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Seismic design and the strength of geosynthetic reinforcements

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ABSTRACT: Tests on polyester and polyethylene geogrids for reinforcement applications show that a geosynthetic under sustained load retains its strength over its useful lifetime. This strength is unaffected by seismic loading provided that the total load and duration do not exceed that obtained from the creep-rupture curve. Simulated seismic loads lead to a step change in strain in the geosynthetic, part of which is recovered instantly and the rest over a period of time. These findings have a profound effect on the manner in which reinforced soil is designed for seismic loading.

1 INTRODUCTION

In recent earthquakes in Japan and the USA, geosynthetic reinforced soil structures performed structurally better than predicted, whilst many unreinforced soil and reinforced concrete structures collapsed or were badly damaged. It is thus of great interest to understand the reaction of reinforced soil structures to seismic events and to draw conclusions concerning their design.

During a seismic event the ground will shake, leading to a sudden increase in the load on the geosynthetic reinforcement. The highest intensity shaking is typically short-lived, with the USGS (2000) reporting that the peak shaking of the Great San Francisco Earthquake of 1906 lasted between forty-five and sixty seconds.

Since the lifetime of a geosynthetic depends on the permanent load it has to sustain, it is important to know how much strength the reinforcement retains in mid-life and by how much it is reduced due to the seismic load.

2 RESIDUAL STRENGTH

Reinforcing geosynthetics operate under sustained load which can ultimately lead to failure. The relation between lifetime and sustained load is described by the creep-rupture or stress-rupture graph, as shown in Fig. 1. At first sight this graph appears to describe the reduction in strength of the geosynthetic over time. This is not correct. Under a sustained load L1 the strength of the geosynthetic reduces according to the residual strength curve specific to the load L1. The residual strength has always to exceed L1 or the material would break. At the point P1 where the residual strength falls to equal L1, rupture occurs. The creep-rupture graph is the locus of all the points P1, P2 etc corresponding to different sustained loads L1, L2 etc. In reality there is considerable variation in lifetimes, extending by an order of magnitude or more, and the creep rupture characteristic is the mean of a scatter band rather than a clearly defined line.

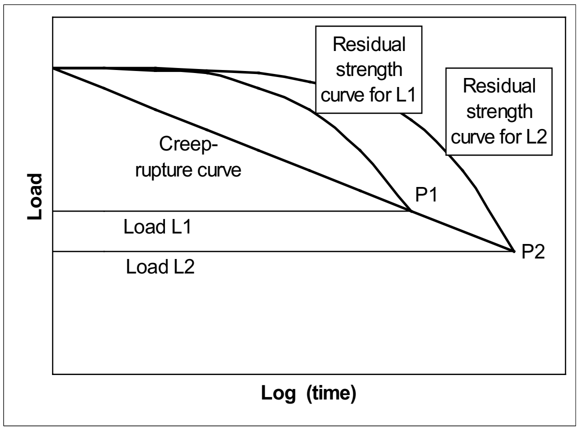

Figure 1. Schematic diagram of residual strengths

In earlier papers (Orsat et al. 1998, Greenwood et al. 2001, Voskamp et al. 2001) we and others have shown that for polyester geosynthetics the tensile strength is unchanged right up to the beginning of the rupture region, that is over the entire useful lifetime of the reinforcement. Tests using both the stepped isothermal method (SIM) and conventional testing for as long as twelve years at 20ºC all lead to the same result. Creep-rupture is evidently a catastrophic event which takes place after a long lifetime during which the only evidence of change to the polyester is a gradual extension and an increase in stiffness.

This is shown in Fig 2 for a polyester geogrid (G1) with a tensile strength measured to ISO 10319 as 70.5 kN/m. Creep-rupture tests were performed using the stepped isothermal method (SIM) (Thornton et al. 1998) on samples 50 mm wide. Simple capstan grips were used with padding to separate overlapping layers of geotextile to prevent them damaging one another The extensometry was independent of the loading and the maximum temperature was 62ºC.

