding text.)

$$e_f = e_i - C_c \log \left(\frac{\sigma'_f}{\sigma'_i}\right) \tag{3.2}$$

$$e_f = 2.0 - 0.635 \log \left(\frac{96}{36}\right)$$

$$e_f = 1.73$$

Equation 3.3 was used to calculate the settlement, from which the new column height was calculated.

$$\Delta H = H \left(\frac{\Delta e}{1+e_i}\right) \tag{3.3}$$

$$\Delta H = 12.2 \left(\frac{2.0 - 1.73}{1 + 2.0}\right)$$

$$\Delta H = 1.1 \text{ m}$$

$$H = 12.2 - 1.1 = 11.1 \text{ m}$$

A 1.1-m settlement of the tailings pile resulted when pore water pressures were reduced from hydrostatic to zero throughout the column.

The next step was to calculate the settlement resulting from placement of a cover. For this example, the cover load was 60 kPa and the initial pore water pressure before placement of the cover was zero. After the cover is added, pore water pressures will rise, then dissipate back to zero. Because the initial and final pore water pressures are zero, any increase in the total stress from the cover can be translated into a similar increase in the effective stress. Thus,

$$\text{Load} = 60 \text{ kPa}$$

$$\sigma_f' = \sigma + \text{load}$$

$$\sigma_f' = 96 + 60 = 156 \text{ kPa}$$

The final void ratio was

$$e_f = 1.73 - 0.635 \log \left(\frac{156}{96}\right)$$

$$e_f = 1.60$$

Using the new column height calculated previously (11.1 m), the settlement caused by the placement of the cover can be calculated.

$$\Delta H = 11.1 \left(\frac{1.73 - 1.60}{1 + 1.73}\right)$$

$$\Delta H = 0.5 \text{ m}$$

As can be seen, the placement of a cover caused an additional 0.5 m of settlement. The final total settlement resulting from the change in the pore pressure and the addition of a cover was

$$\Delta H = 1.1 + 0.5 = 1.6 \text{ m}$$

The final height of the column at the end of settlement under saturated conditions was

$$H = 12.2 - 1.6 \text{ m} = 10.6 \text{ m}$$

The results for the 12-node problem are presented in Table A.1. The major difference from the 1-node problem is that two Cc values were used instead of one to better describe the stress-strain relationship, because the upper 3 nodes initially were not in the linear range of the void ratio curve.

TABLE A.1. Summary of Saturated Settlement Calculations for Each of the 12 Nodes of a 12.2-m Column of Mill Tailings Slimes

	Initial Conditions				Final Conditions[a]		
Node	Void Ratio	Effective Stress, kPa	Total Stress, kPa	Pore Pressure, kPa	Void Ratio	Effective Stress, kPa	Settlement, m
1	2.27	2.8	67.5	64.8	1.83	67.5	0.14
2	2.25	8.3	83.1	74.7	1.77	83.1	0.15
3	2.25	13.9	98.6	84.7	1.72	98.6	0.16
4	2.17	19.6	114.2	94.7	1.68	114.2	0.16
5	2.10	25.4	130.0	104.6	1.65	130.0	0.15
6	2.04	31.3	145.9	114.6	1.61	145.9	0.14
7	1.99	37.3	161.8	124.6	1.59	161.8	0.14
8	1.95	43.4	177.9	134.5	1.56	177.9	0.13
9	1.91	49.6	194.1	144.5	1.54	194.1	0.13
10	1.88	55.9	210.3	154.4	1.51	210.3	0.13
11	1.85	62.2	226.6	164.4	1.49	226.6	0.13
12	1.82	68.6	242.9	174.4	1.47	242.9	0.13
					Total Settlement = 1.69 M		

(a) Final pore pressure was zero throughout the column.

Settlement Time

In this particular problem, the pile was assumed to drain to the point where the pore water pressure was zero before adding the cover. The cover was added, the pore water pressure rose initially to bear the full weight of the cover, and then the excess pressure dissipated back to zero as the tailings pile was drained. The errors inherent in applying Terzaghi's theory of the time dependence of settlement to this type of problem are discussed in Section 3.2.1. In brief, analyzing this type of problem with Terzaghi's theory will yield conservative estimates of settlement time because the theory does not take gravitational gradients into account.

To compute the settlement time, a C_v value [Equation (3.7)] had to be calculated that represented the material and the problem description. Solving for C_v required knowing the average effective stress over the loading increment. At this point, the pore water pressure was zero and the initial and final effective stresses, calculated previously, were 96 and 156 kPa, respectively. The average effective stress was therefore 126 kPa.

The only remaining unknown term for calculating C_v is the hydraulic conductivity, K. A value of K can be estimated (see Appendix B) from the known void ratio. In the previous example, we found that the void ratio, after the pore water pressure dropped to zero and before the cover was placed, was 1.73. For a void ratio of 1.73, the calculated hydraulic conductivity was 6.6×10^{-8} m/s. C_v was then determined using Equation (3.7).

$$C_v = \frac{(1+e_i)\ K\ 2.303\ \sigma'_a}{\gamma_w\ C_c} \qquad (3.7)$$

$$C_v + \frac{(1 + 1.73)\ 6.6 \times 10^{-8}\ 2.303\ 126}{9.81 \quad 0.635}$$

$$= 8.4 \times 10^{-6}\ m^2/sec$$

$$= 0.726\ m^2/day$$

The settlement time was then determined using Equation (3.6). Note that the column height was 11.1 m at this point because some settlement had already occurred as pore water pressures were bought from hydrostatic to zero.

$$t = \frac{T\ h^2}{C_v} \qquad (3.6)$$

$$t = \frac{(1)\ (11.1)^2}{0.726}$$

$$t = 170\ days$$

This estimate of settlement time does not include the time it would take to drain the pile from a hydrostatic condition to zero pore pressures throughout.

PARTIALLY SATURATED SOILS

The analysis of settlement under partially saturated conditions for a 1-node column of mill tailings slimes starts where the analysis of saturated tailings stopped. The initial pore water pressure and effective stress were therefore 0 and 156 kPa, respectively. The unknown terms needed to solve for the settlement of partially saturated tailings [Equation (4.1)] are the value of C_a corresponding to an effective stress of 156 kPa and the final pore pressure (u_a-u_w). The C_a term was (from Figure 4.2)

$$C_a = \frac{67.6}{339 + \left|\frac{\sigma_i}{9.81}\right|^{3.05}} + 0.136$$

$$C_a = 0.149$$

Because of a lack of void ratio data in the 0 to 7 kPa range of pore pressure, C_a was set equal to zero whenever pore pressures were in that range. Thus, no settlement could be calculated until pore pressures were above 7 kPa. In the following calculations, the initial pore pressure term, $(u_a-u_w)_i$, was set equal to 7 kPa. The final pore pressure was equivalent to the height of the node above the drain. Originally, the height of the node was half the column height, or 6.1 m. Because of the settlement of the saturated tailings that had already taken place, the column height was 10.6 m. The new height of the node above the drain was thus 5.3 m, which corresponds to a final pore pressure, $(u_a-u_w)_f$, of 52 kPa.

The amount of settlement of the partially saturated tailings was then calculated using Equation (4.1).

$$\Delta H = \frac{H\ C_a}{1 + e_i} \log \frac{(u_a-w_w)_f}{(u_a-u_w)_i} \qquad (4.1)$$

$$\Delta H = \frac{10.6\ \ 0.149}{(1 + 1.6)} \log \left(\frac{52}{7}\right)$$

$$\Delta H = 0.53 \text{ m}$$

The results for the 12-node problem are presented in Table A.2. As stated previously, no estimate is available for the empirical analysis of the time of settlement for partially saturated soils.

TABLE A.2. Summary of Partially Saturated Settlement Calculations for Each of the 12 Nodes of a 12.2-m Column of Mill Tailings Slimes

	Initial Conditions				Final Conditions[a]		
Layer	Void Ratio	Effective Stress, kPa	C_a	Pore Pressure, kPa	Void Ratio	Pore Pressure, kPa	Settlement, m
1	1.83	67.5	0.23	6.9	1.56	98.8	0.08
2	1.77	83.1	0.20	6.9	1.54	90.2	0.07
3	1.72	98.6	0.18	6.9	1.53	81.8	0.06
4	1.68	114.2	0.17	6.9	1.51	73.4	0.06
5	1.65	130.0	0.16	6.9	1.49	64.9	0.05
6	1.61	145.9	0.15	6.9	1.48	56.4	0.05
7	1.59	161.8	0.15	6.9	1.46	47.8	0.04
8	1.56	177.9	0.14	6.9	1.45	39.2	0.04
9	1.54	194.1	0.14	6.9	1.44	30.5	0.03
10	1.51	210.3	0.14	6.9	1.44	21.8	0.03
11	1.49	226.6	0.14	6.9	1.45	13.1	0.01
12	1.47	242.9	0.00	6.9	1.47	4.4	0.00
						Total Settlement =	0.52 m

(a) For pore pressures between 0.0 and 6.9 kPa, the C_a coefficient was set equal to zero.

APPENDIX B

DATA SET DESCRIPTION

APPENDIX B

DATA SET DESCRIPTION

In order to compare different methods for the analysis of settlement, a complete data set is required. The void ratio, degree of saturation, and partially saturated intrinsic permeability must be described as functions of the two stress state variables, $(\sigma-u_a)$ and (u_a-u_w). Experiments are currently under way at Pacific Northwest Laboratory (PNL) to measure some of these parameters for uranium mill tailings. The data used for the comparisons described in this document are taken mainly from the Master's thesis of Sherry (1982) at Colorado State University. The intrinsic permeability data, however, were derived through experiments at PNL.

