McCartney, J.S., and Zornberg, J.G. (2003). "Assessment of Evapotranspirative Cover Performance using Field Data and Numerical Modeling." Proceedings of the *Fourth International Workshop on Applications of Computational Methods in Geotechnical Engineering*, Ouro Preto, Brazil, August 18-20, Vol. 1, pp. 297-304.

Assessment of Evapotranspirative Cover Performance using Field Data and Numerical Modeling

John S. McCartney
University of Texas at Austin
Jorge G. Zornberg
University of Texas at Austin

Abstract

This paper provides an overview of the use of numerical models such as UNSAT-H for evapotranspirative cover performance assessment. Comparison of field moisture profile monitoring data with numerical modeling results indicates that UNSAT-H provides realistic and accurate results for a short time period using actual meteorological and soil input data. However, the accuracy of this comparison decreases for extended simulation. The soil water characteristic curves for three soil densities were used in the simulations, with the soil density closest to the in-situ values showing the most realistic response. The sensitivity of model results to meteorological parameters was investigated, and it was found that solar radiation, wind speed, and cloud cover had insignificant effects. The use of hysteresis in the soil water characteristic curve was not found to improve the accuracy of the numerical model. Percolation collected by lysimetry was found to correspond well with the computed flux at the base of the soil layer.

1 INTRODUCTION

The overall objective of *any* type of landfill cover system is to minimize the percolation of liquids into the waste. For this reason, basal percolation is typically monitored to ensure the adequate performance of the cover system (e.g., using lysimeters). However, lysimeter measurements only define *if* the cover performs adequately (or not). As the overall performance of an *evapotranspirative* cover system relies on its ability to store moisture until it may be removed by evapotranspiration, other variables (e.g., moisture or suction profiles) should also be used to assess *why* the evapotranspirative cover performs adequately (or not). As monitoring of variables other than basal percolation is often indirect and may not be cost or time-effective, numerical modeling may be used to complement the evaluation of the main variables affecting the performance of evapotranspirative covers.

Using unsaturated flow modeling with site-specific soil, vegetation, and meteorological data inputs, this study assesses the performance of an instrumented evapotranspirative cover constructed atop a lysimeter. Specifically this study evaluates the use of UNSAT-H version 3.1 (Fayer 2000). Although the advantages and limitations of UNSAT-H are not comprehensively addressed, this study highlights the practical usage of this model for evapotranspirative cover performance assessment. After verifying the response of UNSAT-H with actual moisture profile data, this study presents sensitivity analyses to verify the modeling assumptions. UNSAT-H is then used to investigate the variation in basal percolation with time.

2 TEST COVER DESCRIPTION

The evapotranspirative test cover is located in a semiarid climate with an average annual precipitation of 396 mm and an average pan evaporation of 1394 mm (as quantified for the 1948 to 1998 period). The wettest months of the year (April to October) are also the months with the highest pan evaporation.

The cover being modeled has a thickness of 121.92 cm consisting of a silty clay (SC) with 43.4% passing the #200 sieve, a plastic limit of 9 and a liquid limit of 24.4. The cover soil was placed at an average dry relative compaction (RC) of 75.6% (standard proctor density) and at an average gravimetric water content of 6.5%. The pressure plate, hanging column and the filter paper methods (Klute 1986) were used to define the suction-volumetric moisture content relationship for the cover soil at a remolded relative compaction of 72.9%. In addition, to investigate the effects of density on the unsaturated properties of the soil, suction-volumetric moisture content relationships were developed for soils with remolded relative compaction values of 80.9 and 92.6%. Figure 1 shows the suction-volumetric moisture content relationship along with fitted van Genuchten soil water characteristic curves (van Genuchten 1980) for the cover soil at three different densities. The van Genuchten α, n and θ_r parameters, shown in Table 1, were adjusted to provide the best fit of the data through the range of suctions expected most often in the field. The arrows in the figure indicate the trend of the soil water characteristic curves with increasing density.

