Introduction
The R.M. Hardy Lecture of 1999, (Fredlund, 2000), emphasized the theoretical context for unsaturated soil mechanics and explained how the theories should now be put into greater usage in routine engineering practice. The time had come to take advantage of the decades of research into the engineering behavior of unsaturated soils and use it to improve geotechnical engineering practice. In 2005 the Terzaghi Lecture was presented (Fredlund, 2006) and the key findings were summarized for unsaturated soil mechanics over the past few decades. It was again emphasized that the research findings were poised to have a significantly greater effect on geotechnical engineering practice. Research into the behavior of unsaturated soils over the past few decades had provided a theoretical context for the classic soil mechanics topics of seepage, shear strength and volume change. The time appeared to be opportune to move towards a more detailed engineering approach for unsaturated soils.

Checks and Balances
Serious attempts have been made towards the implementation of unsaturated soil mechanics into engineering design and practice. For any new science or engineering procedure, there is also need for the implementation of a series of “checks and balances”. The question needs to be continuously asked, “Are we doing the engineering correctly?”, or “Are we doing the engineering to the best of our ability?” Engineering protocols need to first be proposed, then implemented and the finally verified.

The verification process becomes the “closing of the rationale loop” in engineering decision-making. It is for this reason that case histories with sufficient field measurements are so important. The field measurements provide worthy confidence that the theories are being applied correctly in engineering design. In the absence of the verification process it is possible for engineering design to develop a false confidence or become too optimistic in its predictions. There is often a difference between theory and engineering practice and the verification process can illuminate these deficiencies.

To a large degree, geotechnical engineers are self-regulating of their engineering design procedures. They attempt to study and keep track of what procedures appear to work and which procedures are not working. This has largely been the procedure adopted in the foundation design area. If new procedures are adopted and difficulties are encountered, often the lawyers become involved. We could say that when engineers do not put in-place satisfactory “checks and balances”, or verification procedures, then the courts take over that responsibility.

We would like to select one applications area involving unsaturated soils that has grown quite rapidly over the past few decades and use it to illustrate some questions that we need to be asking of ourselves as geotechnical and geo-environmental engineers. The applications area is that of “Barrier” and “Store and Release” covers or covers in general. Figure 1 shows an oblique view of the reclaimed waste rock and cover
system, at the Equity Silver in British Columbia. Cover systems have begun to be viewed as the solution to a wide variety of near-ground-surface problems. In each case, the covers are designed with the intent of providing long-term environmental protection by regulating the release of undesirable chemicals into the surrounding environment.

**The Move from Theory to Design**

The engineering design of a “Store and Release” cover system, for example, involves the application of unsaturated soil mechanics principles. The cover can change its degree of saturation with time and function in a manner beneficial to the environment. Reductions in the degree of saturation reduce the hydraulic conductivity, (coefficient of permeability) of the cover system as long as the surface soil does not crack due to drying, desiccation influences. The reduction in degree of saturation increases the storage capacity of the cover soil. The intent is for the cover to buffer the extremes of the climate forcing factors by storing water during wet periods and releasing it back to the atmosphere during dry periods.

Expressed simply, the soil-water characteristic curve, SWCC, for the soil defines the storage capabilities of the cover system. The infiltration and transmission ability of the cover system are largely dependent upon the permeability function for the soil (i.e., hydraulic conductivity versus soil suction). The permeability function for the cover material (and the underlying material), is also a function of the soil-water characteristic curve for the material.

From within the framework of theoretical unsaturated soil mechanics the design of a cover system appear to be a relatively straightforward application of unsaturated soil principles. The inherent simplicity and straightforward concepts associated with the theory and design of cover systems can easily lead to an unwarranted confidence in the designed systems. It is easy to forget that the cover system has been put as an interceptor between the ground and the atmosphere and has been called upon to perform satisfactorily under an extremely wide range of diverse flux boundary conditions.

We would like to revisit the design, performance and maintenance of a cover system within the context of a realistic “boundary value problem”. We would also like to ask questions such as, “Are we relying too heavily upon our analytical predictions?” Or, “Is our characterization of the forces of nature sufficiently broad to embrace worst scenarios?” Or, “Is it possible to place sufficient controls on the construction of the cover?” and “Is the vegetation cover properly characterized and sustainable?”