The void ratio surface reported by Sherry (1982) has a ridge about which the surface is warped. Sherry states, "It is believed, therefore, that the warping of the surface results from stress path dependency... More research is needed to investigate the stress path dependency of the surface." The ridge on the surface defines a region where the void ratio increases with increasing pore pressure as the soil drys. The physical interpretation from the void ratio surface is that a soil sample will actually swell as it dries. Preliminary results of the experiments underway at PNL have shown that the void ratio decreases with increasing pore pressure at a given stress state. In other words, the soil samples shrink while drying, provided the stress is held constant. In the experimental results reported by Sherry, samples were subjected to alternating increases in either stress or pore pressure. Such a path would likely lead to hysteretic effects. We therefore believe that the warping of the void ratio surface reported by Sherry may be a result of the stress paths chosen.

To use a particular void ratio surface in the TRUNC code, the surface must satisfy two criteria or the problem cannot be solved. The first criterion is that the void ratio must decrease with increasing pore pressure at a given stress state. This means that as a soil dries, the increasing pore pressure will tend to pull the soil particles together causing the soil matrix to shrink. The second necessary criterion is that the void ratio must decrease with increasing stress at a given pore pressure. This simply means that a soil sample will tend to shrink when a load is applied. The numerical difficulties requiring that these two criteria be satisfied are discussed in Appendix D. As a result of these criteria, TRUNC is capable of simulating consolidation along stress paths only where the degree of saturation monotonically decreases. The model is not capable of simulating the hysteretic effects associated with increasing saturation.

The results reported by Sherry (1982) do not satisfy the first of the two criteria. In order to use his results, we sorted through the data and used only those points that satisfied the two necessary criteria. Because Sherry's data set is the only set currently available, interpreting his data seemed the

only practical way to compare the different methods for the analysis of settlement. The results of this comparison are intended only to indicate the relative differences between the methodologies for predicting total settlement and time required for settlement. We do not have a completely reliable data set at this time and do not intend the results of these comparisons to be interpreted as a realistic field-scale evaluation of mill tailings settlement. The remainder of this section will describe in detail all of the steps used to develop the data set used in this report.

VOID RATIO SURFACE

The surface used to describe void ratio as a function of stress and pore pressure was generated using most of the data reported by Sherry (1982). The data that were not used consisted of the tests labeled 10C-0, and 10C-1 through 10C-6. These tests correspond to stress levels varying from 0 to 32 psi and a pore pressure of 1 psi. Deleting these seven measured data points effectively removed the ridge in the surface.

In the remaining data set, wherever more than one measured void ratio was reported at the same stress and pore pressure, the reported values were averaged. The remaining 19 data points were used to generate a surface using the International Mathematics and Statistics Library (1980) subroutine IQHSCV. The IQHSCV subroutine uses a fifth-degree polynomial to fit a surface to irregularly spaced data points. Data points on an irregular rectangular grid were then calculated on the fitted surface. An irregular rectangular grid was used to obtain a more accurate representation of the surface in regions where material properties were changing more rapidly. When a limited amount of data are available, it may be easier to linearly interpolate from the irregular experimental data to a rectangular grid.

Three calculated data points did not satisfy the criterion that the void ratio must decrease with increasing pore pressure. These three calculated data points were at low stress and pore pressures (under 1.4 m of water or 2 psi) where only one data point from the original data set was used. With the very limited amount of data in this range, the surface fitting routine was unable fit a surface to the data points and still let the void ratio decrease with increasing pore pressure. We arbitrarily changed these data points so that the fitted surface satisfied the necessary condition. The first point at a stress of 0.316 m of water (0.45 psi), and pore pressure of 0.704 m of water (1 psi) was changed from a void ratio of 2.25 to 2.265. The second point at a stress and pore pressure of 0.316 and 1.0 m of water respectively (0.45 psi and 1.42 psi) was changed from a void ratio of 2.213 to 2.215. The third point at a stress and pore pressure of 1.2 and 1.4 m of water respectively (1.7 psi and 2.0 psi) was changed from a void ratio of 2.155 to 2.145.

Because the data did not extend below a pore pressure of 0.704 m of water (1.0 psi), we decided to hold any values extrapolated lower than this pore pressure to the same void ratio. This was done by inserting two rows of data at pore pressures of 0.2 and 0.5 m of water with the same void ratio at each stress level as the row of data at a pore pressure of 0.704 m of water.

The final data set used to characterize void ratio as a function of $(\sigma-u_w)$ and (u_a-u_w) is listed in Table B.1. The two stress state variables listed in this appendix are in meters of water because that is the unit required for TRUNC. Figure B.1 depicts a three-dimensional view of the void ratio surface.

SATURATION SURFACE

The surface used to describe saturation as a function of $(\sigma-u_a)$ and (u_a-u_w) was generated from the data reported by Sherry (1982). For stress levels of 1, 4, and 32 psi, the saturation as a function of pore pressure data reported by Sherry (1982) were used in the curve-fitting computer program HAVERFIT (McKeon et al. 1983). The output from HAVERFIT, using Sherry's data, was three smooth curves describing saturation as a function of pore pressure at each stress level listed above. These smooth curves were then used in the same surface-fitting program described previously. Data points on an irregular rectangular grid interpolated from the fitted surface used to characterize saturation as a function of stress and pore pressure are listed in Table B.2. Figure B.2 depicts a three-dimensional view of the saturation surface.

PERMEABILITY SURFACE

A final surface was needed to describe the permeability as a function of $(\sigma-u_a)$ and (u_a-u_w) and Sherry (1982) does not include permeability data. Consequently, the data used to estimate the saturated permeabilities corresponding to the void ratios on our surface are from saturated consolidation experiments performed at PNL and reported by Schrauf (1984). The saturated hydraulic conductivity as a function of void ratio for Grand Junction slimes is shown in Figure B.3. Because the void ratios reported by Sherry (1982) are significantly greater than any measured by Schrauf (1984), it was necessary to extrapolate beyond Schrauf's measured hydraulic conductivity data. The slope between the last three data points is almost constant, which indicates a linear relationship in that particular range. Therefore, we used the constant slope to linearly extrapolate beyond the range measured by Schrauf. We used Equation (B.1) to extrapolate hydraulic conductivity values (m/d) and then converted to intrinsic permeabilities.

$$K(e) = 0.0064 * e^{-0.0054} \qquad (B.1)$$

where K(e) is hydraulic conductivity and e is void ratio .

Narasimhan (1975) reported a linear relationship, within certain ranges, between void ratio and the logarithm of the intrinsic permeability for two soils, a Bentonite clay slurry and a San Francisco Bay mud. Lambe and Whitman (1969) presented experimental data indicating that the void ratio, e, is linearly related to the log of the hydraulic conductivity, K, for several fine-grained soils.

TABLE B.1. Tabular Void Ratio Surface Data (stress units are in meters of water)

$(\sigma-u_a)$	(u_a-u_w)												
	0.20	0.50	0.70	1.01	1.44	2.06	2.95	4.22	6.04	8.65	12.37	17.70	25.33
0.32	2.265	2.265	2.265	2.215	2.201	2.191	2.163	2.159	2.148	2.119	2.091	2.027	1.994
0.49	2.264	2.264	2.264	2.215	2.176	2.139	2.098	2.067	2.039	2.011	1.983	1.937	1.911
0.76	2.264	2.264	2.264	2.207	2.150	2.093	2.037	1.987	1.945	1.915	1.887	1.853	1.829
1.18	2.243	2.243	2.243	2.204	2.145	2.061	1.970	1.906	1.851	1.824	1.809	1.777	1.752
1.83	2.193	2.193	2.193	2.142	2.110	2.001	1.930	1.861	1.789	1.768	1.750	1.708	1.677
2.83	2.109	2.109	2.109	2.062	2.032	1.966	1.906	1.842	1.767	1.730	1.688	1.643	1.604
4.39	1.997	1.997	1.997	1.963	1.931	1.885	1.842	1.791	1.739	1.680	1.624	1.577	1.538
6.80	1.865	1.865	1.865	1.844	1.819	1.788	1.754	1.708	1.666	1.615	1.564	1.522	1.491
10.55	1.724	1.724	1.724	1.716	1.700	1.673	1.635	1.599	1.558	1.519	1.485	1.457	1.440
16.35	1.591	1.591	1.591	1.589	1.576	1.555	1.522	1.490	1.453	1.414	1.382	1.364	1.358
25.33	1.462	1.462	1.462	1.457	1.441	1.419	1.395	1.367	1.331	1.293	1.260	1.241	1.237