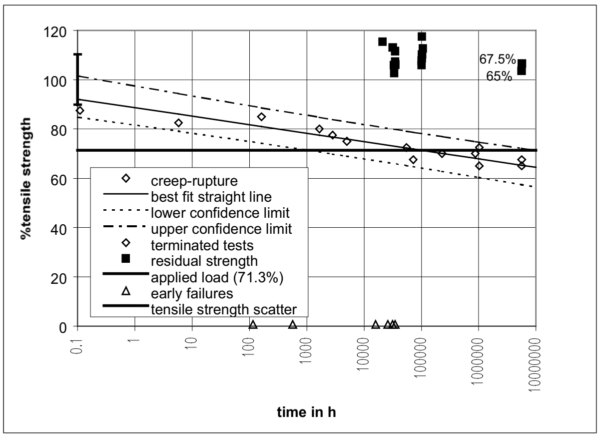

Figure 2. Residual strength of geogrid G1

The results showed that the time to rupture is given by the formula

$$\sigma = 88.6 - 3.45 \log t \qquad (1)$$

where σ is the applied sustained load expressed as a percentage of the tensile strength and t is the time to rupture in hours. The loads corresponding to a lifetime of 11.4 years (10^5 h) and 120 years are respectively 71.3% and 67.8% of tensile strength. In this paper, times extrapolated using SIM are referred to as simulated times. The strains at rupture lay between 10.0% and 12.4% compared with 10.7 ± 0.7% in tensile testing. There was no detectable dependence of rupture strain on applied load.

Tests were then performed in which the load of 71.3%, corresponding to a simulated lifetime of 10^5h, was applied for durations of between 21% and 106% of the mean log expected rupture time. The temperature was then reduced to the reference temperature of 20ºC and the load was increased by adding further weights until the specimen broke. The load at rupture is the residual strength. Two further tests were performed at slightly lower loads, one of them for over four times the expected lifetime. Because the range of expected rupture times extends from 1% to 100 times the mean log expected rupture time, some specimens broke prematurely before the residual strength was measured. This had been anticipated and was taken into account in the test plan.

The results of the residual strength tests are shown in Fig. 2. They show that for the polyester geogrid the residual strength is effectively equal to the original tensile strength for durations up to the expected lifetime.

Similar creep-rupture tests were performed both at ERA and at Newcastle University on an extruded polyethylene grid (G2) with a tensile strength measured to ISO 10319 as 88.7 kN/m. Flat faced grips were used at ERA and profiled grips at Newcastle. In this case the strain at rupture, in the region 20 to 30%, is far beyond the limit of serviceability and the useful lifetime must be defined by the time to reach a strain limit which is taken as a total strain of 10%.

Residual strength tests were then performed: at Newcastle the additional load was provided by pouring lead shot into a container until rupture occurred, and then weighing the lead shot. Fig. 3 shows that the polyethylene grid also retains its strength over its useful lifetime.

The stiffness of the polyester was found to have increased, so the strain to failure is less than in a normal tensile test. This is explained as follows. In a highly oriented semicrystalline polymer the mechanical properties are controlled by a limited number of taut 'tie' molecules which mechanically connect the crystallites through regions of otherwise unoriented material. Under load the side chains attached to these tie molecules rotate to produce a more rigid structure (Voskamp et al. 2001). As the load is increased this process continues until some molecules start to break and rupture ensues catastrophically. Under a constant sustained load, however, the same process continues unimpeded, leading to a rigidity higher than that observed in a tensile test.

