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Modelling the behaviour of geosynthetic reinforcements used to resist combined sustained and shock loading

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ABSTRACT: The shortcomings of the current design codes / methods related to Geosynthetic Reinforced Soil Structures subject to sustained loading plus seismic loading are identified. A possible solution to these is presented, which is based on the use of the Isochronous Strain Energy [ISE] approach. It is suggested that this provides an effective means of analysing the isothermal load-strain-time behaviour of geosynthetics subject to multi-stage loading. In particular it identifies the "Immediately Recoverable" and "Locked-in" components of loads and strains developed during the various stages of loading. Knowing these components, the ability of geosynthetics to resist Multi-Stage Actions, e.g. a sustained loading (self-weight) combined with shock (seismic) loading, can be predicted. On this basis, a fundamental approach to determining the load-strain-time-temperature behaviour of geosynthetic reinforcements subject to combined sustained and shock (seismic) loading is set out.

1 INTRODUCTION

Geosynthetic Reinforced Soil Structures [GRSSs] may be subjected to a wide variety of Actions, (loads or deformations), during their design lifetimes. McGown (2000) suggests that some of these are "Sustained Actions", which persist throughout the life of the structure. Others may be represented as "Equivalent Sustained Actions", which may be accurately represented by a sustained load, or deformations. Some other combinations of loading or deformations cannot be represented by either of these and must be treated separately, "Multi-Stage Actions". Thus appropriate input data for the design of "Sustained Actions" or "Equivalent Sustained Actions" may be obtained from "Single-Stage Loading Tests", but for "Multi-Stage Actions", "Multi-Stage Loading Tests" must be used and these should impose a similar sequence of loading, (or deformation), to that imposed under operational conditions.

Greenwood (1996) recognised that data from "Single-Stage Loading Tests" did not represent the behaviour of geosynthetics subject to Multi-Stage Actions. He suggested that geosynthetics possessed a "Residual Strength" which considerably exceeds the "Design Strength" obtained from sustained loading (creep) tests. The theoretical basis of this statement is not made clear but the point made is correct, in so far as it highlights the fact that sustained loading (creep) tests, being Single-Stage Loading tests cannot represent the behaviour of geosynthetics subject to multi-stage loading.

Thus in this paper, the shortcomings of the current design codes/methods related to sustained plus shock (seismic) loading of GRSSs are discussed. A possible solution to these shortcomings is then presented which is based on the use of the Isochronous Strain Energy [ISE] Approach. On this basis a new approach is set out for the determination of the load-strain-time-temperature behaviour of geosynthetics subject to combined sustained and shock (seismic) loading.

2 CURRENT DESIGN CODES/METHODS USED TO REPRESENT THE BEHAVIOUR OF GEOSYNTHETICS SUBJECT TO COMBINED SUSTAINED AND SHOCK LOADING

To date the development of designs for geosynthetic reinforced soil walls and slopes involving earthquake forces has been empirically based. Fukuda et al (1994) reported that until 1993, designs for earthquake loading were based on the procedures for structures subject to sustained loading suggested by Jewell et al (1984). In this procedure the long-term creep rupture strength of geosynthetics was used as the "Reference Strength". The structures so designed, were reported by Collin et al (1992) to have maintained their stability during the Loma Prieta earthquake in 1989, which had a magnitude of 7.1. Fukuda et al (1994) also reported a similar situation following the Kushiro Offshore earthquake in 1993, which had a magnitude of 7.8. These data were taken to indicate that geosynthetics were capable of taking higher loads applied rapidly, than the long-term creep strength used in their design. On this basis, Fukuda et al (1994), AASHTO (1994) and Jones (1996) suggested that the Reference Strength of geosynthetics for sustained loading should be increased by 1.5 times when designing for sustained loading plus short-term earthquake loading. In more recent design codes/methods, as even more confidence was gained from the performances of Geosynthetic Reinforced Soil Structures during earthquakes, factored CRS strengths were suggested for use in designs for structures subject to sustained loading plus earthquake loading, e.g. AASHTO (1997), NCMA (1997) and DIBt (1998).