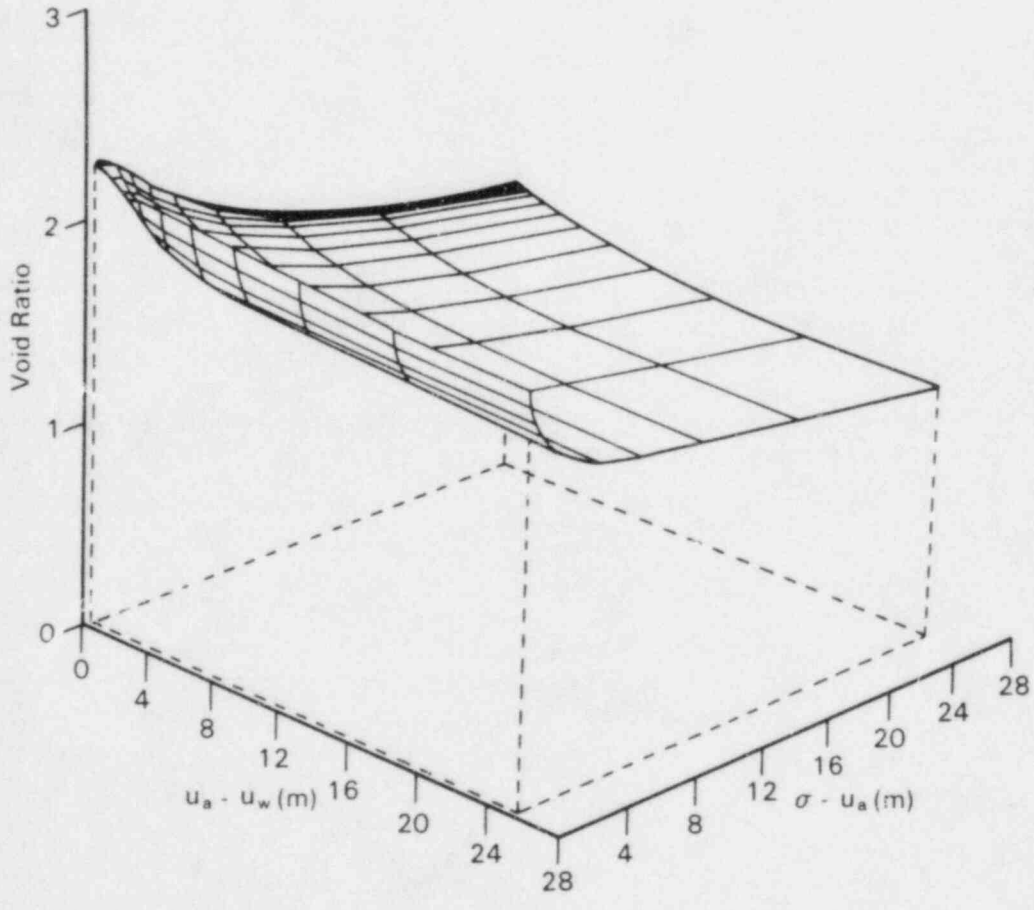

FIGURE B.1. Void Ratio Surface for 100% Slimes (based on data from Sherry 1982)

TABLE B.2. Tabular Saturation Surface Data (stress units are in meters of water)

$(\sigma-u_a)$	(u_a-u_w)										
	0.001	0.002	0.007	0.02	0.06	0.16	0.44	1.21	3.33	9.19	24.33
0.32	1.000	1.000	1.000	0.999	0.998	0.993	0.978	0.926	0.847	0.736	0.632
0.49	1.000	1.000	1.000	0.999	0.998	0.993	0.978	0.933	0.855	0.753	0.667
0.76	1.000	1.000	1.000	0.999	0.998	0.993	0.978	0.941	0.865	0.771	0.700
1.18	1.000	1.000	1.000	0.999	0.998	0.994	0.981	0.948	0.876	0.790	0.732
1.83	1.000	1.000	1.000	1.000	0.999	0.997	0.998	0.955	0.888	0.811	0.763
2.83	1.000	1.000	1.000	1.000	0.999	0.998	0.990	0.962	0.901	0.833	0.793
4.39	1.000	1.000	1.000	1.000	0.999	0.998	0.991	0.971	0.916	0.856	0.821
6.80	1.000	1.000	1.000	1.000	1.000	0.999	0.994	0.981	0.932	0.881	0.847
10.55	1.000	1.000	1.000	1.000	1.000	0.999	0.995	0.983	0.950	0.907	0.871
16.35	1.000	1.000	1.000	1.000	1.000	0.999	0.997	0.987	0.968	0.933	0.892
25.33	1.000	1.000	1.000	1.000	1.000	0.999	0.988	0.995	0.987	0.961	0.901

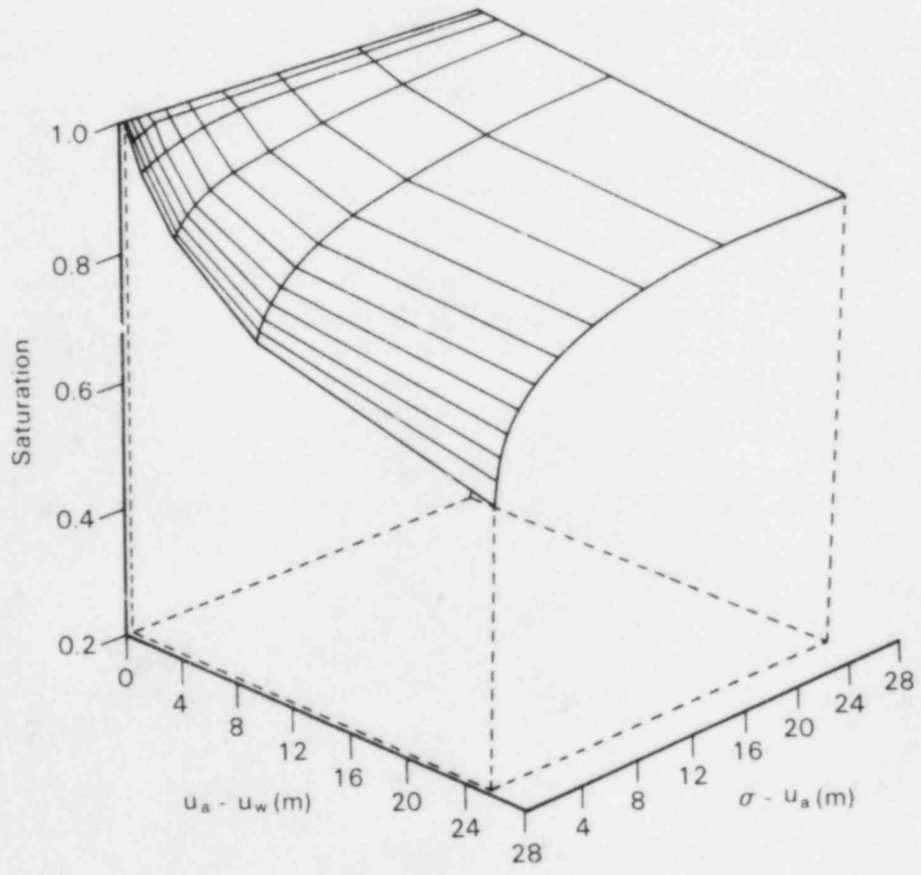

FIGURE B.2. Degree of Saturation Surface for 100% Slimes (based on data from Sherry 1982)

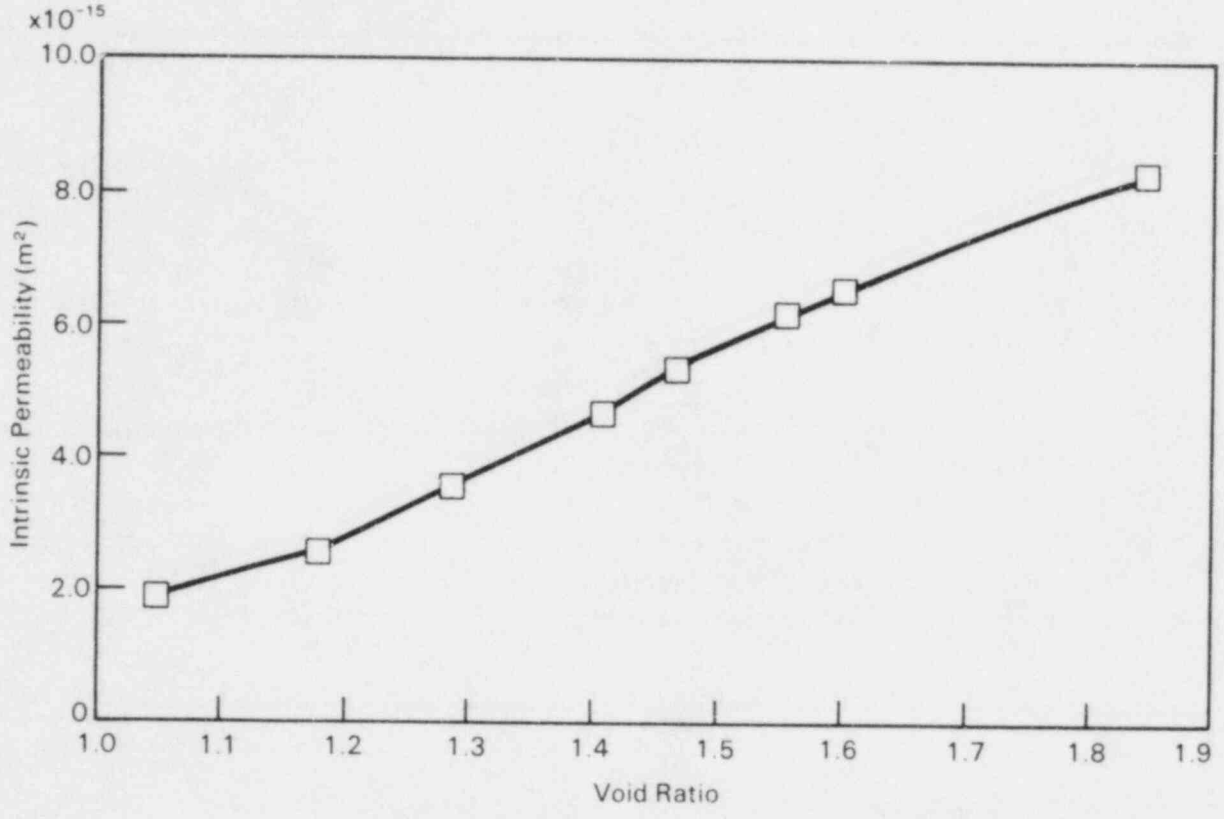

FIGURE B.3. Intrinsic Permeability Versus Void Ratio for 100% Slimes (based on data from Schrauf 1984)

The assumption that intrinsic permeability can be calculated by linearly extrapolating beyond measured values is clearly questionable. The primary goal in developing this data set, however, was not to predict the precise amount and time required for settlement, but rather to compare techniques for evaluating settlement. Because the different techniques use parameters and empirical coefficients derived for the same data set, relative differences between the settlement predicted using different techniques should not be significantly affected by possible errors in the estimation of the intrinsic permeability data.

