Isothermal response of geosynthetics to a multi stage loading

Réponse isotherme de géosynthetiques à un chargement à plusieurs étapes

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ABSTRACT

A study has been undertaken to show the inadequacy in the existing design methods after observing the satisfactory performance of geosynthetic reinforced soil structures (GRSSs) originally designed for carrying less load than what they experienced during the 1994 Northridge, California and 1995 Kobe earthquakes. In order to facilitate a general approach towards understanding the behaviour of geosynthetics under different loading regimes, i.e. under single stage loading and multi stage loading, the 'strain envelop' concept has been developed and presented. On this basis, an approach for design of GRSSs under sustained plus short term loading regime is also suggested.

RÉSUMÉ

Une étude a été entreprise pour montrer l'insuffisance dans les méthodes du designs existants après avoir observé la performance satisfaisante de structures de sol géosynthetiques renforcées (GRSS) originairement conçues pour porter moins de charge que ce qu'ils ont éprouvé pendant les tremblements de terre de 1994 à Northridge, à Californie et le tremblement de terre de Kobe en 1995. Pour faciliter une approche générale vers la compréhension du comportement de géosynthetiques sous régimes du chargement différents, c'est à dire, sous le chargement unique et à plusieurs étapes, le concept "enveloppement de pression" (strain envelop) a été développé et présenté. Sur cette base, une proposition du design de GRSS (structures de sol géosynthetiques renforcées) sous chargement à court terme et en plus, soutenu est aussi évoquée.

Keywords : geosynthetics, strain envelop, multi-stage laoding, available strains

1 INTRODUCTION

The geosynthetic reinforced soil structures (GRSSs) designed according to the current codes/methods suffered little damage compared to other structures in the proximity which either collapsed or were badly damaged during the 1995 Kobe and 1994 Northridge, California earthquakes, Tatsuoka et al (1996) and White and Holtz (1996). The survival list includes the GRSS at Tanata as well that has been reported to have experienced the strongest shock amongst the modern GRSSs. Due to construction constraints, the reinforcement lengths for this structure were curtailed to be shorter than that recommended by railway guidelines. Further, the structures were designed for a low seismic coefficient ($k_h = 0.20$) allowing them to suffer little damage but not a total collapse. Since in the original design, the structures in these areas were designed to withstand earthquake shocks of less than what they experienced, a plausible question may be posed regarding the lack of adequate understanding of the load-strain behaviour of geosynthetic under such multi-stage loading (MSL), i.e. under combined sustained plus short-term earthquake loading in the current design methods.

In fact, neither enough test data pertaining to the behaviour of geosynthetics under such MSL was existent nor any general approach to the understanding of the behaviour of elasto-visco-plastic geosynthetics under such loading was available until Khan (1999) and McGown et al (2004a, b and c) presented the Isochronous Strain Energy [ISE] approach for geosynthetics subject to different loading regimes. A similar but a rather simpler approach, based on 'strain envelop' concept is presented here towards understanding the behaviour of geosynthetics under a single-stage loading (SSL), e.g. long term sustained loading creep test and a MSL, e.g. combined sustained plus short-term earthquake loading.

2 STRAIN ENVELOP FOR CREEP TEST DATA

When subjected to a loading-unloading sequence, the total strain, ε_T of a geosynthetic material appears to be comprised of three strain components; elastic, plastic and viscous components. Upon application of a load at an infinite rate, elastic strain component, ε_E develops instantaneously and may as well be recovered instantaneously upon removal of the load. The plastic and viscous components develop with time under a sustained load. However, the plastic strain component, ε_P is never recoverable and the viscous strain component, ε_V may be recovered with time after removal of the load. Here forth, the recoverable elastic strain is termed as recoverable strain, ε_R and the plastic strain and viscous strain together is termed as locked-in strain, ε_L. Thus by carrying out a series of sustained loading-unloading tests as shown in Figure 1, the load-total strain isochrones and load-recoverable strain curve may be obtained for a geosynthetic.

