TIME DEPENDENT BEHAVIOUR OF GEOSYNTHETIC REINFORCED SOIL WALLS

INFLUENCE DU TEMPS DANS LE COMPORTEMENT DES MURS DE SOUTENEMENT RENFORCES PAR GEOSYNTHETIQUES

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SYNOPSIS: The paper describes a viscoelastic model to simulate the creep behaviour of geosynthetics, which is based on a chain of Kelvin units interconnected in series. The model is efficient and economic because the viscoelastic evolution is transformed into a sequence of n pseudo-elastic calculations, which are easy to perform since each step depends only on the preceding one. The implementation of this model in a finite element code is also discussed. Using the described viscoelastic model a study of long term behaviour of geosynthetics (in geogrid reinforced wall) is carried out. This study leads to the conclusion that changes in inclusion strains during time are composed by two parts, one due to material creep and another, elastic, due to the change in state of stress, and also that the behaviour of walls reinforced with those materials changes more significantly during the first year of service.

INTRODUCTION

Nowadays it is well established that the time dependent behaviour of geosynthetics must be considered in the design of walls reinforced with those materials. The question to be answered is how to do this? In the paper a numerical model based on the finite element method is used. The model allows for the creep behaviour of geosynthetics by means of a material viscoelastic model comprising a chain of Kelvin units interconnected in series.

The paper describes the viscoelastic model used, which was first applied by Bazant *et al.* (1973) for aging concrete, and discusses its implementation in the finite element code. The long term behaviour of a wall reinforced with geogrids is then studied and some conclusions about that behaviour and its evolution during time are drawn.

MODEL DESCRIPTION

Creep Function

The geosynthetic strain caused by variable stress in time is obtained considering the creep of the reinforcement. The creep function used in this paper is derived considering an association of k viscoelastic Kelvin models in series. The function obtained is a Dirichlet series (Bazant *et al.*, 1973; Bazant *et al.*, 1984; Barros, 1987; Lopes, 1992):

$$J(t,x)=\sum_{\mu=1}^{k}\frac{\tau_\mu}{\eta_\mu(x)}\left(1-e^{-\frac{t-x}{\tau_\mu}}\right) \tag{1}$$

where each retardation coefficient, τ_μ, is defined by

$$\frac{1}{\tau_\mu}=\frac{E_\mu(x)+\eta_\mu(x)}{\eta_\mu(x)} \tag{2}$$

In the general tridimensional case, the strain at time t is:

$$\{\epsilon(t)\}=\int_{t_0}^{t}J(t,x)[P]\{d\sigma(x)\} \tag{3}$$

where t_0 is the instant when the actions start, $\{d\sigma(x)\}$ is the tensor of the increments of stress during time and $[P]$ is a Poisson's ratio matrix.

The time is divided into intervals. In each interval $(t_{n-1}\leq t\leq t_n)$ the stress rate $\left\{\frac{\partial\sigma}{\partial t}\right\}=\left\{\frac{\Delta\sigma_n}{\Delta t_n}\right\}$ and the viscosity coefficients, $\eta_\mu(t)=\eta_{\mu n}$, are taken as constant. The solution of the integral from equation (3) leads, after some intermediate steps, to the expression for the stress increment in the time interval $\Delta t_n=t_n-t_{n-1}$ (Bazant *et al.*, 1973; Bazant *et al.*, 1984; Barros, 1987; Lopes, 1992):

$$\{\Delta\sigma_n\}=E_n^{*}[P]^{-1}(\{\Delta\epsilon_n\}-\{\Delta\epsilon_n^{*}\}) \tag{4}$$

where

$$\lambda_{\mu n}=\frac{\tau_\mu}{\Delta t_n}\left(1-e^{-\Delta t_n/\tau_\mu}\right) \tag{5}$$

$$\frac{1}{E_n^{*}}=\sum_{\mu=1}^{k}\frac{1-\lambda_{\mu n}}{E_{\mu n}} \tag{6}$$

$$\{\Delta\epsilon_n^{*}\}=\sum_{\mu=1}^{k}\left(1-e^{-\Delta t_n/\tau_\mu}\right)\{\epsilon''_{\mu(n-1)}\} \tag{7}$$

