PREDICTION OF THE PERFORMANCE OF A GEOGRID-REINFORCED SLOPE FOUNDED ON SOLID WASTE[i]

Discussion by F. TATSUOKA[i], D. HIRAKAWA[ii] and W. KONGKITKUL[iii]

The writers are commended for their successful FEM analysis of the deformation of full-scale geogrid-reinforced backfill, which is still complicated and difficult. No doubt the proper constitutive modelling of the time-dependent deformation and strength characteristics of both backfill and geogrid is one of the essential keys for realistic analysis of the deformation of geogrid-reinforced soil structures that may be subjected to arbitrary and various loading histories for a long life time.

Discussion points: The discussors agree with the writers on the point that creep loading history does not reduce the ultimate strength attained by loading at a certain constant strain rate, as shown in Fig. 21(a). The writers obtained the results presented in this figure from the following pair of wide-width tensile tests of the geogrid:

—Test I, performed at a constant strain rate ($\dot{\varepsilon}=10\%/\mathrm{min}$); and

—Test II, in which a creep test lasting for 100 hours was performed during otherwise monotonic loading at a constant strain rate $\dot{\varepsilon}=10\%/\mathrm{min}$.

It can be seen from Fig. 21(a) that when loading is restarted at the original strain rate following a creep test in test II, the load-strain curve eventually rejoins at point C the original primary loading curve that was obtained by monotonic loading without an intermission of creep test (i.e., test I). The writers pointed out that "approximately the same ultimate tensile strength" and "a similar strain level at failure" were obtained from these two types of tensile tests. A number of similar results have been obtained with geomaterials, including soft and stiff clays, silty sands, clean sands, well-graded gravels and sedimentary soft rocks (e.g., Kavanzanjian and Mitchell, 1980: Tatsuoka et al., 2000, 2001). Hirakawa et al. (2002) also showed that it is also the case with one type of geogrid (as shown below). The tests results presented in this paper and those obtained by Hirakawa et al. (2002) indicate that creep is not a degrading phenomenon for the deformation and strength characteristics of geosynthetic reinforcement, as have been pointed out by Bernard and Paulson (1997).

On the other hand, the writers used in their FEM analysis the tension and tensile strain relationship defined for load duration of 10^6 hours (11 years) that was extrapolated from the isochronous curves obtained from constant-load creep tests shown in Fig. 22 (i.e., Fig. 7 in the original paper). It seems to the discussors that this method, based on the isochronous concept, is inconsistent with the test results presented in Fig. 21(a), as discussed below. The following points are also discussed below:

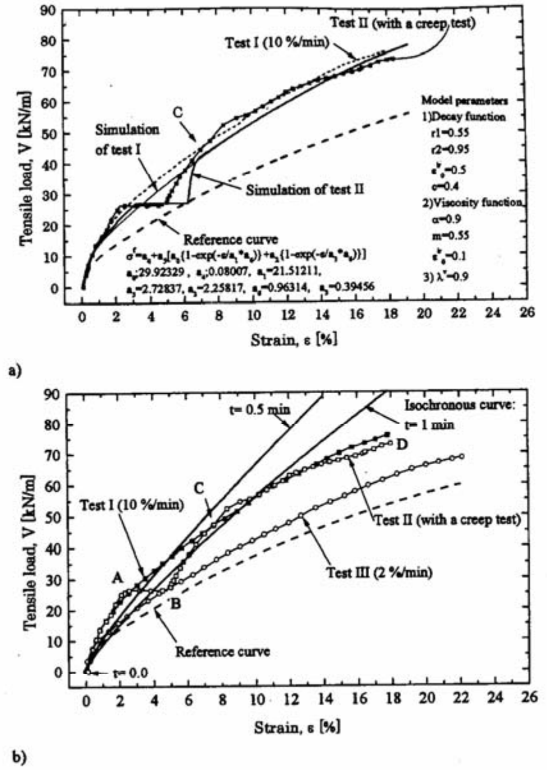

Fig. 21. Results from tensile tests of a geogrid reported in Fig. 8 and their simulation by a non-linear three-component model; a) monotonic loading test I ($\dot{\varepsilon}=10\%/\mathrm{min}$) and monotonic loading test II ($\dot{\varepsilon}=10\%/\mathrm{min}$ with a creep test), b) test I, monotonic loading test III (2%/min) and test II and deduced isochronous curves