These suggested approaches to the choice of the Design Strength for geosynthetics subjected to combined sustained and shock loading are all empirically based and have not been technically justified in detail. In fact, like Greenwood (1996), they are essentially reflecting the widely held judgement that geosynthetics can support a greater combined sustained and shock loading than is presently identified for a sustained load alone in design codes/methods.

The principal shortcomings of the current approaches are that they do not take account of:

a) the timing of the shock loading during the design lifetime
b) the possibility of the repetition of the shock loading, and
c) the strains induced in the structure before, during and after the shock loading.

In order to overcome these shortcomings it is necessary to understand the behaviour of geosynthetics under combined sustained and shock loading and secondly to consider the reaction of the soil-geosynthetic composites to such combined loading.

3 TESTS DATA FROM A GEOSYNTHETIC SUBJECT TO COMBINED SUSTAINED AND SHOCK LOADING

To illustrate the behaviour of geosynthetics subject to combined sustained and shock loading, Kupec (2000) undertook a series of laboratory tests on a HDPE uniaxial geogrid. The tests were all carried out at 20°C, at which temperature the geogrid exhibited a wide width strength of 80 kN/m at a constant rate of strain of 30 % per minute. It has a long-term rupture strength under sustained loading of 33.33kN/m according to BS8006 (1995).

The shock load used was chosen to represent a single earthquake loading. Usually, earthquakes are cyclic in nature with irregular frequency, however, to avoid the complexities of simulating these loading cycles, an earthquake was represented by a uniform load applied over 20 seconds. This loading period was chosen on the basis of the durations of the main strokes of the Kushiro Offshore and Northridge earthquakes, as reported by Fujii et al (1996) and Frankenberger et al (1996), respectively, and is actually more critical than the actual earthquake loadings.

A sustained loading $[P_s]$ of 25 kN/m was applied over 200 hours, with the shock loading $[\Delta P_s]$ applied after 100 hours for 20 sec. Five shock loading levels were applied from 10 to 50 kN/m, in increments of 10 kN/m. (The maximum total load of 75 kN/m was the same value as the strength obtained from CRS testing at 20°C with a strain rate of 25% per minute).

The test data are given in Fig.1 and it can be seen that only with the additional shock load of 50 kN/m did the material rupture. For all lower levels of shock loading, the strain induced was partially recovered immediately on unloading. The strain then steadily reduced to an almost constant value within the next 100 hours. Indeed for shock loads of 10 and 20 kN/m, the subsequent strain behaviour rapidly approached that for the sustained load 25 kN/m with no shock load.

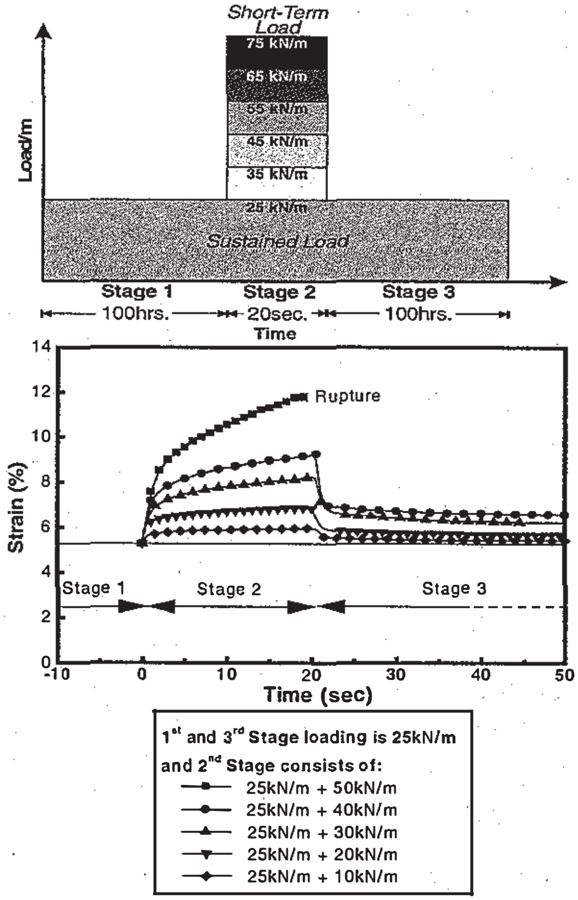


Figure 1. Loading scheme and test results.