The equation (4) shows that the viscoelastic behaviour is transformed in a succession of linear pseudo-elastic problems defined in each interval of time. In that expression E_n^{*} is the pseudo-instantaneous deformability modulus for the time increment in consideration and $\{\Delta\epsilon_n^{*}\}$ can be thought as a initial strain for the same increment. On the other hand, the stress increment, $\{\Delta\sigma_n\}$, in the interval Δt_n depends on quantities relative to the interval and on quantities, $\{\epsilon''_{\mu(n-1)}\}$, defined for the k Kelvin models at the end of the preceding increment. These quantities reflect and condense the stress history until instant t_{n-1} in each Kelvin model. In the generic instant $t = t_n$, they are calculated by

$$\{\epsilon''_{\mu n}\} = e^{-\Delta t_n/\tau_\mu}\{\epsilon''_{\mu(n-1)}\} + \frac{\lambda_{\mu n}}{E_{\mu n}}[P]\{\Delta\sigma_n\} \qquad (8)$$

So, it can be concluded that the application of the Kelvin model to the study of the long term behaviour of geosynthetics leads to important simplifications, namely regarding the storage of the load history, necessary to the definition of stresses, and on the transformation of a viscoelastic problem on a sucession of elastic problems (Bazant *et al.*, 1973; Bazant *et al.*, 1984; Barros, 1987; Lopes, 1992).

Equilibrium of a System Discretized in Finite Elements

Applying the principle of minimum potential energy or the principle of virtual work it can be concluded that the equilibrium of a system discretized in finite elements can be given by the equation:

$$\int_V [B]^T\{\Delta\sigma_n\}dV = \{\Delta R_n\} \qquad (9)$$

where $\{\Delta R_n\}$ stores the incremental components of the external body or surface forces applied in the time interval $\Delta t_n = t_n - t_{n-1}$. Having in mind expression (4) which defines the vector of incremental components of stress and, on other hand, that the vector of incremental components of strain is given by:

$$\{\Delta\epsilon_n\} = [B]\{\Delta d_n\} \qquad (10)$$

where $\{\Delta d_n\}$ is the vector of incremental components of displacements in the nodal points in the interval Δt_n and $[B]$ is the matrix that relates the strains in any point of the system with the nodal displacements, after some intermediate steps it can be obtained

$$[K_n]\{\Delta d_n\} = \{\Delta R_n\} + \{\Delta R_{\epsilon n}\} \qquad (11)$$

where

$$[K_n] = \int_V [B]^T E_n^*[P]^{-1}[B]dV \qquad (12)$$

is the global stiffness matrix and

$$\{\Delta R_{\epsilon n}\} = \int_V [B]^T E_n^*[P]^{-1}\{\Delta\epsilon_n^*\}dV \qquad (13)$$

is a vector where the equivalent nodal forces due to initial pseudo-strain $\{\Delta\epsilon_n^*\}$ are stored.

LONG TERM BEHAVIOUR OF A WALL REINFORCED WITH GEOSYNTHETICS - A NUMERICAL ANALYSIS

Problem Description

The long term behaviour of a symmetric backfill with 6m height and 20m width constructed in 9 steps over a competent foundation with 12m thickness was studied by the viscoelastic model previously described. The reinforcements were in geosynthetics (geogrids) with 4.8m long, placed horizontally with a vertical spacement of 0.75m; the first level of reinforcement was placed at 0.375m from the backfill base. The vertical face units were 0.10m thick and 0.75m height.