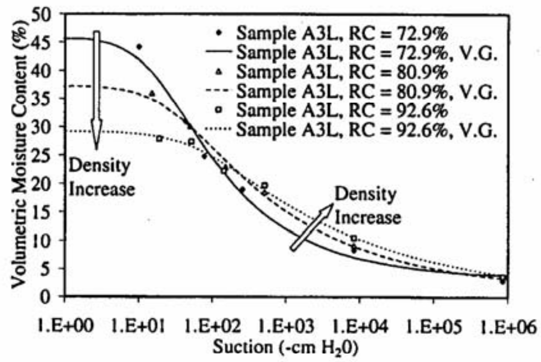

Figure 1: Suction-volumetric moisture content relationship for the cover soil

van Genuchten Parameter	Relative Compaction		
	72.9%	80.9%	92.6%
θ_s	0.4613	0.3741	0.2922
θ_r	0.0334	0.0118	0.0000
α	0.0552	0.0324	0.0147
n	1.3986	1.2744	1.2113

Table 1: Van Genuchten Parameters

Figure 2 shows the van Genuchten-Mualem (Mualem 1976) unsaturated hydraulic conductivity functions used in the model. They were obtained from the saturated hydraulic conductivity values shown in Table 2 and the van Genuchten parameters shown in Table 1. Also in this figure, the arrows in the figure indicate trend in hydraulic conductivity functions with increasing density.

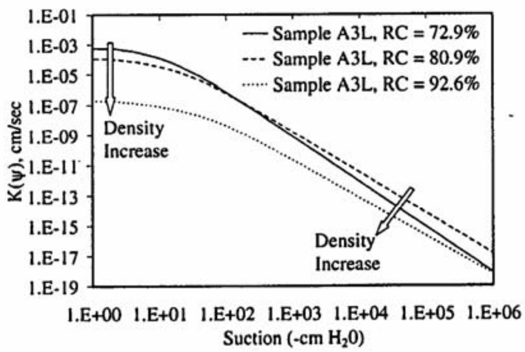

Figure 2: van Genuchten-Mualem unsaturated hydraulic conductivity functions

Table 2: Saturated hydraulic conductivity data

Relative Compaction, %	K_{sat}, cm/s
72.9	1.60E-03
80.9	3.90E-04
92.6	6.70E-07

The different water balance variables in the evapotranspirative cover were monitored at the site on a daily basis. Percolation was monitored by collecting water from a geomembrane lysimeter placed beneath the soil cover and measuring amounts using a tipping-bucket rain gauge. Rain, snow, and irrigation were measured using an all season gauge. Volumetric moisture content was measured using time domain reflectrometry (TDR) probes spaced at depths of 7.6, 26.9, 46.2, 65.5, 84.8 and 104.1 cm below the surface. For redundancy, additional TDRs were placed at 7.6 and 104.14 cm beneath the surface. This array of monitoring devices was selected to allow accuracy, low maintenance, and remote data access. Runoff was monitored using VFPE swales around the perimeter of the cover, leading to a tipping-bucket collection device. In addition, maximum and minimum daily temperature measurements were obtained from a nearby weather station. Monitoring of the cover commenced on July 10, 1998, which is designated as day 1, and is continuing to the present day.

3 NUMERICAL MODEL

The model UNSAT-H is a one-dimensional finite-difference code that simulates liquid water flow using Richards' equation, water vapor diffusion using Fick's law, and sensible heat flow using the Fourier equation. Heat flow was not evaluated in this study. Plant-water uptake is modeled using a sink term in the Richards' equation, and the potential transpiration is calculated empirically using the leaf area index (LAI) of the native grasses and forbs.

4 MODEL INPUT DATA

UNSAT-H requires extensive input data for analysis of evapotranspirative covers, including soil, meteorological, and vegetation data. In addition, several numerical modeling options may be selected. A flux upper boundary condition was selected equal to the precipitation/irrigation. A unit gradient lower boundary condition was selected. The Crank-Nicholson scheme was used for solution, and 53 nodes were used in the finite difference analysis, with six nodes coinciding with the depths of the TDR probes.

The upper flux boundary condition is the combined precipitation and irrigation. The total daily precipitation was applied at midnight, as the monitoring devices only provide a daily precipitation total. All precipitation was assumed to be rainfall (the rain gauge is capable of measuring snow and rain equally), even if it falls as snow. This implies that this analysis will overestimate infiltration during winter months when snow accumulates (neglecting sublimation) and underestimate infiltration during snowmelt. This is anticipated to be a major source of inaccuracy in the UNSAT-H results. The infiltration is assumed to be 100% efficient, with no runoff from the covers, which is consistent with the minimal runoff collected over the covers. The potential evapotranspiration and corresponding variation in LAI, was defined based on other studies on this evapotranspirative cover (Morrison-Knudsen 1998).