We estimated the saturated intrinsic permeability for three void ratios corresponding to stress levels of 0.7, 2.8, and 25.3 m of water (1, 4, 32 psi). The computer program CONDGEN (McKeon et al. 1983) was used to synthesize the partially saturated intrinsic permeability data from the saturation data. CONDGEN uses the method proposed by Mualem (1976), which is based on the relationship between the pore size distribution and the water retention characteristics. The output from CONDGEN is three smooth curves characterizing intrinsic permeability as a function of pore pressure at different stress levels. These curves were then used in the same surface-fitting program described previously to generate a surface. Data points on an irregular rectangular grid interpolated from the fitted surface are listed in Table B.3. Figure B.4 depicts a three dimensional view of the intrinsic permeability surface.

TABLE B.3. Tabular Intrinsic Permeability Data (stress units are in meters of water, intrinsic permeabilities units are in meters squared)

$(\sigma-u_a)$	(u_a-u_w)										
	0.001	0.003	0.007	0.02	0.06	0.16	0.44	1.21	3.33	9.18	25.30
1.00	0.12E-13	0.12E-13	0.11E-13	0.11E-13	0.85E-14	0.49E-14	0.18E-14	0.50E-15	0.92E-16	0.81E-17	0.38E-18
5.03	0.96E-14	0.96E-14	0.95E-14	0.93E-14	0.89E-14	0.78E-14	0.39E-14	0.82E-15	0.17E-15	0.32E-16	0.15E-17
25.30	0.52E-14	0.52E-14	0.52E-14	0.51E-14	0.51E-14	0.49E-14	0.44E-14	0.33E-14	0.14E-14	0.40E-15	0.56E-16

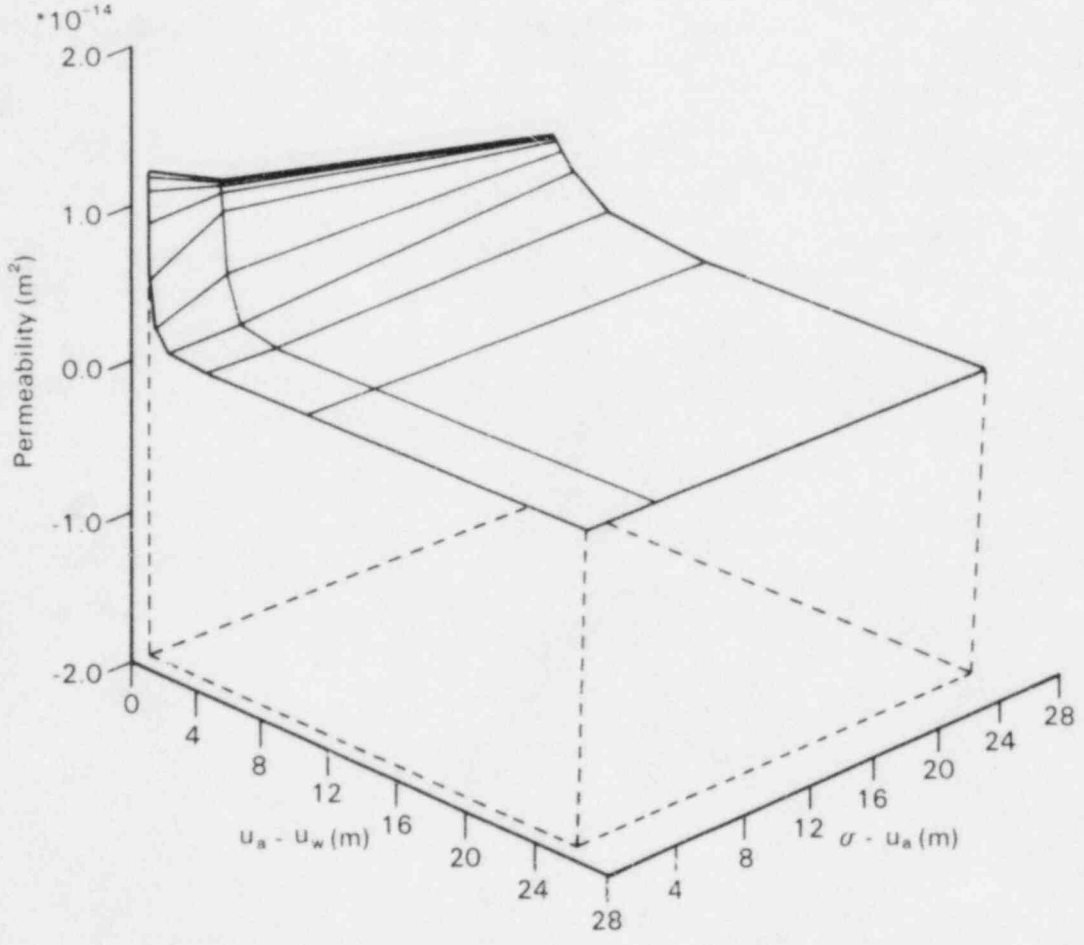

FIGURE B.4. Intrinsic Permeability Surface for 100% Slimes (based (based on data from Sherry 1982 and Schrauf 1984)

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APPENDIX C

TRUNC INPUT MANUAL

APPENDIX C

TRUNC INPUT MANUAL

The computer code TRUNC is a modified version of the TRUST computer code for variably saturated flow in deformable media. The main difference between the two codes is in the way TRUNC calculates void ratio changes caused by changing pore pressure. TRUNC also contains a new subroutine, called STRESS, which handles the stress calculations and output. There are some minor differences in the output format and several new diagnostic messages are included. TRUNC is written in ANSI FORTRAN-77 for the Digital VAX 11/780.

The conceptual model of variably saturated flow through deformable porous media, on which the computer code TRUST is based, was originally formulated by Narasimhan (1975), Narasimhan and Witherspoon (1976, 1977, and 1978), and Narasimhan, Witherspoon, and Edwards (1978). In the partially saturated zone, TRUST relies on the χ-parameter approach of Bishop (1960) to calculate consolidation. The χ-parameter has proven to be a highly nonlinear function of the degree of saturation and therefore difficult to define. TRUNC, on the other hand, uses the two-stress-state approach of Fredlund and Morgenstern (1976). This approach describes the void ratio as a three-dimensional surface, with the two stress-state parameters as the horizontal axes. The virtue of using this approach is that the two stress parameters, pore pressure and stress, can be independently measured.

All of the subroutines from TRUST that are used in TRUNC have been modified to some degree. Therefore, to operate TRUNC, only the new versions of each subroutine can be used. This appendix discusses the changes made to the input blocks from the original documentation (Reisenauer et al. 1982), which blocks have been deleted and which blocks are new, new subroutines, and finally lists the input manual. All variables in the manual are written in their computer form.

We have run a number of consolidation simulations with TRUNC and seem to have worked out the major programming errors. However, some minor errors may still remain undetected. If so, we would be interested in learning of the nature of any problem encountered while using TRUNC and will give due consideration to solving the difficulty.

CHANGES TO BLOCK 1

The KSTDATA term, which caused volumetric strain data to be printed out, has been dropped. The strain data are now routinely printed out by the new subroutine STRESS. A new term, NSTDY, was added to card 2 to deactivate the steady-state criteria. The steady-state criteria are conditions that stop the program execution, conditions such as time steps that are repeated for three consecutive time steps, or when the maximum pressure change is less than 0.1% of PSIVARY (the user-defined maximum allowable water potential change during

one time step). It was discovered that these criteria would sometimes end a problem even though steady state had not been achieved.

On card 3, PCONE has been replaced by SIGONE. SIGONE performs the same function as PCONE (initialize the stress). In addition, if SIGONE is negative, it will cause the new subroutine STRESS to iteratively calculate the total stress for each node, within a given tolerance. Also on card 3, a new term has been added called PSIONE. This option allows the user to set the initial pressure head for any node which does not have a total potential value defined in BLOCK 9.

A fourth card was added with four input values. The first parameter, WTF, is an upstream weighting factor. It allows the user to vary the weight given to each node when calculating the conductance between nodes. The remaining parameters are PCTC, PCTP, and PCTW. They represent the maximum percent change in the moisture capacity, permeability, and moisture content, respectively, that is allowed to occur during a time step. Thus, this option allows the user to select the variable which is considered most important and have it control the time step.

CHANGES TO BLOCK 2

Block 2 still deals with the material properties, but that is where the similarities to the original manual end because of the changes to the calculation of partially saturated consolidation in TRUNC. The soil properties (void ratio, degree of saturation, and permeability) are now input as three-dimensional surfaces, where each property is a function of the pore pressure and stress of the node. Hysteresis, the swelling index, CS, and the specific storage, SS, are not included.