The finite element mesh, showed in Figure 1, had initially 100

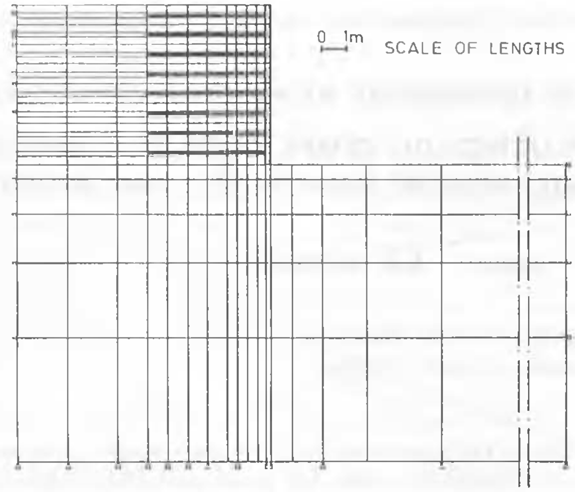

Fig. 1. Finite element mesh

elements, 5 being interface elements; during the constructive sequence the bidimensional, interface and unidimensional elements representatives of the backfill and face, interfaces and inclusions, were activated. In the final step the finite element mesh had 580 elements, 221 being interface elements and 72 unidimensional elements; the number of nodal points was 518. The boundaries were defined taking into account, on one hand, the problem symmetry (left lateral boundary) and, on the other hand, the assumed characteristics of the geological formations (lower boundary placed at 12m depth from the base of the backfill) and supposing that at 40m from the wall the horizontal displacements of the foundation were negligible (right lateral boundary).

The wall was constructed in 9 steps: in the first, the first layer of backfill was placed; in the next seven a layer of backfill was placed and the reinforcement level located in the middle of the underlying soil layer started working; finally, in the last step the upper reinforcement level started working.

The foundation and backfill soils were considered granular and uniform with the same mechanical characteristics; the formation underlying the foundations were supposed indeformable.

The nonlinear behaviour of the soils and interfaces was simulated by perfect elastoplastic models, without hardening and with associative flow. For the soil was adopted the Mohr-Coulomb failure criterion. In Table 1 the characteristics considered for the soil are summarized. These characteristics were defined for the expected *in situ* mean stress level from published triaxial tests results carried with soils currently used in backfills. Table 2 summarizes the characteristics of soil-reinforcement and soil-face interfaces used in the study.

Table 1. Soil characteristics

$\gamma(kN/m^3)$	K_0	$\phi(°)$	$c(kPa)$	ν	$E(kPa)$
17	0.27	47	0	0.35	10000

Table 2. Interface characteristics

	Soil-inclusion	Soil-face
$c_a(kPa)$	0	0
$tg\,\delta$	0.96	0.61
$K_t(kPa/m)$	10000	2000

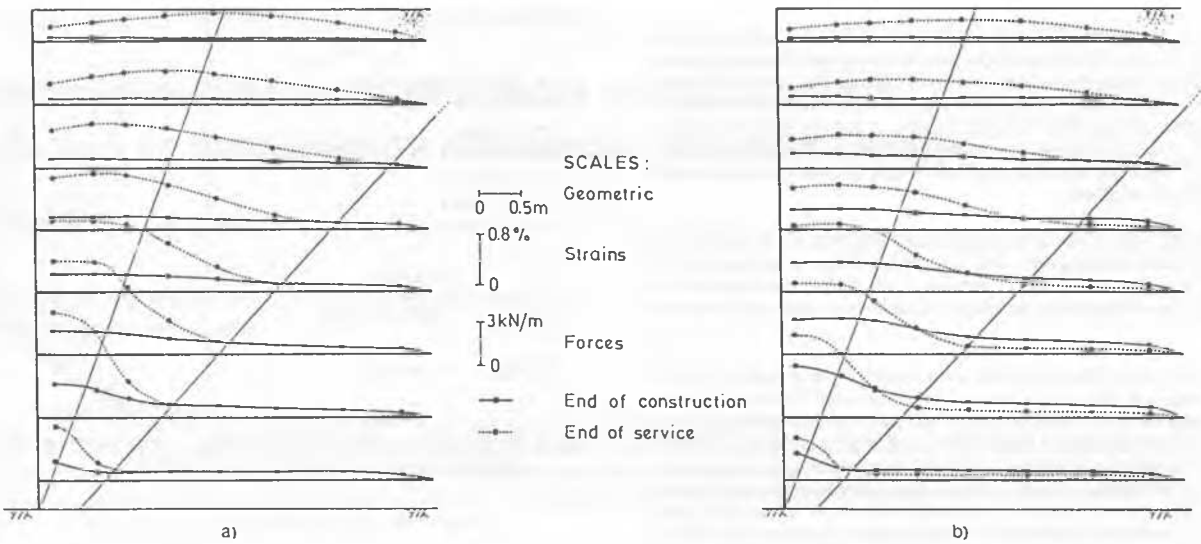

Fig. 2. Reinforcements in the end of construction and end of service: a) strains; b) tensile forces