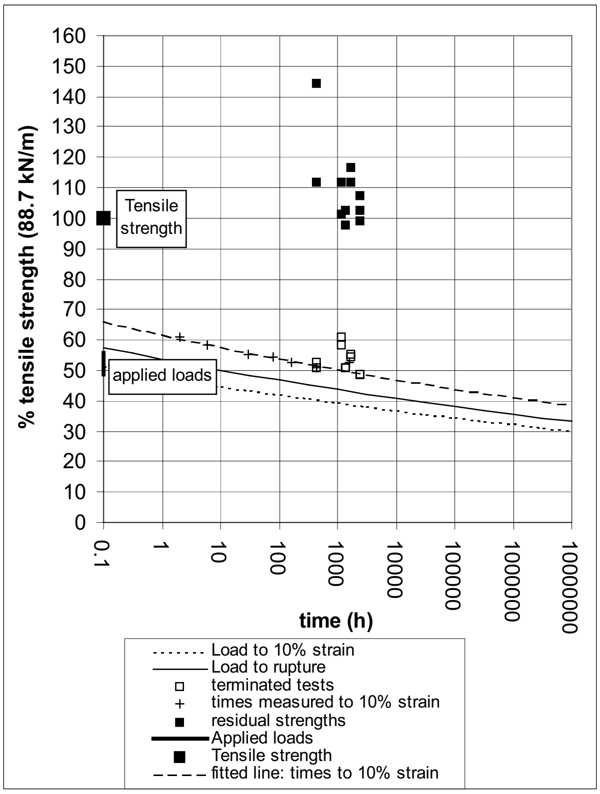

Fig. 3 Residual strength of geogrid G2

The residual tests together with those reported in Refs 1-3 demonstrate that commercially available reinforcing geosynthetics retain their full tensile strength over their useful lifetime, where this is defined as the lower confidence limit on time to creep-rupture or else the time taken to reach a set limiting strain. The rigidity of a polyester geosynthetic increases under sustained load.

3 SIMULATED SEISMIC LOADS

The wide range of times to rupture under sustained load means that for conventional reinforcing applications a substantial safety factor has to be applied. For seismic conditions, however, the reinforcement must withstand a certain sustained load and also a much higher sudden load. If, as has been shown, a reinforcing geosynthetic retains its full tensile strength, then this requirement is met. However, even if a geosynthetic reinforcement can withstand a seismic event irrespective of the level of sustained load, reinforced structures in seismic areas are not built to withstand one earthquake alone. The next question to be asked is: if the reinforcement has survived one eartquake, will it survive the next? Do seismic events progressively reduce the strength?

Seismic tests were performed on the polyethylene geogrid (G2) and on a different coated polyester geogrid (G3) with a tensile strength of 58.4 kN/m.

In a reference test on geogrid G3 (Fig. 4) the sustained load was 40% of tensile strength and no seismic load was applied. After a simulated time of 737159 h, at which point the temperature was 76ºC and the total strain 7.83%, the residual strength and strain were measured at 76ºC and found to be 52.75 kN/m and 13.4% respectively. In a tensile test the corresponding values were 58.4 ± 1.7 kN/m and 11.9 ± 0.6%.

In the first seismic test (at ERA) a further load of 40% of tensile strength was applied after a simulated time of 247592 h at a temperature of 76ºC, making a total of 80%, and then removed. The times of loading and unloading were of the order of 10 s, as fast as could be achieved using the equipment available. At the time of loading the creep strain was 7.5%, when loaded it increased to 10.9%, an increase of 3.4% (modulus 685 kN/m). On unloading it returned to 8.3%, leaving a "permanent" increase of 0.8%. After a simulated time of 1841015 h, at which point the temperature was 76ºC and the total strain 9.0%, the residual strength and strain were measured at 76ºC and found to be 55.18 kN/m (94% of tensile strength) and 13.7% respectively. This is shown in Fig 4.

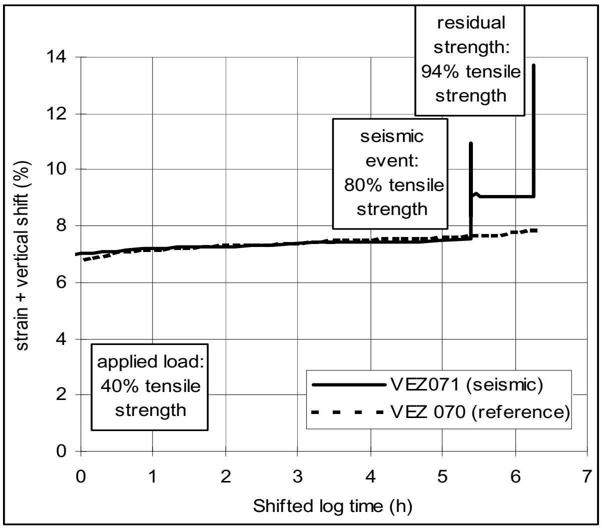

Figure 4. Strain during a seismic test when compared with a reference test on geogrid G3

In the first seismic test at Newcastle the same base load and seismic loads were applied, namely 40% and 80% of the tensile strength respectively. The seismic load was applied during the 26ºC temperature step, maintained for 1 s, and removed. The strain increased by 3% and decreased by 0.7%. The final strain measured, 13%, was identical to the strain of the reference test on which no seismic event had taken place. The residual strength was measured to be 55.9 kN/m after a simulated duration of 114 years. This amounts to 104% of the tensile strength of the material as measured with the same equipment (53.8 kN/m).