Thus, these data indicate that at combined loading values much less then the wide width CRS strength, a very high proportion of the induced shock loading strain was recovered over a short period of time.

However, it must be made clear that in these tests the sustained load was applied for only 100 hours prior to the shock loading. The strain developed in the geosynthetic prior to the shock loading was therefore relatively small. If the sustained load had been applied over a much longer period, then the strain developed would have been greater and it is likely then that the combined load required to cause failure would have been less. Indeed, if the sustained load had been left long enough, it would have caused strains large enough to cause creep rupture. In such a case no additional shock loading is required to cause rupture.

Thus it may be suggested that the strength available to resist shock loading in geosynthetics following different periods of sustained loading will vary. In order to determine just how this varies requires an understanding of the response of elasto-visco-plastic materials to combined loading.

4 THE RESPONSE OF ELASTO-VISCO-PLASTIC MATERIALS TO LOADING

Geosynthetics exhibit elasto-visco-plastic behaviour, viz. when loaded they develop initial elastic and plastic strains then with time develop primary, secondary and then tertiary creep strains which may lead to rupture, Fig. 2. The possibility of developing creep rupture depends on there being both a sufficient load level and a sufficient period of loading, Fig. 3. If either the time or load is insufficient to cause creep rupture, then when the load is removed in part or in whole, there will be an immediate elastic rebound followed by a time dependent rebound. In most situations, there will always be a permanent irrecoverable strain, Fig. 4.

Representation of this complex behaviour can be achieved using rheological models, however, McGown (2000) has recently proposed a new approach to modelling this behaviour which is termed the "Isochronous Strain Energy" [ISE] approach. This has the advantage of being able to make direct comparisons of data obtained from different testing methodologies and to allow consideration of the effects of combining different load, or deformation sequences, i.e. "Multi-Stage Loading". Thus it is proposed that this approach should be used to analyse the behaviour of geosynthetics under combined sustained and shock loading.

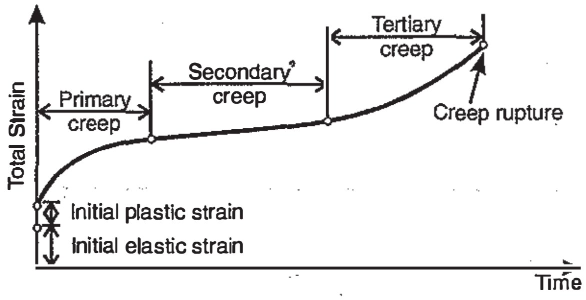


Figure 2. Idealised sustained load (creep) curve at constant temperature.

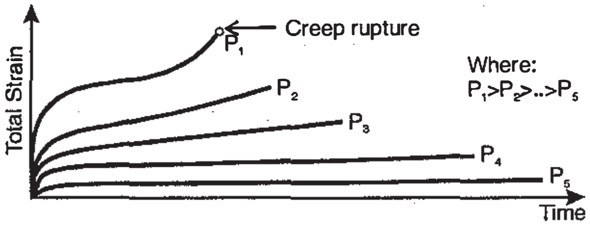


Figure 3. Strain response from sustained loading at different load levels.

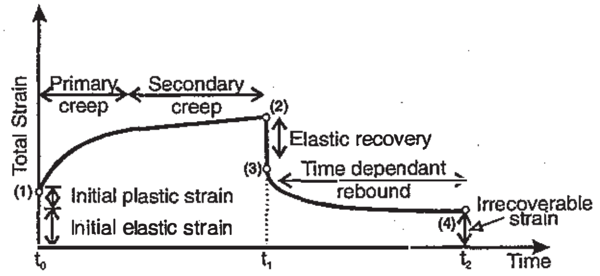


Figure 4. Idealised strain response from sustained loading and unloading.

5 THE ISOCHRONOUS STRAIN ENERGY APPROACH

For single-stage loading under isothermal conditions, the external work done per unit width of a geosynthetic at any time (t) may be taken to be equal to the "Absorbed Strain Energy". All single-stage loading test data can be represented by Isochronous Load-Strain curves and the areas under the curves represent for any specific time, i.e. the Isochronous Strain Energy, Fig. 5.

