Comparative behaviour of earth reinforcing elements under repeated loading
Etude comparative entre éléments de renforcement des sols sous chargements cycliques

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ABSTRACT: Cyclic load tests were performed on 4m length of smooth steel, ribbed steel and geosynthetic Tensar Geogrid reinforcing strips. Comparisons are made of development of strip movement under load with number of alternating load applications. It has been clearly demonstrated that the Tensar Geogrid reinforcement is safer and more efficient than either the smooth or the ribbed steel strips.

RESUME: Des essais de chargement cycliques ont été réalisés sur des éléments de renforcement de 4 m de longueur constitués d'acier lisse, d'acier adhérent et de geosynthetic du type Tensar Geogrid. Une comparaison entre les déplacements de ces éléments sous l'effet de ce mode de chargement a été faite. Les résultats ont montrés que les renforcements du type Tensar Geogrid sont plus sûrs et plus efficaces que les renforcements en acier.

1 INTRODUCTION

It is now recognised that the designer of reinforced earth structures may have to consider different types of reinforcing element and different types of loading e.g. static, repeated, dynamic. Extensive literature will be found on the behaviour of the elements under static loading. However, little data are available in which different forms of reinforcement are compared by reference to tests under similar conditions. A reinforced earth element is a tensile resisting member embedded in a soil mass. Under applied external load the reinforcement will mobilise resistance along its length according to the laws of bond and bearing. Questions very often posed by engineers include: (i) what is the difference between a relatively flexible and a relatively rigid reinforcement; (ii) how does a repeated load application affect the pullout capacity and the « life » of a reinforcement? The ability of the engineer to give reliable answers to these questions is thwarted by a lack of reliable data. To provide a datum against which the performance of reinforced earth elements could be assessed, a program of experimental work has been in progress for 15 years. This paper presents some of this work in an attempt to give an unbiased assessment of the performance of the Tensar Geogrid strip relative to those of both the smooth and the ribbed steel strip. In this study efforts were made to work at large scale (about half scale) to avoid errors associated with « model » testing.

2 THE TEST SYSTEM

The test rig comprised a $4m$ long, $300mm$ square, rigid steel container with the capacity to apply a surcharge pressure up to $200KN/m^2$ on a dry sand surface (Figure 1). The internal walls of the rigid rig are smeared with a frictionless grease, allowing the surcharge pressure, applied via a pressure plate loaded through a water bag, to be transmitted through the sand mass. The test reinforcing strip was placed in the middle of the sand mass and can be loaded either statically under constant stress increments, or under slow repeated loading. For the repeated loading the load was changed every 20 seconds to give a square-shaped pattern between an upper and a lower load level. The load levels were related to the static pullout capacity P_u of the steel strips and the index load PI of the Tensar Geogrid strip. This index load is the ultimate rupture load as defined by Choek (1985). The three elements tested were a smooth steel strip, a high adherence (ribbed) steel strip, and a geosynthetic Tensar Geogrid *SR2* strip. The steel reinforcing strips were made from hard rolled steel of $680N/mm^2$ yield stress and $200KN/mm^2$ modulus of elasticity. The plastic reinforcement was formed by cutting a row of two ribs in width and 35 bars in length of *SR2* Tensar. The width of the strips finally chosen was $32mm$ to ensure that there were no edge effects from the test rig walls. The ribbed reinforcing strip was provided with a series of projections, $3mm$ high × $6mm$ in width, attached to the strip. Both steel reinforcements were provided with special load cells, temperature compensated, at $400mm$ centres, the wires from the cells being carried in grooves machined along the length of each strip to an end terminal. These arrangements required the use of a $6mm$ thickness of strip to avoid possible breakage at the critical machined section under the effect of pull-out loading. Numerous attempts were made to instrument the *SR2* plastic strip but none were successful. As a consequence special axial movement gauges were provided at five locations along the plastic reinforcement to measure the distribution of axial strain with applied load. The sand was used in a dry state being of medium size and uniformly graded ($D_{60}/D_{10} = 1.9$). The specific gravity was 2.67; maximum and minimum densities were 1.78 and $1.42Mg/m^3$ respectively with corresponding void ratios of 0.87 and 0.49. A raining method of sand placement gave an average and repeatable density of $1.57Mg/m^3$ with a density of 0.53.