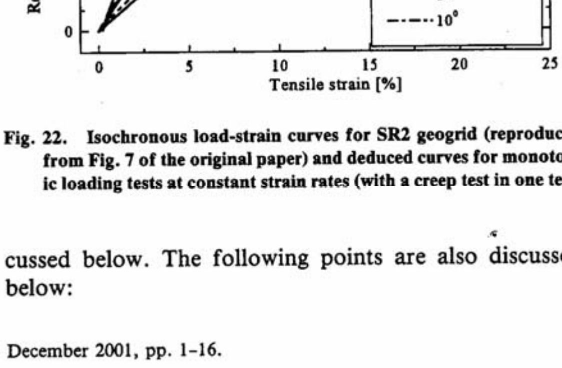

Fig. 22. Isochronous load-strain curves for SR2 geogrid (reproduced from Fig. 7 of the original paper) and deduced curves for monotonic loading tests at constant strain rates (with a creep test in one test)

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—Load that is applied to geogrid-reinforced backfill may increase or decrease at varying rates. Even when the applied total load is kept constant, local tensile load acting at a certain point of geogrid reinforcement and local stresses acting at a certain soil element in the backfill may increase or decrease with time due to possible time-dependent load and stress-redistribution associated with viscous behaviour (such as creep deformation and stress relaxation) of the reinforcement and backfill. For realistic numerical analysis of the deformation of geogrid-reinforced backfill, therefore, it is necessary to be able to predict the stress-strain-time behaviour of geogrid and backfill for any arbitrary histories of load (or strain). However, the above is not possible when based on the isochronous concept.

—Such a prediction as described above may become possible when based on a relevant constitutive model that is not using time as the basic variable, unlike the isochronous concept.

Inconsistency between the isochronous concept and the test results presented in Fig. 21(a): It is readily seen from Fig. 21(a) that the time that has elapsed since the start of loading until point *C*, where the curve in test II rejoins that in test I, is totally different between the two tests. This fact is more than sufficient to conclude that the isochronous concept is not able to predict the behaviour for rather complicated stress history, such as the one in test II. In addition, curves *a* and *b* shown in Fig. 22 are the tension and strain relationships for monotonic loading at two different strain rates that were deduced from the isochronous curves presented in this figure. Suppose that a creep test starts at point *A*, following monotonic loading in test *a*, and ends at point *B*, which is located on the curve for test *b*. Suppose that loading is restarted at the original strain rate from point *B* in test *a*. The test results presented in Fig. 21(a) indicate that curve *B*-*C*-*D*, which rejoins at point *C* the primary curve in test *a*, would be obtained. When following the isochronous concept, on the other hand, the behaviour after the restart of loading from point *B* cannot go above the isochronous curve that passes through point *B*, as we cannot go back to the past, and a curve like *B*-*X* would be predicted. It is naturally deduced that the ultimate strength associated with curve B-X would be smaller than the strength in test *a*, having decreased by this history of creep loading. This ''conceptional test result'' indicates that ''creep is a degrading phenomenon''. Of course, the behaviour *B*-*X* is not realistic. A similar analysis as above is made in Fig. 21(b), in which two isochronous curves deduced from the results of two monotonic loading tests presented in Fig. 21(a) (and Fig. 9 of the original paper) are depicted.

Stress-strain behaviour of geogrid for complicated loading history: Fig. 23 shows results from three monotonic loading tests performed at three different constant strain rates and another test in which the strain rate was changed stepwise several times and a creep test and a stress relaxation test were performed during otherwise

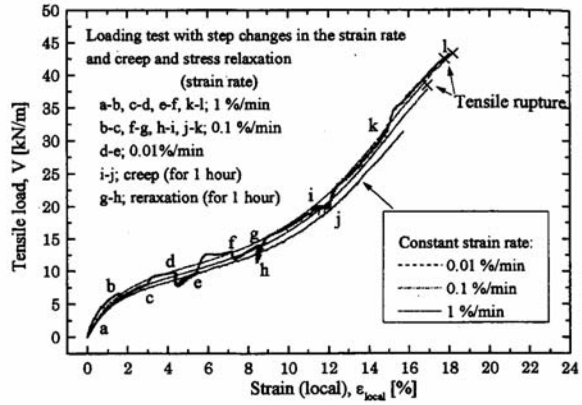

Fig. 23. Results from tensile tests on a geogrid at different constant strain rates and a test in which the strain rate was changed stepwise (Hirakawa et al., 2002)