UNSAT-H requires input of three meteorological variables that were not monitored at the evapotranspirative cover (solar radiation, average wind speed and average cloud cover). These variables were obtained from historical data at a nearby weather station. Although several years of historical data was available, the data for 1981 was used in all simulations. For the sensitivity analyses that will be discussed in Section 6, the data for 1981 was used for all variables except for the one being investigated, which was obtained from the data for 1983.

The initial conditions needed for UNSAT-H include the suction values at each node in the soil profile. As the suction was not monitored at the evapotranspirative cover, the volumetric moisture content at each of the TDR probes was obtained and converted into suction using the van Genuchten parameters in Table 1. Figure 3 shows the initial moisture content for two different starting dates, day 175 corresponding to December 31, 1998 and day 540, corresponding to December 31, 1999. Figure 4 shows the initial suction profile for the cover soil obtained for three different relative compactions. The suction at the surface nodes (i.e., less than 7 mm from the surface), although not monitored, was assumed to be highly unsaturated.

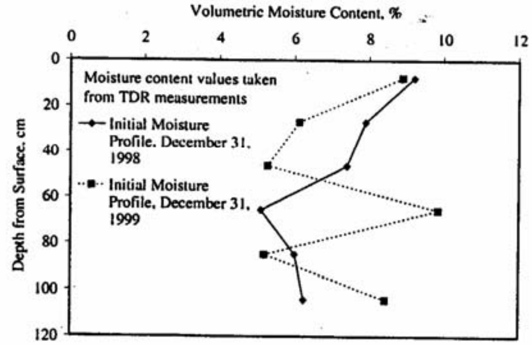

Figure 3: Initial soil moisture content data for model starting dates on January 1, 1999 (day 176) and January 1, 2000 (day 541)

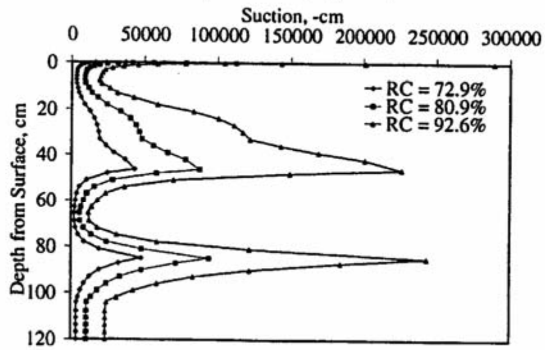

Figure 4: Initial suction data for a model starting date of January 1, 2000 (day 541)

5 MODEL VERIFICATION

Comparison between different input sets is made using the moisture storage in the soil cover. The moisture storage per unit cover area may be calculated as:

$$MS = \Sigma(\theta_i \times L_i) \qquad (1)$$

where θ_i is the volumetric moisture content measured by TDR i, and L_i is the tributary length for TDR i. L_i is calculated as the distance between the midpoints of subsequent TDRs. This is only an approximation of the total moisture storage was deemed adequate for comparison purposes.

Figure 5 shows a comparison of the moisture storage calculated from the TDR probe measurements with the moisture storage calculated from the computed moisture content values at the same depths as the TDR probes using UNSAT-H. The starting point for modeling is January 1, 2000 (day 541), which is sufficient time after the July 10, 1998 (day 1) construction-completion date for the vegetation to mature. This figure shows that the model results are both realistic and accurate until about day 775. Although the results show later a deviation in magnitude they still show similar trends. Figure 5(b) shows the relative error in the computed moisture storage values, and indicates that despite the change in magnitude around day 725, the model has a similar response around day 1000 before further deviation.

