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Numerical study of time dependent behavior of reinforced soil walls

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ABSTRACT: In the recent past, many numerical studies of geosynthetically reinforced soil structures have been performed. A relatively small subset of these studies has accounted for the time-dependent behavior of the geosynthetic reinforcement. In such studies, specific creep laws were typically assumed for the reinforcement; the stress relaxation response of the reinforcement was not considered. As part of research aimed at developing a robust constitutive model that realistically accounts for both creep and relaxation of geosynthetic geogrids, a large number of finite element analyses of geosynthetically reinforced walls with cohesive backfill have recently been performed. The proposed paper will summarize the important constituents of the mathematical models created, and will present selected results of parametric studies that were performed as part of the aforementioned analyses.

1 INTRODUCTION

In order to gain better insight into mechanisms affecting the behavior of geosynthetically reinforced soil structures, engineers have turned to numerical (approximate) analyses. One of the most popular numerical analysis techniques currently in use is the finite element method. This powerful analytical tool holds much promise for simulating the behavior of geosynthetically reinforced soil structures, especially under "working stress" (non-failure) conditions. To date, the majority of finite element analyses of reinforced soil structures have not considered the time-dependent response of the geosynthetic reinforcement, nor of the backfill. While it may be argued that free-draining backfill exhibits little time-dependence, such is not the case if cohesive backfills are considered. Since the use of such materials is becoming more prevalent, the importance of correctly simulating this second source of time-dependence cannot be discounted. In light of the above discussion it is evident that a systematic study of the mechanisms affecting the time-dependent behavior of reinforced soil structures is indeed warranted. Such a study must be comprised of both experimental and numerical components. The former would involve carefully monitored laboratory and field experiments of the constituent materials and of various structural geometries. The latter would investigate mathematical modeling techniques and assumptions used in simulating the behavior of reinforced soil structures. The validation of these techniques and assumptions would be realized by comparing numerical simulations with experimental results generated in the first component of the study.

The purpose of the present work was twofold: 1) Based on the results of high-quality experiments, to develop a realistic constitutive model for geogrid reinforcement that accounts for general time-dependent response, and, 2) To gain insight into the time-dependent behavior of geosynthetically reinforced soil walls primarily under non-failure ("working stress") conditions. Mathematically modeling a laboratory-instrumented wall with cohesive backfill and then performing numerical parametric studies of the wall realized this insight. In each of the studies the number of assumptions associated with the modeling process was minimized. In all cases the soil-wall-reinforcement system was treated as a boundary value problem and analyzed using the finite element method.

2 DEVELOPMENT OF A SIMPLE YET ROBUST CONSTITUTIVE MODEL FOR GEOGRIDS

2.1 *Creep Isochrones*

The time dependent behavior of geosynthetics has primarily been studied by means of creep tests, both in-isolation as well as in-soil. The relative lack of stress relaxation studies is primarily attributed to two factors. First, current simplified design procedures are based on the simple interpretation of creep test data, and thus do not require stress relaxation results. More precisely, current design guidelines (Leshchinsky and Perry 1987) bypass the creep problem by specifying an allowable tensile strength that is a fraction of the ultimate short term tensile strength of the reinforcement. Although such an approach is simple to apply, it completely ignores the interaction between the soil and the geosynthetic. A second reason for the scarcity of stress relaxation data is the perceived complexity of the test. In a creep test the tensile load is maintained constant and the resulting strains are measured with time. However, in a stress relaxation test the strain developed immediately following load application is maintained constant via a reduction of the tensile load with time. Consequently, such a test inevitably requires a more sophisticated device with feedback control. In order to avoid the complexities associated with relaxation tests, researchers have sought to indirectly generate relaxation data through the use of isochronous creep curves or isochrones. Isochrones are plots of (constant) load or stress versus strain recorded at various times during a creep test (Figure 1). Requisite to an investigation of isochrones is the availability of high-quality experimental results of both creep and stress relaxation tests for a particular range of materials. The present investigation is limited to geogrids, tested in-isolation. It uses experimental results described in Leshchinsky et al. (1997). The validity and range of applicability of the isochrone approach has been investigated (Kaliakin et al., 2000).