For the reinforcement, during wall construction, was also used a perfect elastoplastic model without hardening and with associative flow. For that period the mechanical characteristics adopted (tensile strength equal to 70kN/m and tensile modulus equal to 700kN/m) were obtained from published results of tensile tests carried with the geogrid used in the study (McGown *et al.*, 1984; Yeo, 1985).

The deformability modulus of the face material was supposed about 5.5×10^5 kPa, having in mind, by one hand, the diversity of materials that can be facing units and, on other hand, the lower stiffness of the face when composed by several units.

The creep of soils and face was considered negligible; the same happened for the reinforcement only during the wall construction. The viscoelastic behaviour of the reinforcement was modelled by the creep model previously described considering 8 Kelvin units, whose mechanical characteristics were extracted from published creep tests results carried with the geogrid used in this analysis (Yeo, 1985). The period of time was 115 years divided in 39 intervals being the smaller 0.58 hours and the larger 292055 hours. The assumed soil temperature was 10°C.

Analysis of Results

The tensile strains and forces in the inclusions at the end of construction and after 115 years of service are compared in Figure 2 and Table 3. Figure 2a shows that the increase in strains with time is particularly important in the unstable zone of the backfill when it is not reinforced, that is between the face and a surface nearly plane and defined by the angle of natural slope of the soil. Beyond this surface the strains are almost constant.

In what concerns tensile forces (Figure 2b) it can be seen that they increase more or less in the same region where strains also increase, decreasing behind the mentioned surface. This reduction in forces is due, on one hand, to the constant state of strain in the reinforced soil located behind the natural slope surface and, on the other hand, to the reinforcement stiffness reduction with time; so, in this region, the phenomenon in the reinforcement is not creep but relaxation. The increase in tensile forces in the active zone of the reinforced soil is due to the increase in vertical stresses in this region (see Figure 3) and to the interaction with the surrounding soil.

As it can be seen in Table 3 in the more stressed level (2nd level) at the end of service the maximum strain is 3 times the strain at the end of construction, whereas the tensile force is only 1.7.

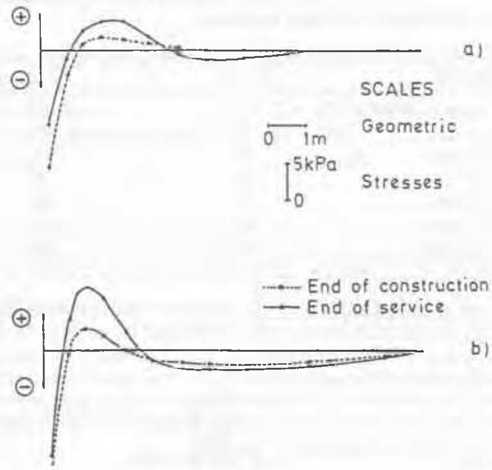

Fig. 3. Theoretical ($\sigma_v = \gamma z$) and predicted vertical earth pressures in two horizontal planes: a) at 2.45m from the top of the wall; b) at 4.30m from the top of the wall

Table 3. Maximum strains and tensile forces in the reinforcements in the end of construction and end of service

Reinforcement	End of construction		End of service	
level	$\epsilon_{máx}$ (%)	$F_{máx}$ (kN/m)	$\epsilon_{máx}$ (%)	$F_{máx}$ (kN/m)
1	0.30	2.09	0.83	2.95
2	0.54	3.66	1.69	5.99
3	0.40	2.71	1.45	5.15
4	0.30	2.06	1.22	4.34
5	0.22	1.48	0.95	3.38
6	0.15	1.02	0.69	2.46
7	0.09	0.63	0.51	1.82
8	0.02	0.17	0.44	1.57

The long term behaviour of reinforced walls with geosynthetics is influenced by two factors: reinforcement creep and change of state of stress due to interaction with surrounding soil. So, having in mind the results in Table 3, the creep curve for the reinforcement material and the mean acting stress during service, it can be seen that from the 1.15% of total increase in strain in the more stressed level (2nd level), 0.72% are due to creep and 0.43% due to elastic strain caused by the increase of stress.