The means still exist to input void ratio versus log of effective stress as a line, or void ratio versus log of permeability as a line. The user can choose whether to use the linear relationships or the edge of the soil property surfaces for saturated cases.

CHANGES TO BLOCK 9

The initial preconsolidation stress, PC, has been replaced with the initial total stress, SSIGMA. Also, a new term, VVSOL, was added that initializes the volume of solids contained in each node. If VVSOL is left blank, the new subroutine STRESS will calculate these values.

CHANGES TO BLOCK 10

It is now left blank.

ADDED BLOCK 11

Four output control parameters were created, which are JPIC, LPLT, LPLT1, and LPLT2. Essentially, these are used to generate data for graphical output.

ADDED BLOCK 12

This block identifies nodes that can undergo consolidation. Also, the lengths of the stress paths between consolidating nodes are input here.

NEW SUBROUTINES

1. INDX is a slight modification of the TRUST subroutine, ENTER, with a new name.

2. INTERP interpolates a value on a two-dimensional curve or a three-dimensional surface and finds the slope of one parameter with respect to a second parameter. This subroutine is necessary to represent soil properties as three-dimensional surfaces.

3. INSTAT is used for interpolating along the stress axis of the void ratio and permeability surface data, when the surface is to be used in the saturated region.

4. PLOT writes data to files specifically for plotting.

5. SECOND calculates the elapsed machine time, the percent of that time used by the user, the percent used by the system, and the percent used by input/output devices. This subroutine is specific for the VAX computer system.

The program reads the following data from logical unit 5. Line printer output is generated on logical unit 6. The restart data file (in BLOCK 9 format) is generated on logical unit 2. The logical units used for generating the plot data files are specified in BLOCK 11 and should not be set to 2, 5, or 6.

BLOCK 1 Problem controls, limits, and constants (required)

CARD 1. Format (9I5, 5X, 2E10.0)

Column No.	Variable	Description
1- 5	IPRINT	Number of time steps between data output, in addition to output on first, second and last time steps and output controlled by TIMEP. Not used if negative, zero or unspecified
6-10	NUM	Identification number of a node for which potential, rate of change of potential, source rate and time will be written for each time step. Useful for following the solution at a point of interest in the flow region. NUM is not used if unspecified.

11-15	KDATA	Controls options on output data, normal amount (0 or unspecified), minimum (-1), maximum (1)
16-20	KSPEC	Node classification and difference-equation control. Normally zero or unspecified. If zero, explicit nodes will be reclassified as implicit nodes only when needed to assure stability and the implicit interpolation factor may vary in the range 0.57 to 1.0. If negative, no nodes may be reclassified and the steady-state criteria will not be used to end the problem. If positive, all nodes are reclassified as implicit nodes before the first time step. If 2, the interpolation factor is set to 1.0 (backward differencing or fully implicit). If 3, the interpolation factor is set to 0.5 (central-differencing or Crank-Nicholson scheme). Individual node classifications may be made in BLOCK 4 with KS. All nodes in BLOCK 6 are classified as implicit nodes. DELTO and SMALL must be specified when KSPEC is positive.
21-25	MCYC	Maximum allowed number of time steps. Not used if zero or unspecified. If negative, problem will be ended after the first time step.
26-30	MSEC	Maximum allowed machine time in seconds. MSEC will not be used if zero or unspecified. If negative, problem will end after the first time step.
31-35	NPUNCH	If nonzero, causes a computer file in BLOCK 9 format to be produced on logical unit 2 at the end of the simulation. The data are the final values of potentials, sources and total stress. The new BLOCK 9 may be inserted in the input deck, which may then be resubmitted to continue the problem.
36-40	NDOT	If nonzero, causes all time derivatives to be maintained at zero during the problem. Not normally used.
41-45		Leave blank
46-50		Leave blank
51-60	TIMEP	Problem time interval between data output, in addition to output on first, second and last time steps and output controlled by IPRINT and JPIC. TIMEP is ignored if negative, zero or unspecified. Output will be written at exact multiples of TIMEP, if possible by adjusting the time step in the range from SMALL to DELTO. The adjustment is also limited to a range from 2/3 to 3/2 of the time step that would otherwise be used. (Units: T)

61-70	SCALE	Scale factor. Set to 1.0 if negative, zero, or unspecified. Will be applied to all geometric input data in BLOCKs 4, 5, and 6 read in following this BLOCK 1 and preceding any other BLOCK 1 with a different scale factor. Lengths will be multiplied by SCALE, areas by SCALE, volumes by SCALE. (Units: L)

CARD 2. Format (2I5, 7E10.0)

Column No.	Variable	Description
1- 5	KD	Symmetry type indicator: 1 for nonsymmetric; 2 for axisymmetric; 3 for centrisymmetric. Input values of DRAD in BLOCKs 4, 5 and 6 read in after BLOCK 1 will be replaced with DRAD, 2πDRAD and 4πDRAD^2 respectively. Set to 1 if unspecified or zero.
6-10	NSTDY	To deactivate steady state criteria set NSTDY equal to 1
11-20	DELTO	Maximum allowed time step size. May be used with SMALL to limit range of time step. DELTO is set to 10^{12} if unspecified or not in the range from 10^{-10} to 10^{12}. DELTO must be specified if KSPEC is positive. (Units: T)
21-30	SMALL	Minimum allowed time step size. May be used with DELTO to limit range of time step. Not usually needed. SMALL is set to 10^{-12} if less than 10^{-12}. If SMALL is unspecified, the program sets SMALL to 2/3 of 1% of the smallest time constant of any explicit node in the system, if at least 1/4 of the nodes are explicit nodes. SMALL should be specified in continuation problems of type 3 or 4, if not specified in the original BLOCK 1. (Units: T)
31-40	PSIVARY	Desired maximum change in potential in each time step. Set to 5.0 if zero or unspecified. Controls size of time step between the limits of SMALL and DELTO. Steady state cannot end the problem until the maximum potential change is less than 0.001 * PSIVARY for two successive time steps. The convergence criteria for iterative calculations for implicit nodes are a change in the weighted average potential change of all connected implicit nodes of less than $5 * 10^{-5}$ * PSIVARY and in the potential change of any finite-volume implicit node of less than $5 * 10^{-4}$ * PSIVARY. (Units: L of water)

41-50	TAU	Initial problem time. Will be set to zero if unspecified. (Units: T)
51-60	TIMAX	Maximum allowable problem time. TIMAX will not be used if zero or unspecified. If negative, problem will end after the first time step. (Units: T)
61-70	PSIMIN	Minimum allowable pressure head in the flow domain. Will be set to 10^{-12} if equal to or larger than PSIMAX or if unspecified. (Units: L of water)
71-80	PSIMAX	Maximum allowable pressure head in the flow domain. Will be set to 10^{12} if equal to or less than PSIMIN, or if unspecified. (Units: L of water)

CARD 3. Format (8E10.0)

Column No.	Variable	Description
1-10	PHIONE	Initial potential (PHI = Z + PSI) for all nodes for which PPHI is not specified in BLOCK 9. (Units: L of water)
11-20	GONE	Constant source or sink rate for all nodes for which GG is not specified in BLOCK 9. (Units: M/TL^3)
21-30	HONE	Fluid mass transfer coefficient for all external connections for which no HSURE or table of HSURT is specified in BLOCK 6. (Units: 1/T)
31-40	SIGONE	Initial total stress for all nodes for which SSIGMA is not specified in BLOCK 9. If SIGONE is less than zero, the program will iterate on the initial total stress until the consolidated volume is within ABS(SIGONE)% of the actual node volume for all nodes, regardless of the values which may be specified in BLOCK 9 (typically a value less than or equal to 0.00001 should be used). This option will only work for a one-column problem. (Units: L of water or %)
41-50	PSIONE	Initial pressure head (PSI = PHI - Z) for all nodes for which PPHI is not specified in BLOCK 9. PSIONE overrides any value that may have been specified for PHIONE. (Units: L of water)

CARD 4. Format (4E10.0)

Column No.	Variable	Description
1-10	WTF	Upstream weight factor used in calculating the overall conductance between nodes. Set WTF = 1.0 for full upstream weight, WTF = 0.5 for equal weight between upstream and downstream nodes. If WTF is zero or unspecified a harmonic mean is used (this is the normally preferred option).
11-20	PCTC	The maximum percent change in the moisture capacity function that is allowed to occur during a time step (default value is 5 percent). The use of the default value is highly recommended.
21-30	PCTP	The maximum percent change in the permeability function that is allowed to occur during a time step (default value is 15 percent). The use of the default value is highly recommended.
31-40	PCTW	The maximum percent change in the moisture content that is allowed to occur during a time step (default value is 10 percent). The use of the default value is highly recommended.

BLOCK 2 System and material properties.