It should be noted that a feature of the ISE approach is that data obtained at the same temperature from different load-strain paths may be plotted on the same ISE - Time plot, McGown (2000).

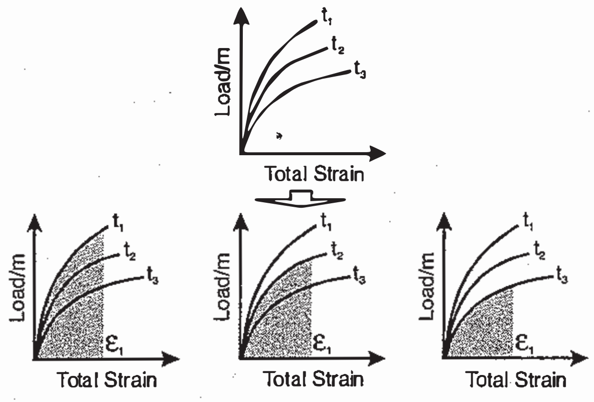


Figure 5. Calculation of isochronous strain energy.

The unit of Isochronous Strain Energy [ISE] for geosynthetics is:

Force per unit width times unit strain

$= (kN/m) \times (m/m) = kN/m.$

To avoid confusion with existing definitions of strain energy it is suggested that another unit for ISE is used as follows:

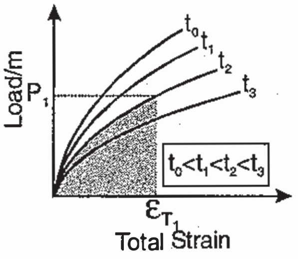
$ISE = (kN/m) \times (m/m) = (kNm/m^2) = kJ/m^2$

Thus at any temperature (T) and time (t) after the application of a particular loading regime, there will be a finite amount of work done per unit width, which can be represented as the "Absorbed ISE" $[A]_t$. The amount of ISE to develop a limiting strain or rupture at that temperature for a particular Single-Stage Loading regime is termed the "ISE Capacity" $[C]_t$ of the geosynthetic at the specified time (t), Fig. 6 (a).

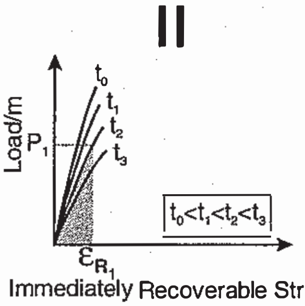
Additionally, Fig. 4 can be reinterpreted in terms of the ISE approach. Upon application of the load immediate strains occur so that there will be an Absorbed ISE at time t_0 (point 1). With time, the Absorbed ISE will increase to the Absorbed ISE at time t_1 (point 2). If the load is removed the Absorbed ISE at time t_2 (point 3) will be reduced and then continue to reduce to that at time t_3 (point 4).

This shows that at time t_1 there were two components of ISE. One component was "Immediately Recoverable" on unloading whilst the other was "Locked-in" at time t_1. This "Locked-in ISE" was partially recoverable with time however some was "Irrecoverable Locked-in ISE". Hence at any time, $[t_1]$, the Absorbed ISE comprises two components, which are the "Immediately Recoverable ISE" $[R]_t$ and the "Locked-in ISE" $[L]_t$. These components vary with time for any limiting strain condition or rupture.

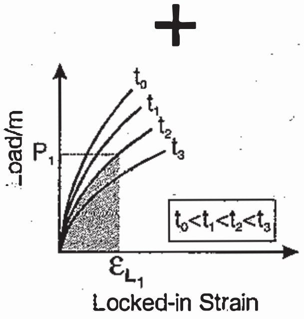
The isothermal ISE Components for any single-stage loading, i.e. $[R]_t$ and $[L]_t$, can be calculated from the areas under the respective "Isochronous Load-Strain" curves for different times and strains, Fig. 6 (b) and (c), McGown (2000). These can then be used to produce the plots shown in Fig. 7.