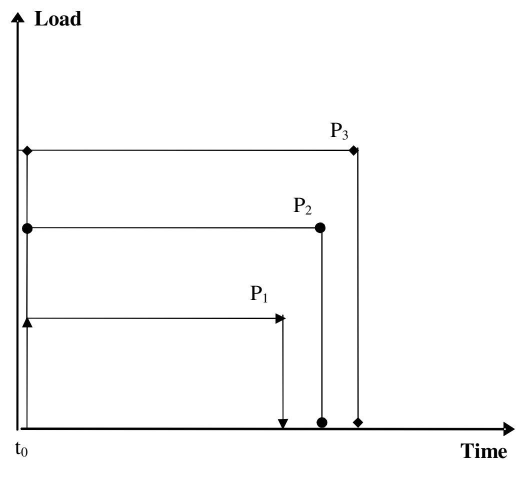

Figure 1. Loading-unloading sequence for obtaining total strain and recoverable strain component

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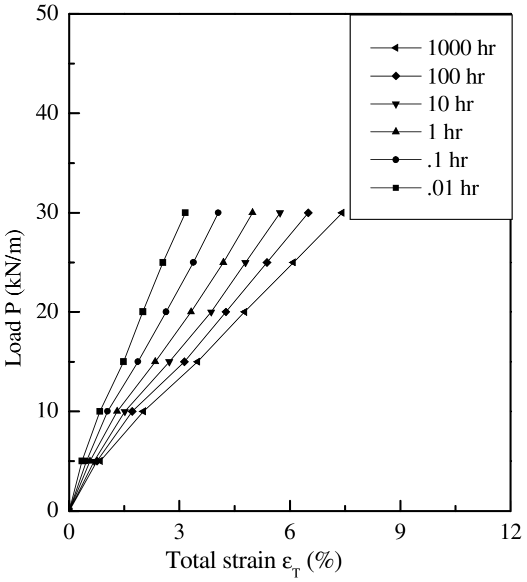

Figure 2a. Load vs Total strain plot from creep test for a uniaxial geogrid at 20°C

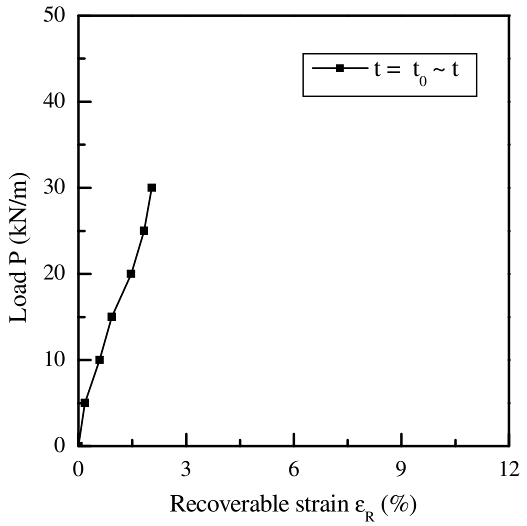

Figure 2b. Load-Recoverable strain ε_R plot for the uniaxial geogrid at 20°C

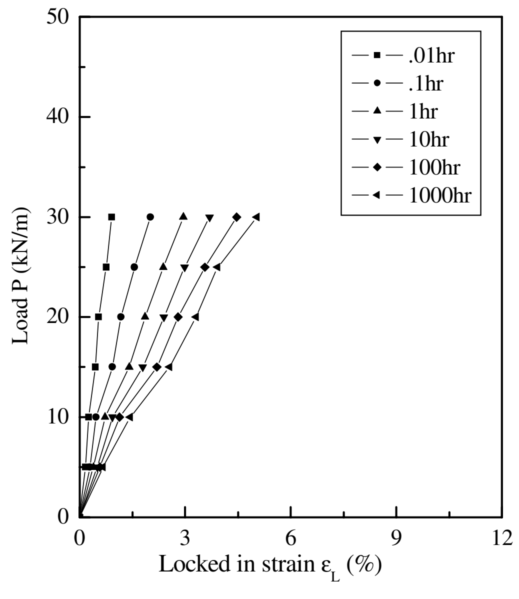

Figure 2c. Load - Locked in strain plot for the uniaxial geogird at 20°C

The load-locked-in strain isochrones may then be obtained by subtracting the load-recoverable strain curve from the load-total strain isochrones. By way of example, this is illustrated in Figures 2a, 2b and 2c for a uniaxial geogrid.

From these data, the total strains and their components vs. time for a limiting total strain of 10% (often considered to be the failure criteria for ultimate state) may be plotted by extrapolation as shown in Figure 3. It may be noted that similar plots could be obtained for other limiting strains and their associated strain components. The strain components, so obtained, may be then plotted against each other giving rise to the ε_R - ε_L plot showing strain envelops for the limiting total strains. Figure 4 shows the ε_R-ε_L plots at 2%, 5% and 10% limiting strains for the uniaxial geogrid. A strain envelop for any limiting strain thus clearly identifies that the total strain that may develop in a geosynthetic material consists of two components, namely recoverable ε_R and locked-in ε_L strains and these two components combine uniquely at different times to yield a particular strain in an isothermal condition.