2.2 *Time-Dependent Models for Geosynthetics*

The most basic models developed to simulate creep response of geosynthetics are simple, empirical, mathematical expressions. For example, the following expression has been proposed

$$\varepsilon = \varepsilon_o + A \log t \qquad (1)$$

where ε represents the total strain, ε_o and A are functions of stress, temperature and nature of the material, and t denotes time.

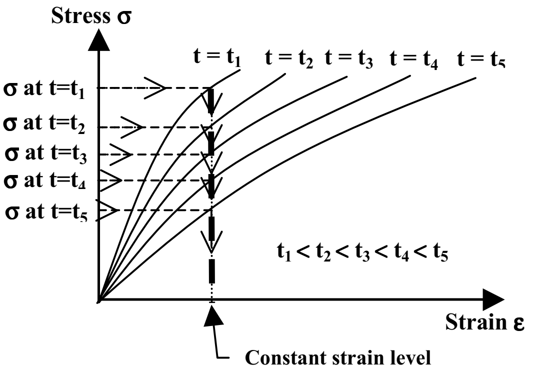

Figure 1 Details of Predicted Stress Relaxation from Isochronous Curve

Koerner et al. (1993) presented the following two-parameter "in house" formula for stress relaxation of geomembranes.

$$\sigma(t) \;=\; c\,t^{-b} \tag{2}$$

where t denotes time, and b and c are constants. This type of behavior has been referred to as "physical stress relaxation," as opposed to chemical relaxation (Debnath, 1985). Sawicki (1998) proposed rheological models for predicting the creep or relaxation response of specific geogrids in equation (3) and (4), respectively.

$$\frac{\varepsilon}{T} = \frac{1}{E^*} - \frac{1}{E_2}\exp\left(-\frac{E_2}{\eta}t\right) \tag{3}$$

$$\frac{T}{\varepsilon} = (E_1 - E^*)\exp\left(-\frac{E_1 + E_2}{\eta}t\right) + E^* \tag{4}$$

where E_1 is the stiffness of the "series" spring and E_2 and η represent the stiffness and viscosity, respectively, of the Kelvin system. The force per unit width in the geogrid is denoted by T, ε is the total strain in the geogrid, and t denotes time. And

$$E^* = \frac{E_1 E_2}{E_1 + E_2} \tag{5}$$

However, no simple models appear to have been proposed that account for both creep and relaxation in a robust yet reasonably accurate fashion. In addition, simple mathematical models, rheological models, and integral techniques all lack one fundamental characteristic that is necessary for their implementation into finite element or finite difference computer programs. Namely, using any of the aforementioned approaches, one cannot compute a consistent incremental tangent modulus,

$$E_t = \partial\sigma / \partial\varepsilon \tag{6}$$

Attention is thus turned to the development of a simple, yet robust constitutive model for geosynthetics that has associated with it a consistent incremental tangent modulus. Rather than employing rheological models or integral techniques, the approach used is based on the conclusions of the creep isochrones. It follows that, although not unique, the force-strain-time states quantified by creep isochrones can reasonably predict the time-dependent response of certain geogrids at relatively low ("working") load levels. Thus, if the creep isochrones can be represented mathematically, this representation will constitute a simple constitutive model for the geogrids that applies to general loading conditions including creep and relaxation. As such, the development of the present model begins with an investigation of the mathematical representation of creep isochrones. Consequently, Dechasakulsom (2000) proposed the following general mathematical representation for isochronous creep curves

$$T \;= c_1\varepsilon^{c_2} \quad \frac{1}{1+\alpha t^{\beta}} \tag{7}$$

where c_1 and c_2 are constants, and α and β are model parameters. The force per unit width in the geogrid is denoted by T, and t denotes time. In light of equation (7), it follows that for the present model

$$E_t = \frac{1}{A}\frac{\partial T}{\partial \varepsilon} = \frac{1}{A}c_1 c_2 \varepsilon^{(c_2-1)}\,\frac{1}{1+\alpha t^{\beta}} \tag{8}$$

where the cross-sectional area (per unit width) A is assumed to remain constant. The inverse form of equation (7) is

$$\varepsilon \;= \left[\frac{T\left(1+\alpha t^{\beta}\right)}{c_1}\right]^{(1/c_2)} \tag{9}$$

For a constant value of T, it follows that the bracketed value, and thus the strain ε, will *increase* with time. This qualitative observation is consistent with the simulation of a creep experiment. For a constant value of ε, a stress relaxation expression, it is already shown in equation (7) and thus the load T will *decrease* with time.