The intent is not to call into question all cover designs. There are cover systems that appear to be functioning well such as the one at one at Equity Silver in British Columbia or the Kidston gold mine in Australia. On the other hand there are other cover systems that do not appear to provide the long-term protection required to protect the environment. There are many factors to balance in the design of a cover system. It is the intent of this article to simply bring into clearer focus the complexity and detailed care that must be exercised when undertaking a cover system design.

**Nature of a Boundary Value Problem**

The advent of the digital computer allowed the formulation of most geotechnical engineering problems within the framework of a “boundary value problem”. There is a relatively standard set of information that is required for solving the problems. It is necessary to know the ground surface geometry and have a fairly well-informed appreciation of the underlying stratigraphic sequence. It is necessary to be able to characterize the conditions on the boundary of the problem. For unsaturated soils problems it is the characterization of the ground surface (net) moisture flux boundary condition that is of primary importance. The characterization of the (unsaturated) soil properties forms another important piece of input information. These are the primary factors that must be known in order to undertake the design of a cover system. And it is in this context that we would like to suggest a series of questions that will cause us to consider whether we are paying adequate attention to all aspects related to cover design and performance.

**Geometry and Stratigraphy**

Covers form the surface geometry of the problem to be analyzed. The stratigraphy associated with the pile has been built into the pile through the methods used to dispose of the waste materials. It is relatively easy to build a cover over tailings areas because of their relatively flat surfaces. Waste rock piles often have steep side slopes making it extremely difficult to construct a cover system on these surfaces. Both waste rock piles and tailings deposits are three-dimensional structures in shape; however, usually design considerations are limited to a one-dimensional analysis to simulate the relatively flat surface at the top of the pile and a two-dimensional analysis for the simulation of the side-slope region.

The original one-dimensional modeling of a cover system was solved with the development of the SoilCover computer code (MEND, 1993) based on the Soil – Atmosphere formulation proposed by Wilson (1990). The first two-dimensional analysis of covers on a sloping surface to control oxygen fluxes was performed by Bussière and Aubertien (2003). And more recently, a three-dimensional energy approach has been developed by Weeks and Wilson (2006). It might rightly be asked whether or not there is need for the sophistication of a three-dimensional analysis for cover designs. Recent studies by Weeks (2006) have shown that the computations of net evaporative flux from the soil surface can be significantly different depending upon the angle between the sun’s rays and the orientation of the surface of the ground. Consequently, the performance of the soil cover can vary significantly from one part of the pile to another part.

In many cases, the geotechnical engineer needs to be aware that the ground surface is not level and that the potential for runoff and ponding is possible. The unevenness of the ground surface can
result from differential settlement of the waste rock or the tailings with the result that the ground surface is highly susceptible to ponding. In other words, the performance of the cover from one location to another can differ considerably from a simple one-dimensional characterization. There may not need to be much change in the orientation of the ground surface to bring about significant changes to the water balance over the ground surface of the pile.

Cover systems, particularly when viewed in a one-dimensional setting, have the appearance of being simply problems to numerically model. This is somewhat deceptive in that while the geometry is simple, the characterization of the soil properties is highly nonlinear and lead to difficulties in obtaining convergence to a correct solution (Shackelford, 2005). It is important that checks be made of water balance calculations as well as benchmarking the software against published known solutions (Fredlund et al., 2005).

**Characterization of Climate**

The characterization of climatic conditions at the site is primarily required in order to quantify the net moisture flux at the ground surface. The primary, independent variables that need to be assessed are: i.) precipitation, ii.) actual evaporation and evapo-transpiration, and iii.) runoff. Net radiation and temperature conditions, along with relative humidity conditions are primarily used to compute evaporative conditions. Daily and sometimes average conditions over a selected period of time are used in the determination of precipitation, actual evaporation and evapo-transpiration.

The computation of net moisture flux conditions at the ground surface were not a part of historical soil mechanics presented in soil mechanics textbooks. These conditions are very much a part of unsaturated soil mechanics developments and it should also be noted that the net moisture flux at the ground surface involves a number of assumptions and complexities. Some of the inherent difficulties are mentioned in the following sections. Other factors such as freezing and thawing are often not be taken into account as well.

**Precipitation Moisture flux boundary conditions:** Precipitation can be in the form of rainfall and snowfall. Its magnitude must be measured at or near the site under consideration. Temperature, relative humidity, windspeed and rainfall are usually the basic variables measured using an elementary weather station. The measurements of precipitation may have been measured over a period of many years and then a typical or an average representation of precipitation is used in the calculations of the accumulated annual precipitation. The accumulated annual precipitation can take one of several forms depending on the annual distribution of moisture for the year as shown in Figure 2. Two differing scenarios are shown; namely, one where there is an even distribution of moisture throughout the year and another where there are two distinct, short-lived monsoon seasons. Even though the total precipitation in a year might be the same for the two cases, the response of a cover system to each situation would be considerably different.