monotonic loading at a constant strain rate. Figures 24(a) and (b) show zoom-ups of the local behaviour of the data presented in Fig. 23. The tested material was a polyester geogrid having an aperture of 9 mm in the longitudinal and transversal directions, coated with polyethylene for protection (the trademark is KTG-4000, Taiyo Kogyo Co., Japan). The ultimate tensile strength at a strain rate of 1%/min is 39.2 kN/m with a strain at failure of less than 22% in both longitudinal and transversal directions. The test specimen was 5 cm wide having five transversal members with a total length of about 90 cm, while the initial length of the unconfined part was 24 cm. Tensile strains were measured locally for an initial gauge length of about 6 cm. The following trends of behaviour may be seen from these figures:

1) The relationships from the three constant strain rate tests are separated from each other, showing noticeable loading rate effects (i.e., viscous effects).
2) The trend of behaviour seen after loading is restarted at a constant strain rate is similar to the one seen in Fig. 21(a). It may be seen from Figs. 24(a) and (b) that the stiffness immediately after the restart of loading following the creep and stress relaxation tests while before rejoining ''the primary loading curve from a continuous loading performed at the strain rate at which the loading is restarted'' is very high. The stiffness in this stress range is similar to the one of elastic behaviour, as represented by a broken line. The elastic behaviour was evaluated by applying small amplitude unload/reload cycles during otherwise monotonic loading.
3) In these tests, the current stress and strain state is basically a function of the instantaneous strain rate (not time), or more rigorously a function of instantaneous irreversible strain rate.
4) As seen from Fig. 24(a), immediately after a step increase in the strain rate, the stress overshoots temporarily the primary curve from a monotonic loading test performed at the constant strain rate