The change in horizontal earth pressure and in stress levels during the wall service is negligible; only just behind the reinforced soil it can be seen a decrease in that pressure due to the increase of the reinforced mass displacement and correlatively an increase in stress levels.

The evolution of the wall behaviour during time is studied by the tensile strains and forces in the more stressed level (2nd level) in the instants: end of construction, half a day, one week and one, five, twenty and a hundred and fifteen years after construction. Table 4 shows for the seven mentioned instants the percentage of increase, in relation to the total increase, of maximum tensile strains and forces in the reinforcement. It can be concluded that it is in the first year of service that the wall behaviour changes more significantly. At this time the increase of maximum tensile strain and force are, respectively, about 69% and 78% from the finals. After that instant the increase of maximum strain reduces with time. In fact, the increase is about 10%, 20% and 30% in the next 4, 19 and 114 years.

Table 4. Percentages of increase of maximum tensile strains and forces during the time in the 2nd level of reinforcement, in relation to the final increase

Instant	Strain	Force
End of construction	0	0
1/2 day	15	33
1 week	35	55
1 year	69	78
5 years	81	86
20 years	90	92
115 years	100	100

As for the tensile strains and forces the more important increase in wall movements took place in the first year of service. In fact, as Table 5 shows, the percentages of final increase in maximum displacement and in the displacement at the top of the wall were, after a year, respectively, 72% and 77%. In the end of service the same displacements were, respectively, 80% and 130% higher than at the end of construction (see Figure 4).

Table 5. Percentages of increase of maximum and top wall displacements during time, in relation to the final increase

Instant	Max. displacement	Top displacement
End of construction	0	0
1/2 day	22	26
1 week	43	50
1 year	72	77
5 years	84	86
20 years	91	92
115 years	100	100

Figure 4 also shows the settlements of the backfill surface at the end of service. It shows that the maximum displacement is near the wall. It reduces with distance to the face, being nearly nearly zero behind the reinforced soil. Settlements are only due to the wall behaviour as in the end of construction they were supposed zero.

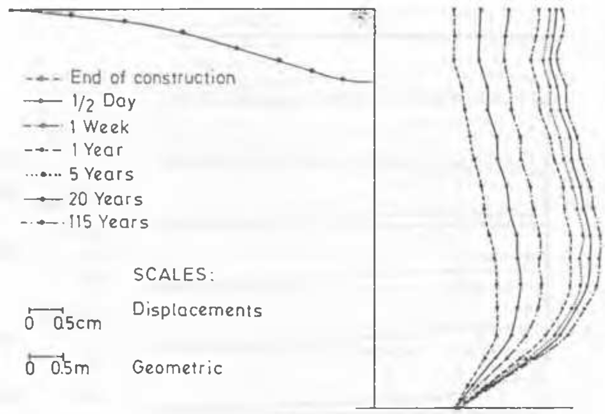

Fig. 4. Wall displacements during time and settlements of the backfill surface at the end of wall service

CONCLUSIONS

In this paper a viscoelastic model was applied to the simulation of geosynthetics long term behaviour.

By the application of that model it was possible to study the long term behaviour of walls reinforced with geosynthetics. From the results of the analysis it can be concluded that: 1) tensile strains and forces increase continuously with time in the front part of reinforcements; 2) changes in strains during time are composed by two parts, one due to material creep and another, elastic, due to the change in state of stress; 3) horizontal pressures and stress levels are almost constant during service; 4) the wall behaviour changes more significantly during the first year of service.

From the results it can be said that the long term behaviour of walls reinforced with geosynthetics must be carefully analysed in each case; only in this way one can predict properly the wall behaviour for the time desired.

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