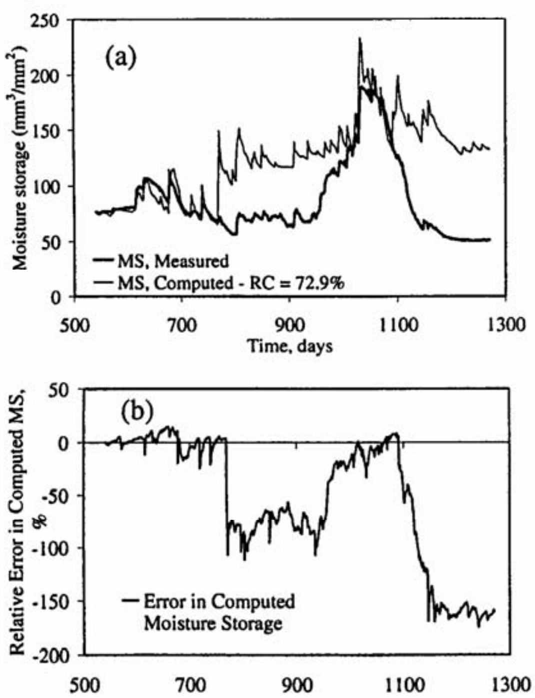

Figure 5: Moisture storage with time: (a) Comparison between monitored and computed moisture storage, (b) Error between monitored and computed moisture storage

Figure 6 shows a comparison between monitored and computed moisture content near the base of the cover with time. This figure shows that the moisture content recorded by the TDR has a significant spike around day 975, while the value computed by UNSAT-H does not respond at the same time or with the same magnitude. This indicates that this spike in moisture content may have been due to preferential flow near this TDR in the field, an element that a numerical model cannot capture.

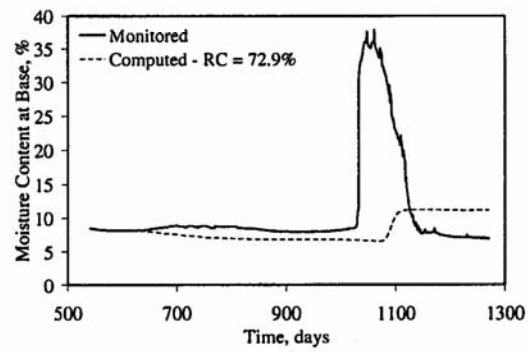

Figure 6: Comparison between monitored and computed basal volumetric moisture content

Due to the deviation in trend after day 775, UNSAT-H may be sensitive to the starting date selected to commence modeling. To investigate this, the model was started at an earlier time (despite the possibility that the vegetation was not mature) in order to observe if the same trend could be replicated. Figure 7 shows the variation in computed moisture storage for starting dates of January 1, 1999 (day 176) and January 1, 2000, with simulation continuing until December 31, 2001 for both cases. It is clear that both simulations follow the monitored moisture storage trend for a short period of time before deviating. However, both simulations yield similar results after day 750. This is interesting as it indicates that the use of initial suction conditions from the monitoring data leads to an accurate response for a short period of time, until the model stabilizes. Deviations between the monitored data and the computed data are probably due to different infiltration rates arising from the presence of a snow cover or frozen soil.

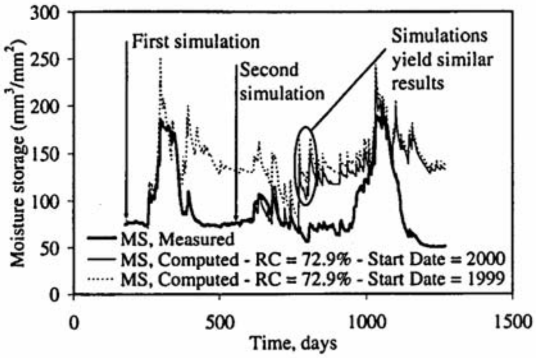

Figure 7: Variation in computed moisture storage for two different model starting dates

6 SENSITIVITY ANALYSES

Numerical modeling allows investigation of the effects of different variables on the overall performance of the evapotranspirative cover (Zornberg et al. 2003). This study investigates the sensitivity of evapotranspirative cover performance to soil density, different meteorological variables that were not measured on a site-specific basis (solar radiation, wind speed, cloud cover), as well as hysteresis in the soil water characteristic curves.

Figure 8 highlights the importance of using the soil water characteristic curve that is specific to the soil in the field. It is clear that the moisture storage for the remolded soil with relative compaction of 72.9% is the closest to the actual monitored moisture storage. It is interesting to see that remolded soil with a relative compaction of 80.9% responds similar to that with a relative compaction of 72.9%, while the computed moisture storage soil with the higher relative compaction of 92.6% does not change with time. This may be due to the fact that the majority of changes in the moisture content profile of the densest occurred in the surface layer, which does not lead to significant changes in the moisture storage calculated using equation 1.