(a) Calculation of ISE Capacity $[C]_t$

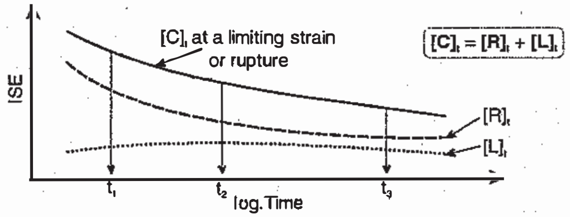


(b) Calculation of Immediately Recoverable ISE $[R]_t$

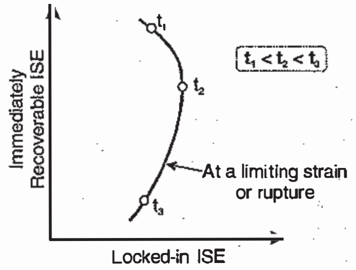


(c) Calculation of Locked-in ISE $[L]_t$

Figure 6. Calculation of ISE.



(a) ISE-Time plot



(b) Immediately Recoverable ISE $[R]_t$ - Locked-in ISE $[L]_t$ Components plot

Figure 7. Derivation of ISE Capacity $[C]_t$ and ISE Components $[R]_t$ and $[L]_t$ plot.

6 INTERPRETATION OF THE BEHAVIOUR OF THE GEOSYNTHETIC SUBJECTED TO COMBINED SUSTAINED AND SHOCK LOADING USING THE ISE APPROACH

The ISE approach can be used to interpret the test data from the uniaxial geogrid under the combined sustained-shock loading, using the following procedure:

a) The Recoverable ISE $[R]_{t1}$ and the Locked-in ISE $[L]_{t1}$ after 100hours of sustained loading are calculated in the manner set out in the previous section and as described in detail by McGown (2000).

b) The Additional Recoverable ISE $[\Delta R]_t$ and the Additional Locked-in ISE $[\Delta L]_t$ due to the shock loading are determined by constructing the Isochronous Load-Total Strain, Load-Recoverable Strain and Load-Locked-in Strain curves. The Additional Recoverable ISE $[\Delta R]_t$ and Locked-in ISE $[\Delta L]_t$ in this stage can then be calculated as the areas under the curves of Isochronous Load-Recoverable Strain and Isochronous Load-Locked-in Strain curves.

Similarly, in order to calculate the Recoverable ISE $[R]_{t3}$ and the Locked-in ISE $[L]_{t3}$ after the removal of the shock loading, it is necessary to construct the Isochronous Load-Total Strain, Load-Recoverable Strain and Load-Locked-in Strain curves for each level of additional shock loading $[\Delta P_s]$. The Recoverable ISE $[R]_{t3}$ and the Locked-in ISE $[L]_{t3}$ in this stage can then be calculated as the areas under the curves of Isochronous Load-Recoverable Strain and Load-Locked-in Strain curves.

Using the above procedure the $[R]_t$–$[L]_t$ plots for the various stages of loading can be plotted. The $[R]_t$–$[L]_t$ relationship for Multi-Stage Loading test data at a limiting strain of 10% is shown in Fig. 8. This figure shows that only at the additional shock load $[\Delta P_s]$ of 50 kN/m did the geogrid reached the 10% limiting strain. For additional shock loads less than this, the Locked-in ISE at the end of 200 hours almost reverted back to the Absorbed ISE for the sustained load alone at 100 hours. However, it is important to appreciate that in the longer term, the Absorbed ISE due to the sustained load alone will continue to increase and will eventually exceed this value.

Further it is important to note that the uniaxial geogrid reached the 10% limiting strain in 7 seconds only at 50 kN/m of additional shock loading $[\Delta P_s]$. For other levels of shock loading, 10% strain was not reached within 20 seconds. Therefore, it may be thought that this geogrid would be able to withstand at least 40 kN/m of additional shock loading $[\Delta P_s]$ at any time during its operational lifetime, however this may not always be true.