In the second such test the same load was applied during the 40ºC temperature step. The strain increased by 3.3% and was followed by a period during which there was no increase in strain. The residual strength was measured to be 53.6 kN/m (99.6% of the tensile strength) after a simulated duration of 107 years.

In the third, fourth and fifth tests at Newcastle the same load was applied at progressively later stages of the SIM test. On these occasions the 80% load led to immediate rupture. Upon inspection the failed specimen appeared to be stiffer.

In Newcastle's sixth test a simulated seismic event was applied to a conventional creep test on a different batch of the same geogrid in which the base load of 60% of the 50 kN/m tensile strength had been maintained for over 10000 h. The seismic event consisted of an additional load of 20% of tensile strength applied for 40 s. The specimen did not fail. The strain rose from 9.6% to just over 10%. After the removal of the additional seismic load, the specimen experienced a strain recovery of about 0.2%. It then appeared to undergo a periodic fluctuation in strain. The residual strength of this sample was measured to be 53.2 kN/m or 106.4% of its 50 kN/m tensile strength.

Four seismic tests were performed on polyethylene grid. The results are given in Table 1. The residual strengths all exceed the tensile strength.

Table 1: Seismic tests on Tensar

Applied load (kN/m)	18	18	36	36
Duration to seismic load (h)	504	504	504	504
Strain to seismic load (%)	2.45	2.60		6.55
Additional seismic load (kN/m)	18	36	18	36
Strain post seismic load (%)	3.00	3.70	6.80	7.20
Duration to residual strength (h)	648	648	648	648
Residual strength (kN/rib)	94.5	97.2	99.0	94.5
Residual strain (%)	10.40	fault	13.93	10.25

All these results show that a seismic event with a maximum load of 80% of tensile strength leads to no reduction in residual strength. Only when it is applied at higher temperatures can it lead to rupture. This would be expected from the creep-rupture behaviour of polyester geogrids where the times to failure are short, particularly at higher temperatures.

A seismic event leads to an increase in strain, only part of which is immediately recoverable. If the seismic event occurs early in the life of the reinforcement, leaving a long period between the seismic event and rupture, the strain reverts to the level it would have reached had there been no seismic event. If the seismic event occurs later, rupture occurs before this can happen.

4 DISCUSSION

The implications of the results of the research with respect to seismic design are profound. Current seismic design of reinforced soil structures is based upon the use of stress rupture curves; these do not recognise the existence of residual strength. Using stress rupture curves it is tacitly assumed that the strength of the geosynthetic reinforcement reduces steadily with time up to creep rupture. The implication of this philosophy with respect to seismic conditions is that the use of geosynthetic reinforcement can be shown to be safe early in the design life of the structure but could be questioned if the seismic event occurs late in the life of the structure. On the contrary, the findings of the current research, namely that the strength of the geosynthetic reinforcement is retained up to the end of the design life, shows that the use of geosynthetic reinforcement for seismic conditions is always safe. The occurrence of a seismic event during the life of the structure can result in increased strain in the reinforcement (leading to minor distortion) but the stability and safety of the structure is not compromised.

No specific index test is necessary for the determination of residual strength. The tensile strength is measured to ISO 10319 and the stress-rupture curve to ISO 13431. The results of these two tests provide all the information that is necessary.

5 CONCLUSION

A geosynthetic under sustained load retains its strength over its useful lifetime. This strength is unaffected by seismic loading provided that the total load and duration do not exceed that obtained from the creep-rupture curve.

Simulated seismic loads lead to a step change in strain in the geosynthetic, part of which is recovered instantly and the rest over a period of time. For polyester geosynthetics under sustained load the modulus increases to a level significantly greater than that measured in a simple tensile test.

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