An unsaturated soil can only accept water at a particular rate dependent primarily upon its present hydraulic conductivity and storage capabilities. While it is possible for the soil to accept water at a rate in excess of the saturated hydraulic conductivity, it is quite likely
that the intensity of rainfall during a storm can readily exceed the ability of the soil to accept water. Figure 3 shows the intensity of rainfall versus time along with the capacity of the soil to accept water. When the intensity of precipitation exceeds the infiltration capacity the remainder of the moisture becomes runoff or ponding on the ground surface. The conventional collection of precipitation data does not allow for the character of a particular storm to be quantified. In other words, the rainfall for an entire day may be spread over a day with no consideration of whether the storm was 10 minutes long or 10 hours long. This is an inherent weakness in the conventional manner in which rainfall data is collected and used in engineering design.

**Actual Evaporation:** Potential evaporation from a soil surface can be theoretically computed (or estimated) based on conditions of net radiation, temperature, wind speed and relative humidity at a particular site. Potential evaporation considerations can then be combined with the stress state in the soil at the ground surface in the form of a soil-atmospheric model to compute the actual evaporative moisture flux.

**Evapo-transpiration, Vegetation and its Characterization:** Plants can be viewed as small pumps that remove water more efficiently from the soil than is done through evaporation from the soil surface (Tratch et al., 1995). Evapo-transpiration from plants can be up to 10 times as high as actual evaporation. Therefore, it is important to take the ground surface vegetation into consideration. However, experientially the effect of vegetation has proven to be more difficult than initially anticipated.

Evapo-transpiration is primarily a function of the root uptake zone and the leaf area index, LAI, of the plants. The growing season for the vegetation must be assumed and nutrients must be available in the soil to sustain plant growth. The long-term sustainability of plant growth has proven to be a problem in numerous situations.

Numerical modelers find themselves having to make numerous assumptions with regard to vegetation effects and these assumptions have a large effect on the outcome of the analysis. It is fair to say that much more research is necessary with regard to how to characterize the effects of vegetation and how the results should be incorporated into a vegetation moisture flux model (Wilson et al., 2003).

**Water Balance and Runoff:** There are many factors that have an influence on the net infiltration at the ground surface. It seems that most assessments and judgments are made by determining average conditions for the soils involved and the imposed moisture flux load. In other words, the average and accumulated effect may not be providing an accurate picture of long-term performance of the cover system. Possibly closer attention needs to be paid to the high intensity storms; the 1:100 intensity rainfall that can cause serious problems. It is suggested that it is the extreme climatic conditions that cause the most serious failures of the cover systems. We need to be careful that we have not made too many simplifications to cover design.

**Soil Parameter Assessment**

The main soil properties required for the design of a cover system are the water storage characteristics and the permeability function relating the hydraulic conductivity to soil suction. These are both unsaturated soil properties that are dependent upon the soil-water characteristic curve, SWCC, for the soil, along with the saturated hydraulic conductivity. These soil properties need to be known for the proposed cover material(s), as well as for the underlying tailings or waste rock.

A variety of estimation procedures...
have been proposed for obtaining the required unsaturated soil properties. The estimation procedures range from use of the grain size distribution curve (Fredlund et al, 1999), to the direct measurement of the SWCC in the laboratory. Database “mining” has also been used (SoilVision, 1997). Generally it is the desorption curve that is used to obtain the unsaturated soil property function even though all required soil property function may have considerable hysteretic effects. Hysteresis in the SWCC means that a different curve should be used when simulating the drying process than when simulating the wetting process. While the hysteresis nature of the SWCC if of importance there are other factors of greater concern that need to be taken into consideration.

The material(s) used for the cover system may change considerably with time because of the environment to which they are subjected. Cracking due to settlements and volume change is certain to occur. Furthermore, the growth of vegetation creates a network of root holes, fissures and cracks. Freezing and thawing cycles tend to produce a nugget-type structure in the soil. There may also be microbial contamination and other bio-intrusions that also are factors affecting the soil structure.