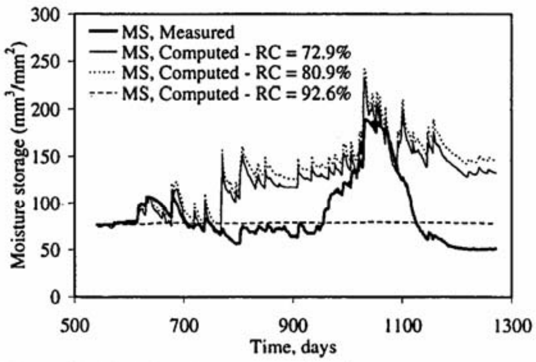

Figure 8: Variation in computed moisture storage for three densities

Figure 9(a), 9(b) and 9(c) shows the model sensitivity to different meteorological input parameters. In these analyses, all input parameters remain the same except for the radiation, wind speed or percent cloud cover, which are replaced by the values from a different year. For comparison, both the monitored moisture storage and the moisture storage computed using the same meteorological data as in Figure 5 (e.g., radiation data set 1, wind speed data set 1, cloud cover data set 1) are shown in these figures. Figure 9(a) shows that the different data set for the solar radiation does not lead to an appreciable difference in the computed moisture storage. Similar observations may be made the wind speed and cloud cover in Figure 9(b) and 9(c).

UNSAT-H version 3.1 is capable of analyzing soils that exhibits hysteresis, such as the sandy loam soil used in the evapotranspirative cover. Although laboratory tests were not conducted to quantify the hysteretic features of this soil, the primary drainage curves shown in Figure 1 were scaled to form hysteresis rewetting and drainage curves. Figure 10 shows the sensitivity of the model results to the use of hysteresis in the soil water characteristic curves. It is apparent that the use of hysteresis does not have a significant impact on the model results.

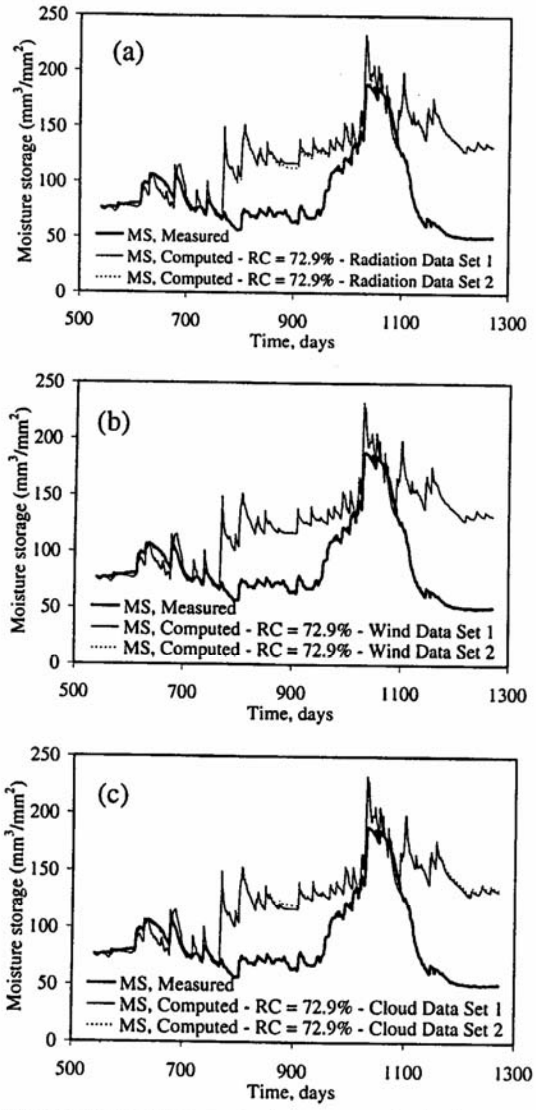

Figure 9: Sensitivity analysis to meteorological input parameters: (a) Solar radiation; (b) Wind speed; (c) Percent Cloud Cover

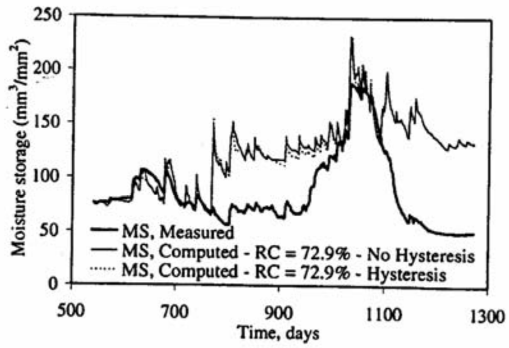

Figure 10: Effect of including hysteresis in the soil water characteristic curves