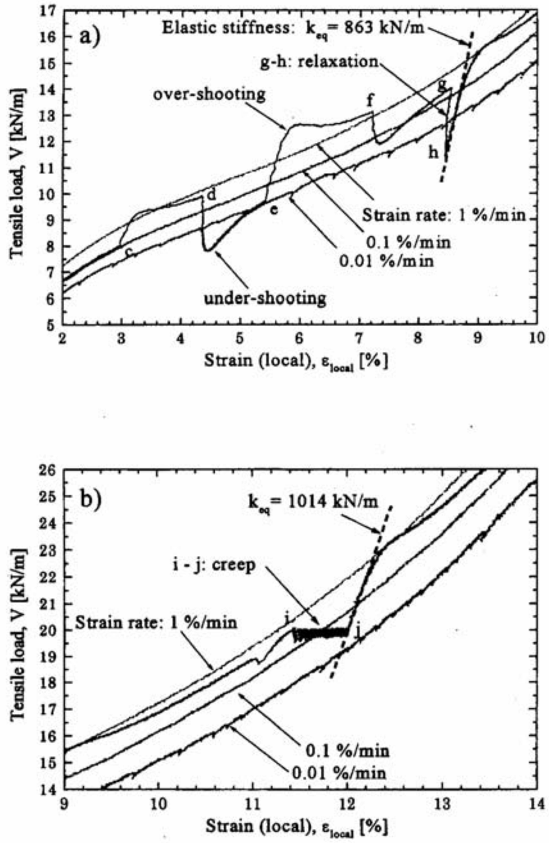

Fig. 24. Zoom-up of the local behaviour of the data presented in Fig. 23

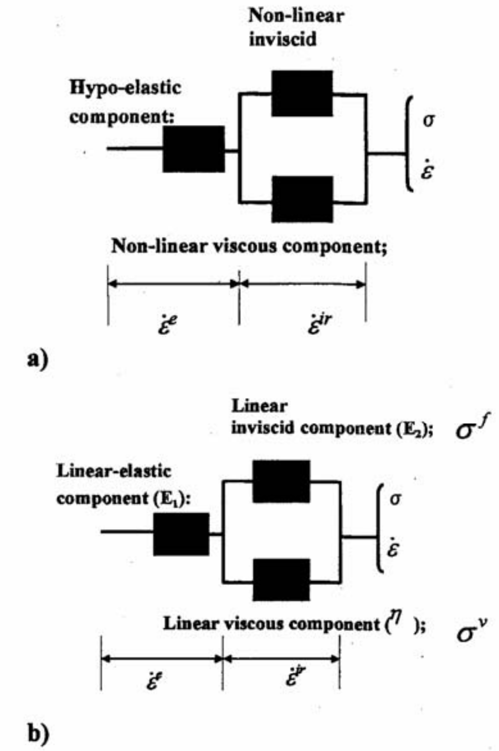

Fig. 25. a) Non-linear and b) linear three-component models

after a step increase. On the other hand, temporary undershooting of stress is observed immediately after a step decrease in the strain rate is made.

It is readily seen from the above that the same stress-strain state can be reached after totally different elapsed times by different loading histories (e.g., monotonic loading at a constant strain rate or monotonic loading with changes in the strain rates or monotonic loading with intermediate creep and stress relaxation tests). It is obvious that it is not possible to predict such behaviour as above based on the isochronous concept.

Prediction by a three-component model: Di Benedetto et al. (2002) and Tatsuoka et al. (2002) have shown that such a non-linear three-component model as illustrated in Fig. 25(a) can simulate very well the stress-strain-time behaviour of geomaterials subjected to arbitrary stress histories. This model is one type of sophistication of the classical linear three-component model (Fig. 25(b)). The test results of a geogrid presented in Figs. 21(a), 23 and 24 were simulated based on this model (Fig. 25(a)).

According to this model, the strain rate $\dot{\varepsilon}$ is decomposed as:

$$\dot{\varepsilon} = \dot{\varepsilon}^{e} + \dot{\varepsilon}^{ir} \tag{2}$$

where $\dot{\varepsilon}^{e}$ and $\dot{\varepsilon}^{ir}$ are the elastic and irreversible (inelastic) strain rates. This strain decomposition is relevant to simulate the trend of behaviour 2) described above. The stress σ is decomposed as:

$$\sigma = \sigma^{f}(\varepsilon^{ir}) + \sigma^{v}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s) \tag{3}$$

where $\sigma^{f}(\varepsilon^{ir})$ is the inviscid stress that is a unique function of the instantaneous irreversible strain ε^{ir} for monotonic loading cases. The $\sigma^{f} - \varepsilon^{ir}$ relation is called the reference curve, which was determined by try and error in the present simulation (as shown in Figs. 21(a) and 26(b)).

The viscous stress $\sigma^{v}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s)$ is a function of ε^{ir}, its rate $\dot{\varepsilon}^{ir}$ and the strain history parameter h_s. The following was assumed to simulate the observed trends of viscous behaviour:

$$\sigma^{v}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s) = \lambda^{v} \cdot \sigma^{v}_{iso}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}) + (1 - \lambda^{v}) \cdot \sigma^{v}_{TESRA}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s) \tag{4}$$

where λ^{v} is the material constant between zero and unity. The viscous stress $\sigma^{v}_{iso}(\varepsilon^{ir}, \dot{\varepsilon}^{ir})$ (called the isotach viscosity component), is a unique function of the instantaneous values of ε^{ir} and $\dot{\varepsilon}^{ir}$, σ^{v}_{iso} was introduced to simulate the trend of behaviour 3) described above. Based on the test results, it was assumed that:

$$\sigma^{v}_{iso}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}) = H_v(\sigma^{f}) \cdot g_v(\dot{\varepsilon}^{ir}) \tag{5a}$$

where $H_v(\sigma^{f})$ is a function of $\sigma^{f}(\varepsilon^{ir})$. It was found that the following approximation is acceptable:

$$\sigma^{v}_{iso}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}) = \sigma^{f}(\varepsilon^{ir}) \cdot g_v(\dot{\varepsilon}^{ir}) \tag{5b}$$

$g_v(\dot{\varepsilon}^{ir})$ is the viscosity function, which is a non-linear function of $\dot{\varepsilon}^{ir}$, given as:

$$g_v(\dot{\varepsilon}^{ir}) = \alpha \cdot \left[1 - \exp\left\{1 - \left(\frac{\dot{\varepsilon}^{ir}}{\dot{\varepsilon}^{ir}_r} + 1\right)^m\right\}\right] \quad (\geq 0) \tag{6}$$

where α, m and $\dot{\varepsilon}^{ir}_r$ are the positive material constants. Due to the contribution of the component $\sigma^{v}_{iso}(\varepsilon^{ir}, \dot{\varepsilon}^{ir})$ (Eq. 5b), the stress-strain relationships in monotonic loading tests at constant but different irreversible strain rate $\dot{\varepsilon}^{ir}$ are separated from each other and the separation becomes larger with the increase in ε^{ir}, as seen in Figs. 21 and 23.