Changes in the soil structure tend to significantly change the soil-water characteristic curve for the materials involved. Figure 4 illustrates the changes that might occur in a typical SWCC that contains some clay content. It is possible that the SWCC takes on a bimodal character and that the saturated hydraulic conductivity increases by several orders of magnitude. Consequently, numerical modeling simulations based on the properties of originally placed materials can be considerably different from reality.

**Design Relative to Performance**

There are many assumptions that are made as part of the design procedure for a cover system. The soil conditions can change with time due to the effects of weathering and freeze-thaw conditions with the result that the soil properties become far from the initially measured or assumed values. The changes can prove to differ by orders of magnitude from initial compacted or placed conditions. This does not make realistic design impossible but simply shows that much greater care and detail must be given to the assessment of the unsaturated soil properties.

The climatic quantification that provides the final “net moisture flux” has inherent in it many broad assumptions. The tendency to always work with average conditions may tend to cause a deviation from the real performance of the cover system. In other words, maybe the extreme weather conditions, not simply wet or dry years, that need to be more carefully evaluated during cover design. For example, extreme conditions where the runoff results in significant erosion problems.

The question is once again asked with respect to the soil and ground surface moisture flux conditions; “Has the problem been simplified too much and are we too encounter long-term problems as a result of relying too heavily upon ‘average’ conditions?” Put another way, “Are we putting too high a dependence upon the soil cover to solve our environmental problems associated with waste management?”

The intent of the above questions is not to discourage the design of cover systems but rather to ensure that all of the available engineering capabilities are brought to bear on the design of cover systems. For example, we have the opportunity to utilize probability theory for a more thorough and realistic characterization of the climate and the soil properties. There appears to have been too much emphasis on design for the mean, wet and dry conditions and in the end the design proves to be inadequate for extreme events. Consequently, many of the cover designs may be inadequate, too thin, or even too complex and expensive such that natural weathering will degrade the initial soil properties used for design and result in poor performance over the long-term.

The effect of cracks forming in a clay rich soil can completely change the soil response to infiltration and exfiltration. Unsaturated soil properties are highly nonlinear and may even change to be bilinear in character. These extreme conditions need to be given more attention and may even turn out to be the controlling factor once the clay content is of a certain percentage. Cover materials constructed using well graded gravels with a minor amount of silt and clay will remain more intact in the presence of extreme weather conditions and may function in a superior manner.

**Field Monitoring; Design Performance and Theory Verification**

Field monitoring needs to be an essential part of major cover systems. Measurements need to be taken to ensure that the cover system is performing as anticipated and as-designed. In fact, it is the field monitoring that has been performed on several cover systems that has given rise to the realization that closer attention may need to be given to the various components of cover design.

A typical field monitoring system for a cover system would involve the installation of: i.) lysimeter, ii.) weather station, iii.) soil suction measurements within the soil cover and iv.) water content measurements within the soil cover. Equipment is available commercially for each of the mentioned measurements. If it was necessary to place a hierarchy on the items required for monitoring, the hierarchy would probably follow the order shown above. In other words, the lysimeter would be the number 1 item to be installed.

The design details for the lysimeter are extremely important in order that it will provide accurate measurements of infiltration. The lysimeter may need to be in the order of 10 to 20 meters in length to yield accurate results (Benson et al, 2000).

Weather stations can be purchased for $10,000 to $15,000 and should be placed at the site of the cover system. While the cost of the weather station is modest, its maintenance and servicing may entail considerable expenditure.

It must also be remembered that visual field inspections and reporting
Long-Term Integrity
Long-term integrity of soil cover systems may increasingly become an activity within geotechnical and geo-environmental engineering. Soil cover designs have rapidly emerged and open-minded evaluation of their performance is essential for ensuring their long-term integrity and acceptability.

Acknowledgements
Fundings for the research that was conducted at the University of Saskatchewan were provided by the following agencies: CCRP, Placer Dome Inc. and Placer Dome Environmental Engineering. Graduate student support and numerous field sites for the research that was conducted at the University of Saskatchewan was conducted at the University of Saskatchewan.

References

Delwyn G. Fredlund, Senior Geotechnical Engineering Specialist, Golder Associates Ltd., 145 - 1st Avenue North, Suite 200, Saskatoon SK., Canada S7K 1W6, email: unsaturatedsoil@yahoo.com or del_fredlund@golder.com
Dr. G. Ward Wilson, Professor and Chair, Mining & the Environment, Dept. of Mining & Mineral Processing Engineering, Room 517, 6350 Stores Road, University of British Columbia, Vancouver, B.C., Canada, V6T 1Z4