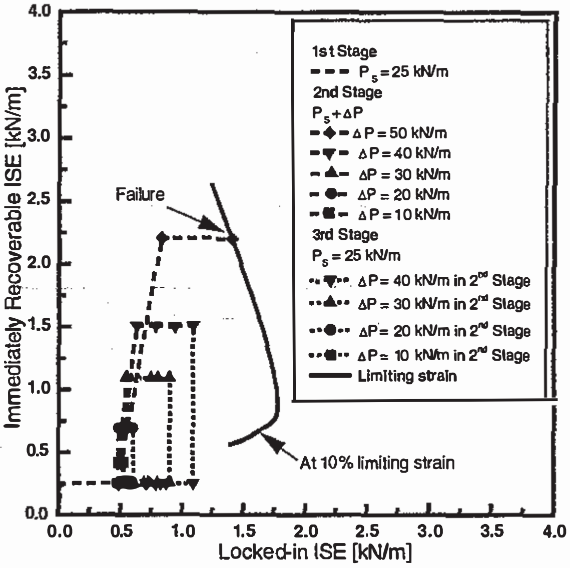


Figure 8. $[R]_t$ - $[L]_t$ relationship for the various stage of loading

It is suggested that the amount of additional shock load $[\Delta P_s]$ that can be taken by any geosynthetic depends upon when this load is applied. Under the action of the sustained load the geosynthetic will continue to strain (creep) with time, hence the difference between the developed strain and the limiting or rupture strain will diminish with time.

Thus the additional shock load $[\Delta P_s]$ that the geogrid will be able to take will depend on the "Available Strain", i.e. the difference between the strain before the shock (earthquake) loading and the limiting or rupture strain. For example, if for a Sustained Load $[P_s]$ the strain in a geosynthetic is equal to 8% and the limiting strain is 10%, then the Available Strain is 2%. Thus the geogrid will be able to take only the amount of shock loading to develop 2% strain.

7 MODIFIED MATERIAL PROPERTIES APPROACH

The above indicates that the current practice of using a single value of Design Strength over the entire design lifetime could be unsafe, particularly towards the end of design life of a GRSS. Further, it implies that GRSSs which survived the recent earthquakes will not necessarily survive similar earthquakes in the future. Thus more understanding of the response of the ISE components under sustained plus shock loading is required. In addition, the effects of being confined in soil need to be further assessed.

However, for design purposes it is suggested that in order to allow for sustained loading plus shock loading, a "Modified Material Properties Approach" should be adopted. Within this approach, a new Par-

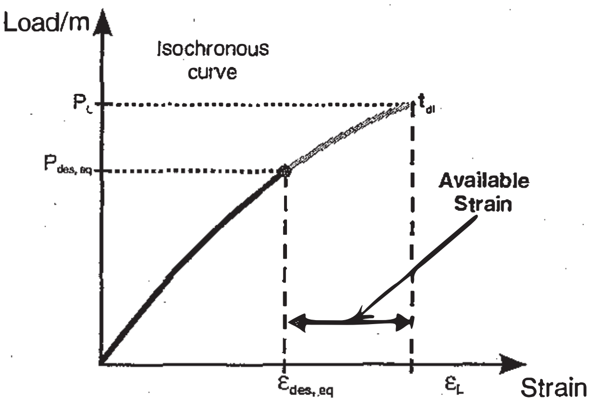


Figure 9. Modified Material Property Approach.

tial Factor, called the "Short Term (or Shock) Load ing Factor", should be applied to the Limiting or-Rupture Strain [ε_L] in order to obtain a Factored Limiting Strain [$\varepsilon_{des,eq}$], Fig 9. The sustained load at the design lifetime corresponding to this Factored Limiting Strain would then be the "Modified Design Strength" [$P_{des,eq}$]. The purpose of applying the Short Term or (Shock) Loading Factor to the Limiting Strain [ε_L] is to allow sufficient Available Strain to accommodate the shock load (or possibly several shock loads) at any time during the design lifetime of the GRSS.

Thus in this approach, the GRSSs is first designed for Single-Stage Actions or Equivalent Sustained Actions using the Modified Design Strength [$P_{des,eq}$] and then the reinforcement layout is checked for an Additional Short Term (or Shock) Load [ΔP_s], (or several of these as considered appropriate).

8 DISCUSSION

It has been shown that the present methods of designing for sustained loading plus shock loading are empirical. It is suggested that in order to design for sustained loading plus shock loading, a Modified Material Properties Approach should be used. Within this approach, a Short Term (or Shock) Loading Factor is applied to the limiting strain or rupture. This allows an Available Strain for additional shock loading to be developed. Further research is required to provide a better understanding of the behaviour of geosynthetics under sustained loading plus shock (earthquake) loading when confined in-soil.

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