The viscous stress component $\sigma^{v}_{TESRA}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s)$ in Eq. 4 is called the TESRA component (TESRA = Temporary Effects of Strain Rate and strain Acceleration). This component was introduced to simulate the trend behaviour 4) described above, which is given as:

$$\sigma^{v}_{TESRA} = \int_{\tau=\varepsilon^{ir}_{I}}^{\varepsilon^{ir}} [d\sigma^{v}_{iso}]_{(\tau)} \cdot \{r(\varepsilon^{ir})\}^{(\varepsilon^{ir}-\tau)} \tag{7}$$

where ε^{ir} is the current irreversible strain; ε^{ir}_{I} is the irreversible strain at the start of loading where the viscous effect is negligible ($\varepsilon^{ir}_{I} = 0$ in the present case); σ^{v}_{iso} is obtained from Eq. 5b; τ is the irreversible strain at which the viscous stress increment $d\sigma^{v}_{iso}$ takes place; $\{r(\varepsilon^{ir})\}^{(\varepsilon^{ir}-\tau)}$ is the decay function, which decreases with the increase in the irreversible strain difference $\varepsilon^{ir} - \tau$; and $r(\varepsilon^{ir})$ is a function of ε^{ir}, which decreases from unity at $\varepsilon^{ir} = 0$ towards a value lower than unity (r_f) for $\varepsilon^{ir} \geq c$. Due to the contribution of the component $\sigma^{v}_{TESRA}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s)$, the viscous effects become noticeable when the strain rate changes, as seen in Figs. 23 and 24, while the value of $\sigma^{v}_{TESRA}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s)$ decreases with the increase in ε^{ir} when loading continues at a constant strain rate. The introduction of the TESRA viscosity component is necessary to simulate the behaviour 4) described above.

Figures 26(a) and (b) show the simulation of the results presented in Fig. 23 and those from other monotonic loading tests at different constant strain rates. The parameters of the model that were used in the simulation are shown in Fig. 26(b). It may be seen that the observed viscous properties of the tested material are well simulated by the non-linear three-component model. The simulation of the results of tests I and II, reported in the paper, is presented in Fig. 23a. The reference curve and model parameters that were used in the simulation are also presented. It is seen that both behaviours during and after the creep test are well simulated.

Summary: The whole time-dependent aspects of the deformation and strength characteristics of geogrid, including behaviours during and after a creep test, that are described in the original paper and this discussion are due to the viscous properties and they can be simulated based on a non-linear three-component model having the material parameters that do not change with time

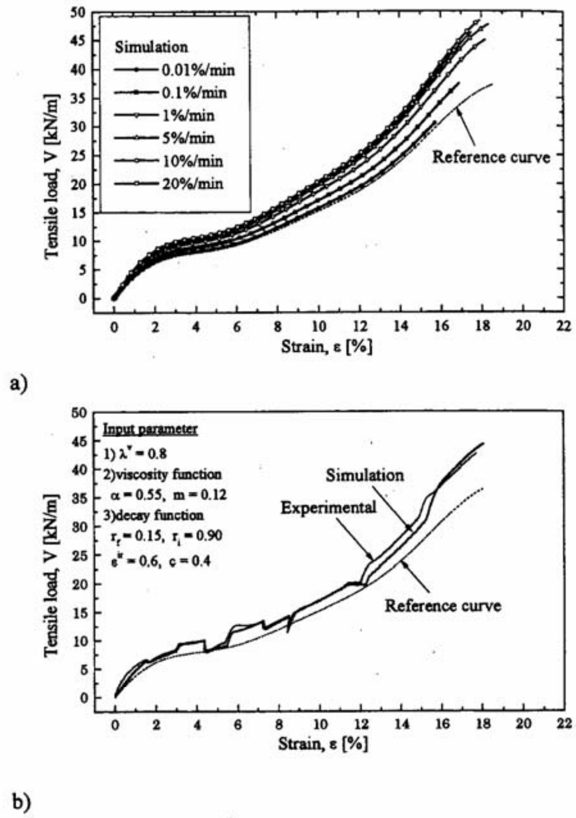

Fig. 26. Simulation by the proposed non-linear three-component model of test results: a) monotonic loading tests at constant strain rates, and b) test under complicated loading history (Hirakawa et al., 2002)