3 COMBINED SUSTAINED PLUS SHORT-TERM LOAD TEST DATA AND THEIR INTERPRETATION

A combined sustained plus short-term loading test was designed by Khan (1999) to simulate the loading on a GRSS during an event of earthquake. The loading scheme chosen for the tests is as shown in Figure 5.

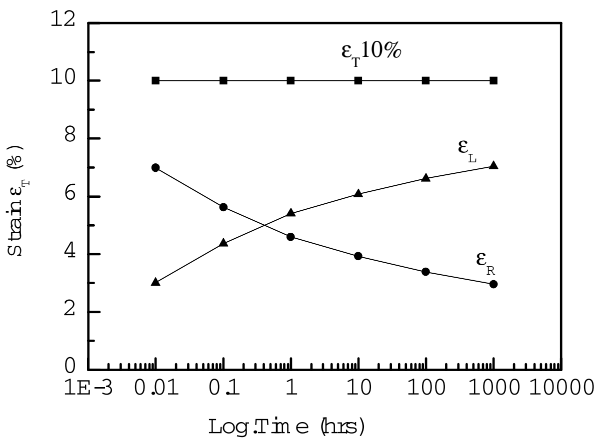

Figure 3. Total strain and its components vs. Time plot for the geogrid

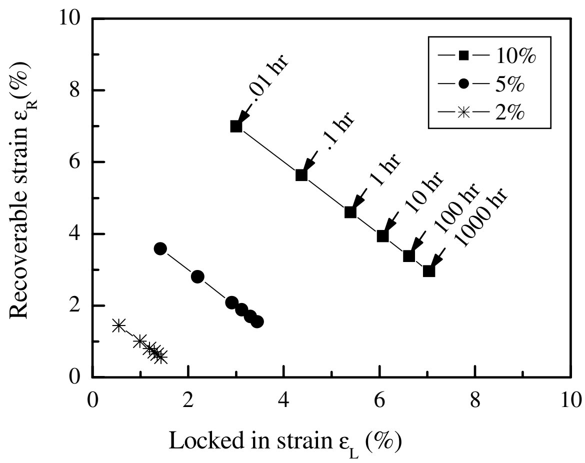

Figure 4. Strain envelop at different strain levels for the geogrid at 20°C

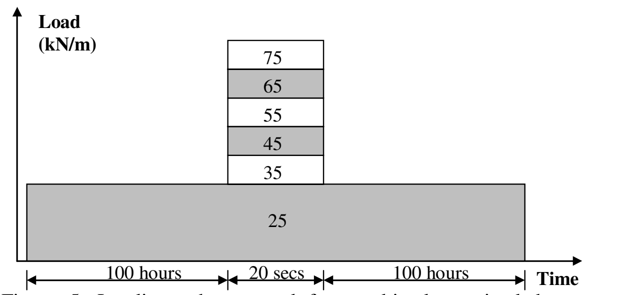

Figure 5. Loading scheme used for combined sustained-short term loading test (after Khan, 1999)

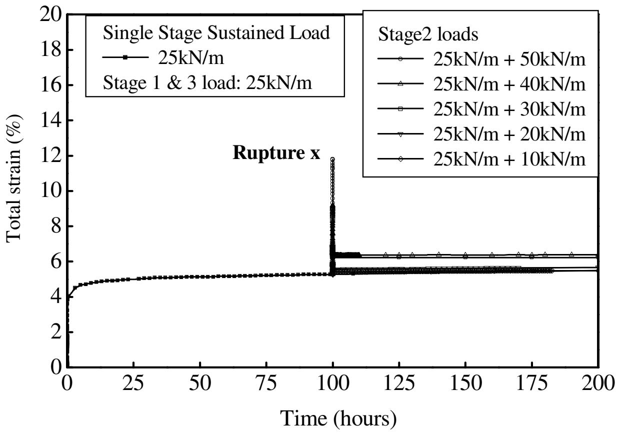

Figure 6(a). Results of combined sustained-short term loading tests (Time in hours scale),after Khan (1999)