CARD 1. Format (A5, 7I5, 3E10.0)

Column No.	Variable	Description
1- 5	AMAT	Name of material.
6-10	MAT	Material identification number.
11-15	LTABEP	Number of tabulated void ratio values along the PA-PSI axis.
16-20	LTABES	Number of tabulated void ratio values along the SIGMA-PA axis.
21-25	LTABSP	Number of tabulated saturation values along the PA-PSI axis.
26-30	LTABSS	Number of tabulated saturation values along the SIGMA-PA axis.
31-35	LTABPP	Number of tabulated intrinsic permeability values along the PA-PSI axis.
36-40	LTABPS	Number of tabulated intrinsic permeability values along the SIGMA-PA axis.
41-50	EV	Void ratio if constant. If EV is negative, 1) the program will calculate the initial stress and void ratio for each node, 2) consolidation will not occur, and 3) the degree of saturation and permeability will be taken from the respective property surface using the calculated initial stress. (Units: L^3/L^3)
51-60	SV	Saturation if constant. (Units: L^3/L^3)
61-70	PV	Intrinsic permeability if constant. (Units: L^2).
71-80	DENS	Soil particle mass density. Only required if BLOCK 12 will be used. (Units: M/L^3).

CARD 2a. Omit if LTABEP*LTABES is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	EP(1)	(PA-PSI) values (Units: L of water).
11-20	EP(2)	
	.	
	.	
	.	
	EP(LTABEP)	

CARD 2b. Omit if LTABEP*LTABES is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	ES(1)	(SIGMA-PA) values. (Units: L of water).
11-20	ES(2)	
	.	
	.	
	.	
	ES(LTABES)	

CARD 2c. Omit if LTABEP*LTABES is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	EV(1,1)	Void ratios corresponding to EP,ES (Units: L^3/L^3).
11-20	EV(2,1)	
	.	
	.	
	.	
	EV(LTABEP,1)	
	EV(1,2)	
	.	
	.	
	.	
	EV(LTABEP,LTABES)	

CARD 2d. Omit if LTABEP*LTABES is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	PELIM	The value of (PA-PSI) that separates the region where the void ratio is a function of the effective stress (SIGMAP) from the region where the void ratio is a function of the two stress-state variables (SIGMA-PA, PA-PSI). (Units: L of water).
11-20	CC	The compression index (ie. the slope of the void ratio versus log(SIGMAP) line) that is used to calculate void ratios for values of (PA-PSI) that are less than PELIM. E = EZ - CC * LOG10(SIGMAP/SIGPZ)
21-30	AV	The coefficient of compressibility (ie. the slope of the void ratio versus effective stress line) that is used to calculate void ratios for values of (PA-PSI) that are less than PELIM. This method of calculating void ratio is used only if CC is zero. E = EZ - AV * (SIGMAP - SIGPZ)
31-40	EZ	Reference void ratio on the void ratio versus log(SIGMAP) or SIGMAP line. (Units: L^3/L^3).
41-50	SIGPZ	Reference effective stress corresponding to EZ. (Units: L of water)

Note: If both CC and AV are zero the values of void ratio versus SIGMA-PA will be used to compute the void ratio. The first column of void ratio values (ie. corresponding to EP(1)) will be used. Therefore the void ratio surface should accurately represent the void ratio as a function of effective stress at EP(1) if this option is used.

CARD 3a. Omit if LTABSP*LTABSS is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	SP(1)	(PA-PSI) values. (Units: L of water).

11-20	SP(2)	
	.	
	.	
	.	
	SP(LTABSP)	

CARD 3b. Omit if LTABSP*LTABSS is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	SS(1)	(SIGMA-PA) values. (Units: L of water).
11-20	SS(2)	
	.	
	.	
	.	
	SS(LTABSS)	

CARD 3c. Omit if LTABSP*LTABSS is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	SV(1,1)	Saturations corresponding to SP,SS (Units: L^3/L^3).
11-20	SV(2,1)	
	.	
	.	
	.	
	SV(LTABSP,1)	
	SV(1,2)	
	.	
	.	
	.	
	SV(LTABSP,LTABSS)	

CARD 4a. Omit if LTABPP*LTABPS is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	PP(1)	(PA-PSI) values. (Units: L of water).

11-20	PP(2)	
	.	
	.	
	.	
	PP(LTABPP)	

CARD 4b. Omit if LTABPP*LTABPS is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	PS(1)	(SIGMA-PA) values. (Units: L of water).
11-20	PS(2)	
	.	
	.	
	.	
	PS(LTABPS)	

CARD 4c. Omit if LTABPP*LTABPS is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	PV(1,1)	Intrinsic permeabilities corresponding to PP,PS (Units: L^2)
11-20	PV(2,1)	
	.	
	.	
	.	
	PV(LTABPP,1)	
	PV(1,2)	
	.	
	.	
	.	
	PV(LTABPP,LTABPS)	

CARD 4d. Omit if LTABPP*LTABPS is less than 2
Format (8E10.0)

Column No.	Variable	Description
1-10	PPLIM	The value of (PA-PSI) that separates the region where the intrinsic permeability is a function of the void ratio

from the region where the intrinsic permeability is a function of the two stress-state parameters (SIGMA-PA, PA-PSI).
(Units: L of water)

11-20 CK1 Slope of the void ratio vs log(permeability) line that is used to calculate permeabilities for values of (PA-PSI) less than PPLIM. CK1 is used for void ratios less than or equal to EPZ.

21-30 CK2 Slope of the void ratio versus log(permeability) line that is used to calculate permeabilities for values of (Pa-PSI) less than PPLIM. CK2 is used for void ratios greater than EPZ.

$$CON = PZ * 10^{\left(\frac{E-EPZ}{CK1}\right)} \qquad E < \text{or} = EPZ$$

$$CON = PZ * 10^{\left(\frac{E-EPZ}{CK2}\right)} \qquad E > EPZ$$

21-30 EPZ Reference void ratio on the void ratio versus permeability line.
(Units: L^3/L^3).

31-40 PZ Reference intrinsic permeability corresponding to EPZ.
(Units: L^2)

Note: If both CK1 and CK2 are zero the values of permeability versus SIGMA-PA will be used to compute the permeability. The first column of permeability values (ie. corresponding to PP(1)) will be used. Therefore the permeability surface should accurately represent the permeability as a function of effective stress at PP(1) if this option is used.

Note: End BLOCK 2 with a blank card

BLOCK 3 Fluid properties.

CARD 1. Format (10A1, 4E10.0)

Column No.	Variable	Description
1-10	AFLUID	Name of fluid.
11-20	VISC	Coefficient of viscosity. (Units: M/LT)
21-30	BETA	Compressibility of fluid. (Units: LT^2/M)
31-40	RHOZ	Fluid density at PSI equal to zero. (Units: M/L^3)
41-50	GEE	Acceleration due to gravity. (Units: L/T^2)

Note: It is not necessary to end BLOCK 3 input with a blank card.

BLOCK 4 Node descriptions.

CARD 1. Format (5I5, 5X, 5E10.0)

Column No.	Variable	Description
1- 5	NODE	Node identification number. Use a negative number if the node lies on or will lie on a seepage face.
6-10	NSEQ	Number of identical nodes to be generated in sequence.
11-15	NADD	Increment between successive values of NODE when NSEQ is used.
16-20	NODMAT	Identification number of the material of which the node is a part.
21-25	KS	Node type indicator. Node will be an implicit node if KS is nonzero. Only used when KSPEC in BLOCK 1 is negative. Not needed for zero-volume or surface nodes.
26-30		Leave blank.
31-40 41-50 51-60	DLONG DWIDE DRAD	Geometric factors whose product with SCALE is equal to the node volume, if KD = 1. For KD = 2 or 3, the input value of DRAD is replaced with 2πDRAD, or 4πDRAD^2, respectively, before calculation of the volume. The program substitutes 10^{-24} if the calculated volume is zero. (Units: L)
61-70	DELZ	Increment between successive values of elevation, Z, when NSEQ is used. (Units: L)
71-80	Z	Elevation of node. (Units: L)

Note: End BLOCK 4 with a blank card.

BLOCK 5 Internal fluid flow connections.

CARD 1. Format (2I5, 3I3, I1, 4E10.0)

Column No.	Variable	Description
1- 5	NOD1	Identification numbers of the connected nodes.
6-10	NOD2	
11-13	NSEQ	Number of additional identical connections, or if DRAD is preceded by a minus sign, connections with DRAD values incremented by the difference between DRAD for this connection and DRAD for the immediately preceding connection.
14-16	NAD1	Increments between successive values of NOD1 and NOD2,
16-19	NAD2	respectively, when NSEQ is used.
20	NZ	Indicates NAD1 and NAD2 are each to be multiplied by 10^{NZ} before use in generating a sequence of connections.
21-30	DEL1	Lengths, when multiplied by SCALE, of the fluid flow
31-40	DEL2	paths from the nodal points in NOD1 and NOD2, to the connected interface. Both should not be zero. (Units: L)
41-50	DLONG	Geometric factors whose product with SCALE is the
51-60	DRAD	area of the connected interface if KD = 1. For KD values of 2 or 3, the input value of DRAD is replaced with 2πDRAD or 4πDRAD^2, respectively, before calculating area. (Units: L)

Note: End BLOCK 5 with a blank card.

BLOCK 6 External fluid flow connections.