(Fig. 25(a)). That is, in the simulation, creep was not treated as a time-dependent degrading phenomenon but it was simulated as a viscous response of the model. The discussors believe that it is now the time to stop the use of the isochronous concept in the design and research of geosynthetic-reinforced soil, because this concept is not realistic and may lead to a wrong notion that "creep is a degrading phenomenon". It also seems that it is not relevant to correct a tensile strength obtained by a monotonic loading test at a certain high strain rate to a smaller value to obtain the design strength for a specified design life time by considering (wrongly) that the tensile strength decreases with time because of creep deformation at working loads. This issue is discussed by Greenwood et al. (2001).

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PREDICTION OF THE PERFORMANCE OF A GEOGRID-REINFORCED SLOPE FOUNDED ON SOLID WASTE[i]

Closure by Jorge G. Zornberg[ii]
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The writers thank the discussers for their interest in the paper and their insightful comments. The three-component model developed by the discussers is an important contribution with significant value for predicting the behavior of geogrid reinforcement subject to multi-step load paths. However, this advanced and sophisticated tool was neither available to the writers at the time the project was completed nor vital to represent geogrid behavior for the simple load path analyzed in that study, which involved rapid initial loading, subsequent creep loading, and final rapid loading to failure.

A central issue raised by the discussers is that the use of isochronous curves is inconsistent with geogrid behavior under combined rapid loading and sustained creep. Specifically, the discussers suggest that the test results presented in Fig. 8 (and Fig. 21(a)) of the paper are inconsistent with the isochronous curves presented in Fig. 7. While the writers agree that isochronous curves should not be used to predict complex load histories such as those presented in Fig. 23 by the discussers, the isochronous curves in Fig. 7 are consistent with the test results presented in Fig. 8 for the simple load history evaluated in the paper. The data point in Fig. 8 at the end of 100 h of creep corresponds to a 100 h (10^2 h) isochrone. This data point (unit tension of 26.3 kN/m and strain of 5%) is consistent with a linear isochronous curve characterized by a stiffness of approximately 500 kN/m (i.e. $26.3/0.05=526$ kN/m). Consistent with this result, the initial stiffness of the 100 h (10^2 h) isochrone curve in Fig. 7 is also approximately 500 kN/m. This close correspondence is remarkable considering that isochronous curves in Fig. 7 were reported by the geosynthetic manufacturer, while the test results in Fig. 8 were obtained by testing performed as part of the project documented in the paper on archived samples of the geogrid used in the construction.

Another important, and related, issue raised by the discussers is that the use of isochronous curves in the design and research of geosynthetic-reinforced soil may lead to the erroneous notion that "creep is a degrading phenomenon". The authors fully agree with the discussers that it is erroneous to consider creep of geogrids a degrading phenomenon. However, the writers disagree with the discussers that the use of isochronous concepts leads to this erroneous conclusion. The fact that creep loading does not necessarily lead to a significant degradation (i.e. reduction) of the ultimate tensile strength of the geogrid is clearly shown by the experimental results presented in Figs. 8 and 9 of the paper. The conclusion that sustained loading did not lead to a significant reduction in the ultimate tensile strength of the reinforcement was crucial information for the limit equilibrium analyses conducted as part of the case history documented in the paper. While Greenwood et al. (2001) document similar behavior, at the time the testing program described in the paper was conducted (1995), no information was available regarding the residual tensile strength of geogrid reinforcements following a period of sustained creep loading.