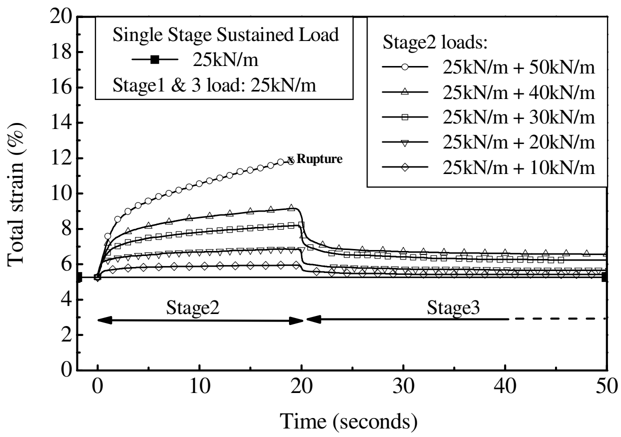

Figure 6(b). Results of combined sustained-short term loading tests (Time in seconds scale),after Khan (1999)

The Stage 1 Sustained Load [P_s] was 25 kN/m which is the long term Design Strength of the uniaxial geogrid at 20°C according to BS8006 (1995). The Stage 2 Additional Short Term Loads [ΔP_s] were varied from 10 kN/m to 50 kN/m in increments of 10 kN/m, applied over a period of 20 seconds. The maximum total load of 75 kN/m in Stage 2 was chosen as this was the strength obtained from CRS tests carried out at a strain rate of 10% per minute. The duration of Additional Short Term Load [ΔP_s] was chosen on the basis of the durations of the main strokes of Kushiro Offshore Earthquake in 1993 and Northridge Earthquake in 1994, reported by Fujii et al (1996) and Frankenberger et al (1996), respectively. After the loading in Stage 2 is removed, i.e. the earthquake shock is gone; in Stage 3 the geosynthetic reinforcement is subjected to sustained loading similar to the loading in Stage 1. Figures 6(a) and (b) portray the test results over the entire period of 200 hours in 'hours' and in 'seconds' Time scale.

It should be noted that only under Additional Short Term Load [ΔP_s] of 50 kN/m in Stage 2 the material strained more than 10% and rupture in 18 seconds. Therefore, no Stage3 was available for this combination of load. For other Additional Short Term Loads [ΔP_s], i.e. for 10 kN/m to 40 kN/m, the Total Strain of the material was less than 10%.

Figure 7 shows the superposition of ε_R-ε_L plot from the results of the test onto the strain envelop at 10%. It may be observed that the combination of strain components at 50 kN/m only exceeds the 10% strain envelop. Other strain components from all up to 40 kN/m of Stage 2 additional short-term loads are well within the envelop. That means the specimen did not fail at the lower levels of Stage 2 additional Short term loads up to 40kN/m but at 50 kN/m. Now, let the Stage 2 load be assumed to apply after 10000 hrs from the commencement of the sustained load to the same specimen. The corresponding ε_R-ε_L plot shown in Figure 8 reveals that the combination of strain components due to Stage 2 loading of 40kN/m also surpasses the envelop and even that due to 30kN/m is very close to the failure strain. This indicates that time of occurrence of earthquake is important for anticipating how much additional short term load will be carried by a geosynthetic reinforcement without failure.

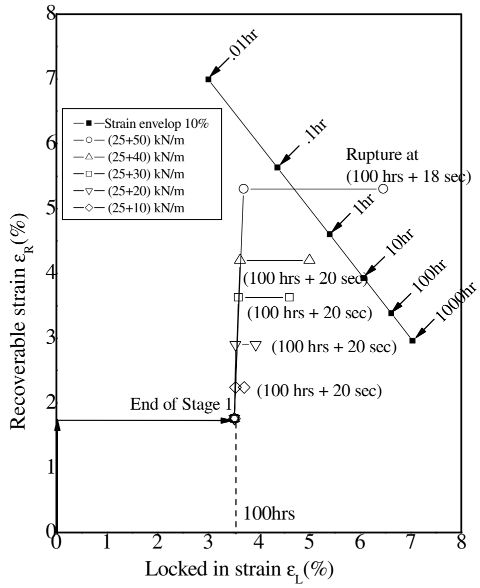

Figure 7. Superposition of MSA test results on the strain envelop at 10% limiting strain(time of event after 100 hrs of construction)