2.3 *Simple Finite Element Simulations*

The constitutive model described by equation (7) was next incorporated into the APES (Analysis Program for Earth Structures) computer program (Kaliakin 2000). The APES program is written in FORTRAN 90. It can be used to perform two-, or three-dimensional quasi-static analyses of continua. For two-dimensional analyses, the solution domain can be idealized assuming conditions of plane strain, plane stress, or torsionless axisymmetry. Since the formulation used in the program takes into account the coupling between stress and flow, APES is able to analyze saturated backfill soil. It is important to note, however, that the program is written in such a manner as to avoid unnecessary computations when this coupling is not desired in an analysis (such as the case of the present simulations). In short, the efficiency of the program is not compromised in such a case.

3 NUMERICAL SIMULATION OF A GEOSYNTHETICALLY REINFORCED SOIL RETAINING WALL

The aforementioned constitutive model is used in mathematical models for the finite element analysis of soil walls reinforced with geosynthetic inclusions; i.e., the so-called mechanically stabilized earth walls (MSEW). By using the now verified model in the analysis of such boundary value problems, insight can be gained into their time dependent response in a structure subjected to confining pressure. Two sources of time dependence potentially contribute to the performance of such structures, namely the time-dependent behavior of: 1) The backfill and foundation soil; and, 2) The geosynthetic reinforcement. In order to include the former source of time dependence in the model assessment, the backfill and possibly foundation soil should be a clay of silty clay. Provided the soil structure is reinforced with a geosynthetic, the latter source of time dependence will be assured. A search of the pertinent literature turned up the so-called "Denver Wall" Wu (1992a) as the best candidate for the present model assessment.

3.1 *Numerical Modeling*

The actual dimensions of the Denver wall (Figure 2) were used in the finite element model. Guided by the results of sensitivity studies, the mesh shown in Figure 3 was determined to be sufficiently fine so as to minimize the effects of discretization error on the solution. This mesh consisted of 2157 four-node quadrilateral (Q4P0) elements that discretize the backfill soil and wall facing, 768 zero-thickness (LK1) interface elements that allow for relative displacement between the reinforcement and the soil, and 415 bar (L2P0) elements that represent the geotextile reinforcement. Four rows of quadrilateral elements were used in between each of the layers of reinforcement.

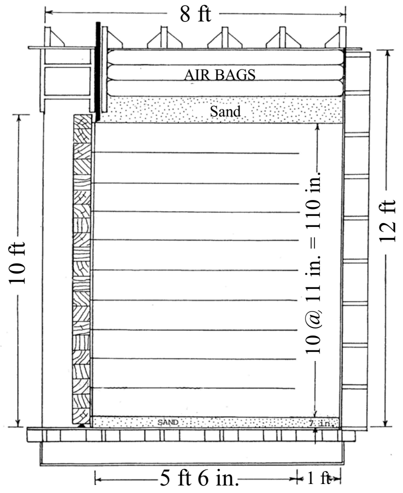

Figure 2 Details of Denver Wall Geometry (after Wu 1992a)