CARD 1. Format (6I5, 5E10.0)

Column No.	Variable	Description
1- 5	NODS	Surface node identification number. NODS should be either a zero-volume node or a node with the nodal point on its external surface.
5-10	NODSB	Boundary node identification number.
11-15	NSEQ	Number of additional identical connections, or, if DRAD is preceded by a minus sign, connections with DRAD values incremented by the difference between DRAD for the connection and DRAD for the immediately preceding connection.
16-20	NADS	Increments between successive values of NODS and NODSB
21-25	NADSB	respectively, when NSEQ is used.
26-30	LTABH	Number of tabulated values of surface fluid transfer coefficients. Positive if versus potential, negative if versus pressure head.
31-40	DLONG	Geometric factors whose product with SCALE is the area
41-50	DRAD	of the external surface of NODS if KD = 1. For KD = 2 or 3, the input value of DRAD is replaced by 2πDRAD or 4πDRAD^2, respectively, before calculating the area. (Units: L)
51-60	HSURE	Surface fluid transfer coefficient if constant. (Units: 1/T)

CARD 2 Omit if LTABH equals zero.
Format (8E10.0)

Column No.	Variable	Description
1-10	HSURT(1)	Surface fluid transfer coefficient.
11-20	PSIVARH(1)	Potential, if LTABH is greater than zero; pressure head, if LTABH is less than zero.
21-30	HSURT(2)	

31-40	PSIVARH(2)
	.
	.
	.
	HSURT(LTABH)
	PSIVARH(LTABH)

Note: End BLOCK 6 with a blank card.

BLOCK 7 External boundary potentials.

CARD 1. Format (2I5, 7E10.0)

Column No.	Variable	Description
1- 5	NODB	Boundary node identification number.
6-10	LTABPHI	Number of tabulated boundary potential values. To obtain sinusoidal variation of boundary potential with time let LTABPHI = 100.
11-20	ZB	Elevation of boundary node. (Units: L)
21-30	PHIB(1)	External potential. Average value of sinusoidal variation, if LTABT equals 100.
31-40	TIMEB(1)	Time corresponding to PHIB(1). Period of sinusoidal variation , if LTABT equals 100.
41-50	PHIB(2)	External potential. Amplitude of sinusoidal variation, if LTABT equals 100.
51-60	TIMEB(2)	Time corresponding to PHIB(2). Phase advance time of sinusoidal variation, if LTABT equals 100.
61-70 71-80	PHIB(3) TIMEB(3)	Up to 3 pairs of values on this card, and 4 pairs on each additional card that is required, if LTABT is not zero. Use format (8E10.0) for additional cards.

Note: End Block 7 with a blank card.

BLOCK 8 Variable fluid generation rates.

CARD 1. Format (4I5, 6E10.0)

Column No.	Variable	Description
1- 5	NODG	Node identification number.
6-10	NSEQ	Number of additional nodes with identical variation of volumetric fluid generation rate as NODG.
11-15	NADG	Increment between successive values of NODG when NSEQ is used.
16-20	LTABG	Number of tabulated fluid generation values. To obtain exponential decay of fluid-generation rate with time, LTABG must be between -1 and 1, or unspecified, and GT(1) and TVARG(1) specified.
21-30	GT(1)	Fluid generation rate corresponding to TVARG(1), or at zero time (SUMTIM = 0), if exponential decay is specified. (Units: M/TL^3)
31-40	TVARG(1)	Potential or time corresponding to GT(1), or half-life of exponential decay if the latter is specified.
41-50	GT(2)	Fluid generation rate.
51-60	TVARG(2)	Potential or time.
61-70 71-80	GT(3) TVARG(3)	Up to 3 pairs of values on this card, and 4 pairs on each additional card that is required, if LTABT is not zero. Use format (8E10.0) for additional cards.

Note: End Block 8 with a blank card.

BLOCK 9 Initial conditions and constant fluid generation rates.

CARD 1. Format (3I5, 5X, 4E15.0)

Column No.	Variable	Description
1- 5	NOTE	Node identification number.
6-10	NSEQ	Number of additional nodes with identical initial conditions.
11-15	NADD	Increment between successive node numbers when NSEQ is used.
16-20		Leave blank.
21-35	PPHI	Initial potential. Set to PHIONE (BLOCK 1) if unspecified. (Units: L of water)
36-50	GG	Fluid generation rate. Set to GONE (BLOCK 1) if unspecified. Has no effect if GT versus TVARG is specified for this node in BLOCK 8. (Units: M/TL^2)
51-65	SSIGMA	Initial total stress. Set to SIGONE (BLOCK 1) if unspecified. Only required if consolidation is being simulated. (Units: L of water)
66-80	VVSOL	Initial volume of solids contained in the node. If zero or unspecified VVSOL will be calculated from the initial node volume and the void ratio. Only required if consolidation is being simulated. (Units: L)

Note: End BLOCK 9 with a blank card

BLOCK 10 is reserved for future enhancements

BLOCK 11 Graphical output controls.

CARD 1. Format(3I5)

Column No.	Variable	Description
1- 5	JPIC	Number of time steps between generation of data for graphical output, in addition to output generation for first, second, and last time steps, and output controlled by TIMEP (BLOCK 1). No graphical output will be obtained if JPIC is unspecified or zero.
6-10	LPLT	Logical unit number to which the graphical output data will be written. The generated file on unit LPLT must be saved through job control. If LPLT is negative an unformatted file is generated. The output includes potentials, porosities, volumetric moisture content and fluid fluxes.
11-15	LPLT1	Logical unit number for writing additional graphical output. The generated file on unit LPLT1 must be saved through job control. The output includes elevations, potentials, saturations and volumetric moisture contents.
16-20	LPLT2	Logical unit number for writing additional graphical output. The generated file on unit LPLT2 must be saved through job control. The output includes the consolidated volume and cumulative volume change.

Note: An ending blank card is not required.

BLOCK 12. Stress calculation path.

CARD 1. Format (2I5, 3I3, I1, 2E10.0)

Column No.	Variable	Description
1- 5	NODS1	Identification number of the upper node. The nodes must be input from top to bottom. The rest of the nodes will be below the first node. It is assumed during the stress calculations that the top node is located in the center (vertically) of the top element. If more than one column is to be simulated, input all of the node data for one column before starting the next column.
5-10	NODS2	Identification number of the lower node.
11-13	NSEQ	Number of additional identical stress-path connections.
14-16 17-19	NADS1 NADS2	Increments between successive values of NODS1 and NODS2, respectively, when NSEQ is used.
20	NZ	Indicates that NADS1 and NADS2 are each to be multiplied by 10^{NZ} before use in generating a sequence of connections.
21-30 31-40	DELS1 DELS2	Lengths of stress paths from nodal points of NODS1 and NODS2, respectively, to the connected surfaces. (Units: L).

Note: End BLOCK 12 with a blank card.

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APPENDIX D

TRUNC USER'S GUIDE

APPENDIX D

TRUNC USER'S GUIDE

The main purpose of this section is to help the user in setting up and running TRUNC and to pass on to other users information that we learned through our experience with the code. The TRUNC code is a tool that can be used (or misused) to evaluate a variety of groundwater flow problems, particularly those of saturated and partially saturated flow through deformable porous media. Using this or any other computer code effectively depends on the experience of the user and the familiarity of the user with the specific code. The topics to be discussed in this section include 1) the necessity for reliable data, 2) defining initial conditions, 3) common problems encountered using TRUNC and the steps taken to overcome those problems, and 4) new diagnostic messages.

The TRUST user's manual (Reisenauer et al. 1982), which discusses in detail the equations and the solution algorithm used in the original TRUST code, can also be applied to TRUNC. We have not modified the TRUST solution algorithm. We have only modified the input and output formats and the methods used to approximate changes in void ratio resulting from changes in pore pressure. This user's manual is intended for use as a supplement to the original TRUST user's manual. Much of the information necessary to understand and effectively apply TRUNC is in the original TRUST document and is not covered in this appendix.

RELIABLE DATA

The output from TRUNC, such as potentials, settlements, fluxes, and other predictions of the real physical system, is based on the input parameters. These input parameters are used to characterize the physical properties of the the flow system and the geometry of the flow domain. The predictions of the model are only as good as the input parameters. The TRUNC code requires a large amount of data to effectively use its capability to simulate partially saturated flow through deformable media, and its output is thus subject to the reliability of the data set.

INITIAL CONDITIONS

The initial conditions necessary to use TRUNC to simulate deformable porous media are the the total potential, elevation, and the total stress at each node. The initial pore water pressure is calculated from the total potential and elevation. The effective stress is calculated as the difference between the total stress and the pore water pressure at each node. Given the effective stress, the initial void ratio of each node is calculated using one of two methods described in Chapter 3. Briefly reiterating those two methods, the void ratio can be calculated using the classical log-linear relationship

between the effective stress and the void ratio or it can be linearly interpolated between data points on the actual curve of void ratio versus effective stress.

If initial conditions are not defined properly (i.e., nodal volumes are not equal to the calculated volume of voids plus the volume of solids for each node), the model will predict an instantaneous expansion or settlement such that the new nodal volumes are equal to the sum of the voids and the solids. This change in volume will occur on the first time step, no matter what time units are being used.

The following is a description of an algorithm we used to define initial conditions, and it gives nearly identical results to those iteratively calculated by TRUNC. We assumed that the original pore water pressure, u_w, of a saturated system at hydrostatic equilbrium can be defined as the depth below the surface. We also assumed that the weight of the cover load is initially carried by an increase in the original pore water pressure equal to and offsetting the weight of the cover load. Starting at the top node,

1. guess an initial void ratio,
2. calculate the total potential, $\phi = u_w + z$ (includes cover load)
3. calculate the total stress as a function of the void ratio, soil and water densities, and the volume of soil and water in the column above the node center
4. calculate the effective stress, $\sigma' = \sigma - u_w$
5. calculate the void ratio corresponding to the σ' value
6. compare the calculated void ratio with the previous guess. If the magnitude of the difference is less than a specified tolerance, accept the σ and e estimates for that node and go to the next node, returning to step 1. If the difference is greater than the tolerance, return to step 3 with the new estimate for the void ratio.