7 PERFORMANCE ASSESSMENT

As the results in Figure 5 indicate that UNSAT-H provides realistic results, the basal percolation computed by the model was compared with that of the lysimeter. Figure 11 shows the cumulative basal percolation computed using UNSAT-H for starting dates on January 1, 1999 and January 1, 2000 (whose moisture storage values are shown in Figure 6) and the monitored basal percolation. A good comparison between monitored and computed percolation can be observed. The model does not predict the pulse-type percolation recorded by the lysimeter, but shows gradual increases with time. The difference in the starting date of modeling affects , but again the trthe computed magnitude of the percolation, but similar trends can be found in both simulations.

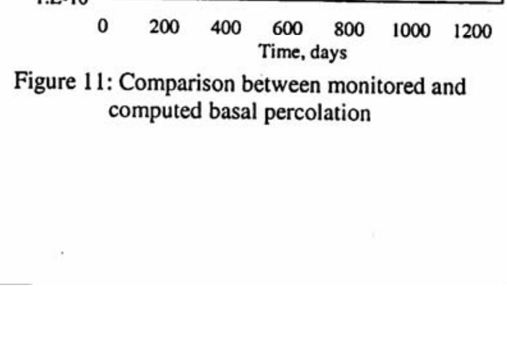

Figure 11: Comparison between monitored and computed basal percolation

Although the computed percolation values are similar to those obtained by lysimetry, it is still important to verify the results of UNSAT-H using another set of monitoring data (e.g., moisture content data). Blind use of a numerical model may have serious implications in model reliability, even if the final results (e.g., percolation) are observed to be consistent.

8 CONCLUSIONS

Numerical modeling provides an important tool for evapotranspirative cover performance assessment. UNSAT-H allows consideration of the individual variables affecting the cover system separately, and is flexible in it input requirements. Several conclusions may be made from the results of the analysis:

- UNSAT-H provides a realistic and accurate simulation of the actual behavior of the cover for a short duration, until it deviates in magnitude but not in trend
- Different starting dates lead to the same trend after a long period of time
- Soil density leads to marked changes in the soil water characteristic curve, which in turn lead to significantly different simulations
- UNSAT-H is not sensitive to the selection of solar radiation, wind speed, cloud cover, or hysteresis in the soil water characteristic curve
- UNSAT-H provides similar percolation results to those observed in the field using lysimetry

REFERENCES

Fayer, M.J. (2000). "Unsaturated Soil-Water and Heat Flow Model, Version 3.0." US Department of Energy. [Note: Same manual for Version 3.1]

Klute, A. (1986). "Water Retention: Laboratory Methods." Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, Soil Science Society of America, Madison, WI, 635-662.

Morrison-Knudsen. (1998). "RCRA-Equivalent Cover Demonstration Project: Final Design Package (Issued for Construction)." Rocky Mountain Arsenal, Denver, Colorado.

Mualem, Y. (1976). "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media." *Water Resources Research*, 12(3), 513-522.

van Genuchten, M. (1980). "A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils." *Soil Science Society American Journal*, 44, 892-898.

Zornberg, J.G. LaFountain, L. Caldwell, J.A. (2003). "Analysis and Design of Evapotranspirative Cover for Hazardous Waste Landfill." *Journal of Geotechnical and Geoenvironmental Engineering*. Vol. 129, No. 6, 427-438.

PROCEEDINGS OF THE 4th INTERNATIONAL WORKSHOP ON APPLICATIONS OF COMPUTATIONAL MECHANICS IN GEOTECHNICAL ENGINEERING
OURO PRETO/BRAZIL/18-20 AUGUST 2003.

Applications of Computational Mechanics in Geotechnical Engineering

Edited by

R.F.AZEVEDO
Department of Civil Engineering, Federal University of Viçosa, Brazil

E.A.VARGAS
Department of Civil Engineering, Catholic University of Rio de Janeiro

L. RIBEIRO E SOUSA
National Civil Engineering Laboratory & University of Porto, Portugal

M. MATOS FERNANDES
Faculty of Engineering, University of Porto, Portugal