Additional evidence that creep is not a degradation phenomenon is provided by time-temperature superposition data from research currently being conducted by the lead author at the University of Colorado. Testing using this technique substantiates the conclusion that sustained loading does not necessarily reduce the ultimate tensile strength of geosynthetics, even after long periods of creep. Figure 27 presents the results of a test conducted on a polypropylene geosynthetic subject to a load history similar to that shown in Fig. 8 (i.e. rapid initial loading, subsequent creep loading, and final rapid loading to failure). The rapid initial loading was conducted at a temperature of 24°C, the creep loading was conducted while increasing temperature to 60°C in stepped isothermal temperature jumps over a period of 8 h, and the final rapid loading to failure was conducted at a temperature of 60°C. Based upon principles of time-temperature

[i] Vol. 41, No. 6, December 2001, pp. 1–16. (Previous discussion by F. Tatsuoka, D. Hirakawa and W. Kongkitkul, Vol. 42, No. 5, October 2002, pp. 125–129.)
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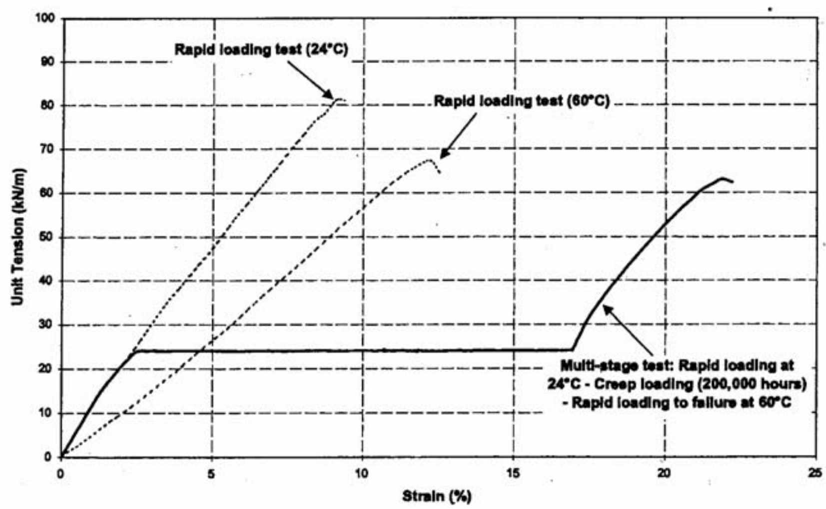

Fig. 27. Results of geosynthetic test performed using time-temperature superposition to represent rapid loading to failure after 200,000 hours of creep loading

superposition, the data gathered during the 8-h creep-loading portion of the test corresponds to 200,000 h of creep loading at a constant temperature of 24°C (Knudsen and Zornberg, 2002). The results from wide width, rapid loading tensile tests conducted at 24°C (T_{ult} $= 81.2$ kN/m) and at 60°C ($T_{ult} = 67.2$ kN/m) are also shown in the figure. The stiffness obtained for the wide width tensile test conducted at 24°C agrees with that obtained during initial loading in the multi-stage test and the stiffness obtained for the wide width tensile test conducted at 60°C agrees with that obtained during the rapid loading to failure in the multi-stage test. As the ultimate tensile strength in the multi-stage test (T_{ult}) of 63.6 kN/m was 95% of the value obtained in the wide width tensile test performed at 60°C, it may be concluded that no significant tensile strength loss, i.e., no degradation, took place even after significant creep strain.

The use of isochronous curves for the project described in the paper was an engineering expedient used to predict the safety of the geogrid toe buttress subject to a major earthquake. To account for the limitations of the use of isochronous curves, finite element analyses conducted by the authors for this project used different values of reinforcement stiffness when evaluating: (1) the time-dependent behavior of the toe buttress induced by static loads, and (2) the response of the structure to rapid (earthquake) loading. The writers fully agree with the discussers that isochronous curves are not capable of representing load histories with more than one interval of sustained creep. However, a recent study that evaluated the performance of a significant number of instrumented reinforced soil walls concluded that the response of these structures under static loads is consistent with reinforcement stiffness values obtained from isochronous curves (Allen and Bathurst, 2001). Therefore, while use of isochronous curves is not suitable for complex load histories (e.g. those accurately represented in Fig. 23 by the model proposed by the discussers), it remains a useful and expedient tool for engineering analysis under static loads and other simple load paths.

In summary, the discussers are commended for developing a powerful three-component model capable of accurately representing the behavior of geosynthetic reinforcement subject to complex load histories. However, the simplified isochronous representation of the creep behavior of geosynthetic reinforcement is still adequate for finite element analyses of many practical problems, including the case history documented in the paper.

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