COMMON PROBLEMS AND SOLUTIONS

Most of the problems we encountered in using TRUNC were related to the characterization of void ratio and degree of saturation as three-dimensional surfaces with the two stress-state parameters as axes in the horizontal plane. To describe these problems, we must first examine the fundamental conservation of mass equation used in the TRUNC code, which is

$$G + \int_\Gamma \rho_w \frac{k\rho_w g}{\mu} \nabla \phi \cdot \vec{n} \, d\Gamma = \frac{d}{d\psi} (\rho_w V_n S) \frac{D\psi}{Dt} \qquad (D.1)$$

where G = fluid generation rate of a node
Γ = surface bounding a subregion
ρ_w = density of water
k = intrinsic permeability
g = gravity
μ = viscosity of water
∇ = delta or vector differential operator
ϕ = total potential ($\psi + z$)
$\hat{n}$ = unit outward normal vector
ψ = pore water pressure or pore pressure
d = derivative operator
V = volume of a subregion
n = porosity
S = saturation
$\frac{D}{Dt}$ = total derivative operator
t = time.

Note that the symbol ψ is used here to represent two distinctly different variables. When the system is saturated, ψ refers to the water pressure u_w. When the system is partially saturated, ψ refers to the pore pressure ($u_a - u_w$). On the right hand side of Equation (D.1) is a term referred to as the fluid mass capacity, M_c.

$$M_c = \frac{d}{dt} (\rho_w V_n S) \tag{D.2}$$

After several manipulations and differentiation, Equation (D.2) can be rewritten as

$$M_c = V_{sol}\ \rho_w \left(S e \rho_{wo} \beta g + S\frac{de}{d\psi} + e\frac{ds}{d\psi}\right) \tag{D.3}$$

where ρ_{wo} = density of water at atmospheric pressure
β = coefficient of compressibility of water

Equation (D.3) is the form of the fluid mass capacity term that is incorporated in the TRUNC model. This parameter, M_c, represents the mass of fluid that a nodal volume, V, can absorb or release as a result of a change in the average value of ψ over the volume. The first term represents the compressibility of water; the second term, the deformability of the soil matrix; and the final

term, the ability of the soil matrix to release water from the pores (desaturation). Note that the second term, $Sde/d\psi$, is different from that in the original TRUST code.

Most of the problems we encountered related directly to the second term, deformability of the soil matrix, specifically $de/d\psi$, in the fluid mass capacity equation. These problems were caused by extrapolation beyond our data set (to higher or lower stress values) and multivalued void ratio surfaces characterized by some sort of a ridge.

The first extrapolation problem we encountered occurred while analyzing saturated consolidation using the curve of void ratio versus stress. Our data set did not extend to a pore pressure of zero (0.704 m of water was our lowest pore pressure). The model would extrapolate void ratios at pore pressures below our last data point and would get reasonable values. However, to evaluate the second term in Equation (D.3), it is also necessary to estimate $de/d\psi$ (for the saturated case, $de/d\psi$ is equivalent to de/du_w). The model would extrapolate $de/d\psi$ values using the values from the two intervals between the lowest three pore pressure data points. $de/d\psi$ was decreasing between those two intervals, hence the extrapolated $de/d\psi$ value could become negative. Physically, a negative $de/d\psi$ value means that the void ratio decreases as the pore water pressure increases. The mass capacity term can become negative under these circumstances and the model would not be able to converge to a solution.

When the fluid mass capacity term becomes negative, Equation (D.1) predicts that an increase in pore water pressure over a time step should result in a decrease in the mass of water within the node, which defies the law of conservation of mass. This problem can be observed in the printed output results as a negative fluid mass capacity term at any particular node. Other manifestations of this problem are 1) many time steps consistently on the order of $1*10^{-12}$ time units (whatever the time units being used are); and 2) failure of the model to converge because of a violation of the minimum time step. It is important to note that this problem occurs when analyzing settlement under saturated conditions using the actual curve of data points to characterize void ratio as a function of the total stress. This problem does not occur using a log-linear representation of the stress versus void ratio relationship.

To overcome this problem, two methods may be employed. First, measured data can be obtained that characterize void ratio as a function of the two stress-state parameters, $(\sigma-u_a)$ and (u_a-u_w), in the range where (u_a-u_w) is close to zero. Because it was not possible for us to obtain the necessary void ratio data for low values of pore pressure, we used a second method. The second method was to insert two columns of data in the void ratio table (see Table B.1) at (u_a-u_w) values of 0.2 and 0.5 m of water with the same void ratio at each stress level as our lowest original (u_a-u_w) value of 0.704 m of water. This effectively makes the surface flat in this region and any extrapolated values will remain constant.

The problem of multivalued void ratio surfaces under partially saturated conditions is mentioned in the data set description in Appendix B. Two necessary criteria of the void ratio surface are discussed:

1. The void ratio must decrease monotonically with an increase in the stress-state parameter, (u_a-u_w), if the other stress-state parameter, $(\sigma-u_a)$ is held constant.

2. The void ratio must decrease monotonically with an increase in the stress-state parameter, $(\sigma-u_a)$, if the other stress-state parameter, (u_a-u_w), is held constant.

The numerical difficulties requiring these two criteria to be satisfied are related to the deformability of the soil matrix in the fluid mass capacity term $de/d\psi$ [for the partially saturated case, $de/d\psi$ is equivalent to $de/d(u_a-u_w)$]. If a void ratio surface is multivalued indicating some sort of a ridge, the estimate for $de/d\psi$ will be negative on one side of the ridge. All of the problems discussed previously concerning a negative mass capacity term can occur. These include time steps on the order of $1*10^{-12}$ and failure of the model to converge because of a violation of the minimum time step.

The estimates of $de/d\psi$ for each region of the void ratio surface are listed with the void ratio table in the printed results. These data should be examined carefully. If negative $de/d\psi$ values exist, the void ratio surface must be redefined.

Another problem occurs because of extrapolation beyond the input data, when the total stress becomes greater than the highest stress in the saturation table. This problem did not occur for the simulations and data set listed in this document, but we did run into problems on previous simulations with other data. Extrapolated values of saturation at high stresses, in some instances, became greater than 1.0. This problem was overcome by inserting another row of data into the saturation table at a higher $(\sigma-u_a)$ level with identical values of saturation at each (u_a-u_w) level. This makes the surface flat [with respect to $(\sigma-u_w)$] between the last two rows of data. Thus, extrapolated saturation values remain constant.

DIAGNOSTIC MESSAGES

Some new diagnostics are printed by TRUNC during each output cycle. The diagnostics can be found on the first line of output data describing controls and parameter changes in a given time step. The first new diagnostic parameter is labelled DPRES. It stands for the maximum change in pore pressure of all nodes over a given time step. The second diagnostic parameter not present in TRUST, labelled NT, is very useful for trouble shooting (see Table D.1). The NT parameter is used to note which physical property had the greatest change over the current time step and possibly limited the size of the time step. The numerical values of NT and their meaning are listed in Table D.1.

The third diagnostic parameter, labelled DPMAXS, is of use when NT is equal to 1, 2, or 3. If NT is equal to 1, DPMAXS is equal to the maximum allowable change in capacity (input parameter labeled PCTC), times the product of the maximum change in capacity and PSIVARY (input parameter used to control maximum change in potential). If NT is equal to 2, DPMAXS is equal to the

TABLE D.1. User's Guide to the Diagnostic Message NT

NT value	Meaning
0	Pore pressure
1	Capacity function
2	Moisture content
3	Permeability
4	Boundary potential
5	Boundary fluid mass transfer coefficient
6	Fluid generation rate

maximum allowable change in permeability (input parameter labelled PCTW) times the product of the maximum change in permeability and PSIVARY. If NT is equal to 3, DPMAXS is equal to the maximum allowable change in moisture content (input parameter labeled PCTW) times the product of the maximum change in moisture content and PSIVARY. The final diagnostic parameter is labeled NDMAX, which stands for the node number at which the parameter denoted by NT had its maximum change.

REFERENCES FOR APPENDIX D

Reisenauer, A. E., K. T. Key, T. N. Narasimhan and R. W. Nelson. 1982. TRUST: A Computer Program for Variably Saturated Flow in Multidimensional, Deformable Media. NUREG/CR-2360 (PNL-3975), U.S. Nuclear Regulatory Commission, Washington, D.C.

APPENDIX E

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Two empirical methods of settlement analysis (Terzaghi's theory and a simplified version of the Fredlund-Morgenstern two-stress-state approach) were compared to the computer code TRUNC, a modified version of the TRUST code for variably saturated flow in deformable porous media. The three methods were used to predict settlement of a 12.2-m-deep pile of tailings slimes with a drain at the bottom.

The simpler, empirical methods of settlement analysis were just as effective as TRUNC in predicting total settlement. For saturated tailings, predictions of total settlement by Terzaghi's theory and TRUNC were in close agreement (1.69 and 1.73 m, respectively). For partially saturated tailings, the simplified stress-state approach and TRUNC predicted similar total settlements (0.52 and 0.51 m, respectively).

Terzaghi's theory, as applied, overestimated the time of settlement under saturated conditions (170 days versus 140 days predicted by TRUNC) because it did not account for gravitational gradients. No empirical or analytical means were available to predict the time of settlement under partially saturated conditions. If the magnitude of partially saturated settlement is considered significant, then the time over which it occurs will most likely be the deciding factor in determining when to place the cover on the tailings pile.

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