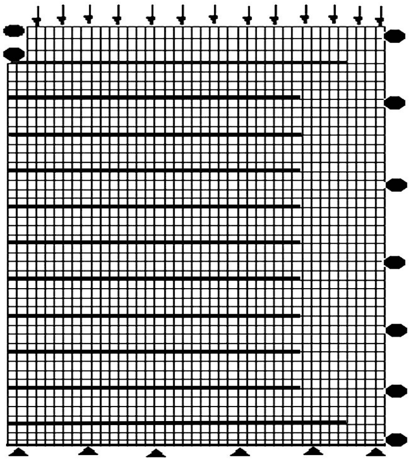

Figure 3 Finite Element Mesh Used in Analysis of the Denver Wall

In this study, the backfill soil is represented by standard four-node (Q4P0) quadrilateral elements. Its behavior was modeled using the bounding surface model for cohesive soils. It was idealized as an elastoplastic-viscoplastic continuum Kaliakin and Dafalias (1991). The reinforcement is represented by two-node (L2P0) bar elements. The time-dependent model used herein is applied by creep isochrones, from equation (7). For the analyses of the Denver wall, values for the model parameters c_1, c_2, α and β were determined by matching the isochrones. The resulting values of these parameters were 97.23, 0.55, 0.5, and 0.17, respectively. In Figure 4, the approximate isochrones generated using these parameter values are compared to the values from experiment. Using equation (7) in conjunction with the above values of c_1, c_2, α and β the creep predictions shown in Figure 5 were generated. As evident from this figure, the predictions are quite accurate, particularly at the lowest and highest levels of sustained load. The actual construction history (Figure 6) was accurately duplicated using the process of "incremental construction". The loading sequence (Figure 7) for the wall consisted of the application of a 15 psi surcharge after completion of construction. This was followed by a period of 100 hours during which the load was maintained constant. Thereafter, equal increments of 3 psi surcharge were applied until a failure condition was developed for a total surcharge of 33 psi.

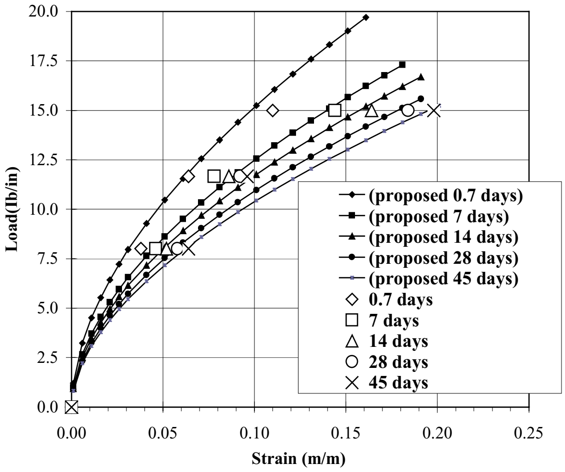

Figure 4 Simulated and Experimentally Derived Isochrones for Geotextile Reinforcement

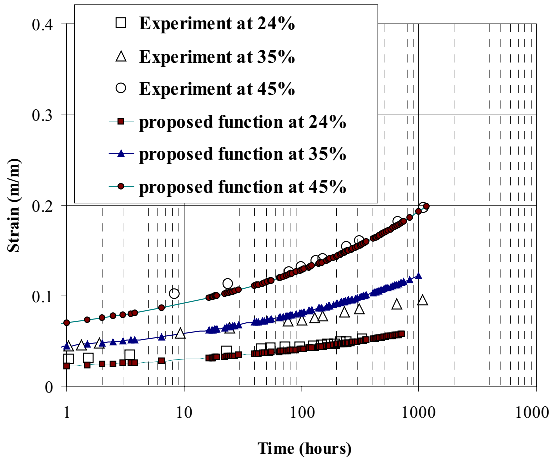

Figure 5 Simulated and Experimental Creep of Geotextile Reinforcement

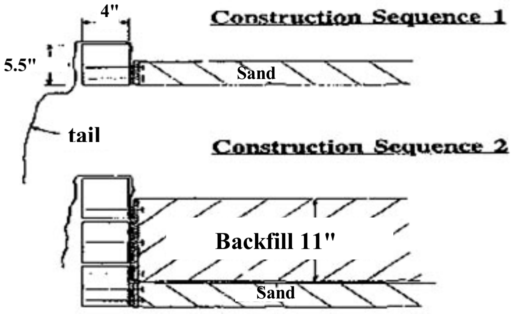

Figure 6 Construction Sequence in Denver Wall (after Wu 1992a)

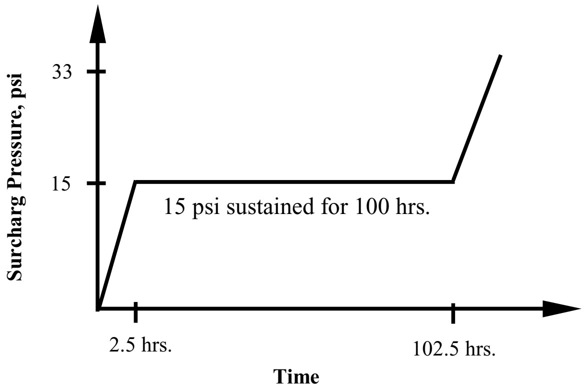

Figure 7 Loading sequence in Denver Wall (after Wu 1992a)

4 RESULTS

The results of the FEM analysis employing a *time-dependent* idealization of the geotextile reinforcement compared with the field measurement are presented in Figure 8 to 10. In Figure 8, the predicted displacement profile of the top of the fill is compared to measured values. The predicted lateral displacement of the timber facing is compared to measured values in Figure 9. The predicted strain and force distributions in the geotextile reinforcement at 18" is shown in Figure 10.