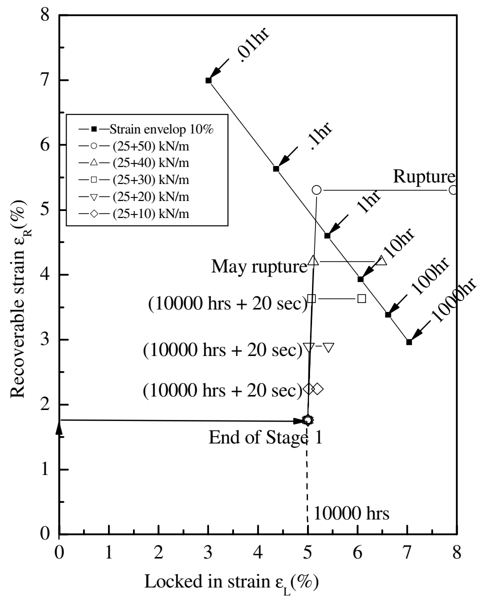

Figure 8. Superposition of MSA test results on the strain envelope at 10% limiting strain (time of event after 10000 hrs of construction)

4 SUGGESTED APPROACH OF DESIGNING GRSS FOR SUSTAINED PLUS EARTHQUAKE LOADINGS

On the bases of understandings made so far, it may be noted that the ability of a GRSS to withstand additional short-term load due to an earthquake decreases with its service life. This may be attributed to the reduction in 'Available Strain' in the geosynthetics, which is defined as the difference between the limiting strain and the strain just before an event. Naturally, the available strain decreases with the age of the structure, because there is a continuous development of 'Locked- in Strain' in the geosynthetics due to the sustained load. For this reason, a GRSS is likely to withstand greater shocks in the initial stage of its service life than that in the latter stages.

Therefore, while designing GRSSs for combined sustained plus short-term loading, the approach should be such that there is still some amount of 'Available Strain' at the end of design life (EDL) of the GRSS. This is to ensure that the GRSS is able to withstand the shocks due to probable earthquakes even at the EDL. In order to design a GRSS for sustained plus short-term loading, the force, ΔP_s induced from an earthquake event may be estimated in advance. It should be appreciated that there will be a unique pair of strain components namely ε_R and ε_L, due to the short-term load ΔP_s, the major contribution being in 'Recoverable Strain' ε_R part since the material would not get much time to develop significant amount of 'Locked-in Strain' ε_L in the event of a short duration earthquake. For design purposes, therefore, this ε_L part may be ignored and the total strain due to the earthquake load ΔP_s may be considered to be wholly recoverable. The additional 'Recoverable Strain' $\Delta\varepsilon_R$ due to this additional load ΔP_s may be obtained from the Load-Recoverable Strain curves from unloading test. Let the value of $\Delta\varepsilon_R$ be equal to 4%. Thus the Available Strain equal to $\Delta\varepsilon_R$ or 4%, should be left in the reinforcements in order to take the additional short-term load of ΔP_s at the EDL, i.e. if the failure criteria is set at a limiting strain of 10%, under the sustained loading the strain in the geosynthetic reinforcements should not exceed 6% at the EDL.

5 CONCLUDING REMARKS

Geosynthetic reinforced soil structures (GRSSs) stood unexpectedly satisfactorily during the 1994 Northridge, California earthquake and 1995 Kobe earthquake. The geosynthetic reinforced soil walls and slopes in these areas were not designed for the high earthquake forces which they experienced. This raised question regarding the inadequate understanding of the behaviour of the GRSSs subjected to multi-stage loadings, e.g. combined sustained plus short-term earthquake loading. In fact, most of the test results pertaining to the strength of the geosynthetics are obtained from the short term constant rate of strain (CRS) test or long term sustained load creep test for a limiting strain in order to avoid instability or rupture. For the design of GRSSs for earthquake loadings, these reference strengths are enhanced by an arbitrarily chosen modification factor of 1.5 or alike, Fukuda et al. (1994). However, choice of such modification factors is not technically justified for geosynthetics subjected to multi stage loadings.

In the present study, it has been shown that the geosynthetic reinforcements when subjected to a loading combine in a unique ratio of recoverable strain and locked-in strain to reach a limiting strain in a particular time. This means that if a limiting strain is to be reached in a short period of time due to a loading there will be more recoverable strain than locked-in strain and vice-versa. This concept of strain envelop facilitates understanding of the behaviour of geosynthetics due to any loading regime. By way of example, test results obtained from a combined sustained plus short term loading have been superimposed on the ε_R-ε_L plot for a uniaxial geogrid which shows that for designing against earthquake forces it is very important to consider the time of occurrence of earthquake after the construction of a GRSS. If an earthquake hits the structure immediately after the construction of a GRSS, it will be able to take more earthquake force than if it is hit after 10 years of its construction. On the basis of this understanding a design approach is suggested which incorporates the concept of 'available strain' defined as the difference between the limiting strain (failure criteria) and the strain just before an event. The suggested approach, however, remains open to further validation by full scale model tests on geosynthetic reinforced soil structures.

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