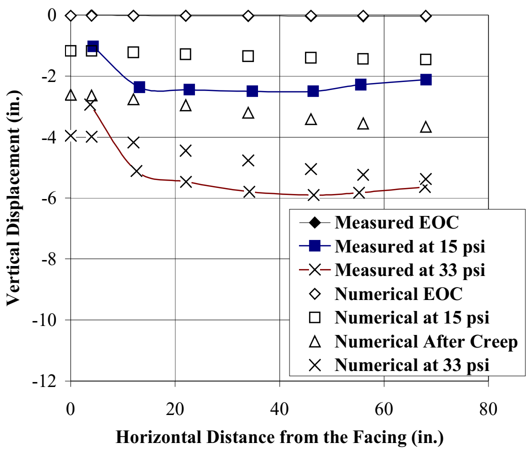

Figure 8 Displacement Profile of Top Fill Surface

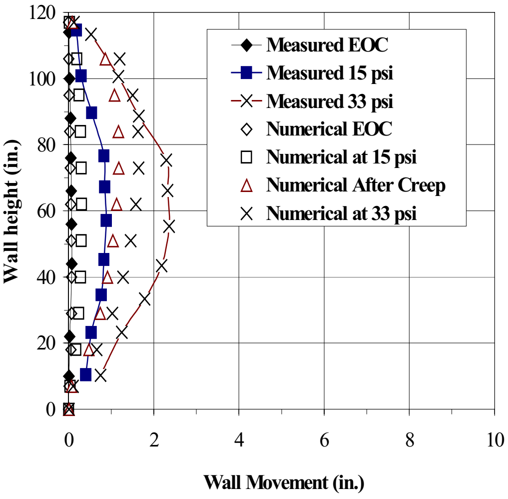

Figure 9 Displacement Profile of Timber Facing

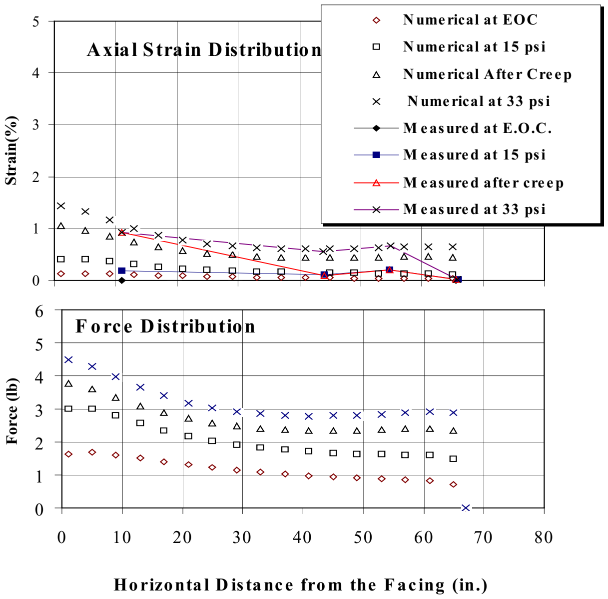

Figure 10 Predicted and Measured Strain and Force Distribution in Reinforcement 18" Above Base of Wall

5 CONCLUSIONS

A simple constitutive model, capable of simulating both creep and relaxation response of geogrids, was developed. The analytical form of the model yields a consistent instantaneous tangent modulus. This in turn facilitates the numerical implementation of the model into finite element computer programs. Numerical study of time dependent behavior of reinforcements was studied. A full-scale, laboratory instrumented geosynthetically reinforced wall was modeled and finite element analysis was performed. The FEM prediction results were compared to the field observations.

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