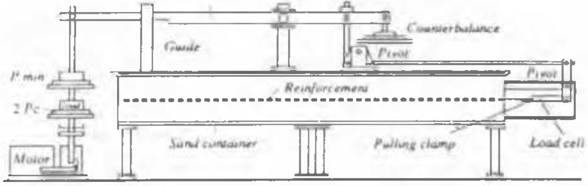
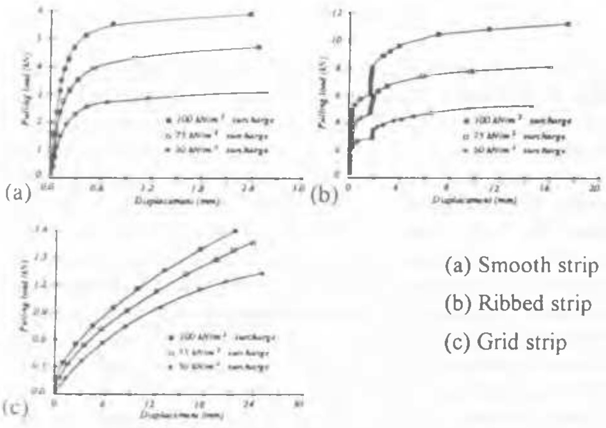


Figure 1. The test rig.

3 STATIC LOAD TEST BEHAVIOUR

The three reinforcing elements were first subjected to a series of static loading in order to predict their pull-out capacity under this type of loading. Three levels of normal stress, 50, 75 and $100KN/m^2$ were applied to the sand surface and each reinforcement was loaded statically. The shapes of the pull-out load-displacement curves are given in Figure 2. It is clear that these trends are reflecting the complex interaction between the strains necessary to mobilise skin friction and bearing resistances and the effects of the axial flexibility of the Geogrid strip. The ribbed and the Tensar strips are much more load efficient and safer than the smooth strip. These different trends in load mobilisation with displacement can be attributed to the difference in the mechanism whereby load is mobilised. For the smooth strip, load is mobilised essentially by frictional resistance only, whilst for the ribbed strip and the plastic strip both friction and end bearing on the projections are mobilised.

Data for the smooth and ribbed strips are given in Figure 3 showing the distribution of load along the length of the strips whilst the strains along the Geogrid strip are given in Figure 4. A most interesting feature is observed. In contrast to the steel strips where the axial load was gradually mobilised along the full length of the strip, the load in the Geogrid was mobilised along the front part of the strip only, the parts towards the distal end being unstrained. This observation would indicate that unless a very low confining stress be used it would be impossible to pull out the plastic strip.



(a) Smooth strip
(b) Ribbed strip
(c) Grid strip

Figure 2. Load displacement relationships.

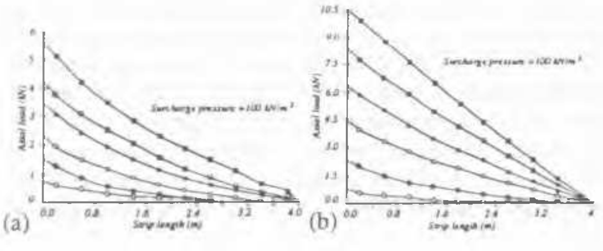


Figure 3. Axial load mobilization: (a) smooth stirp, (b) ribbed strip.

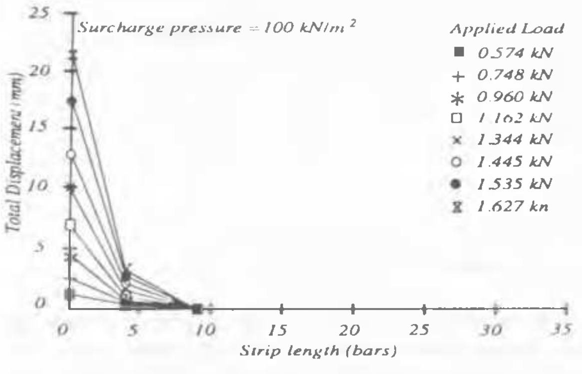
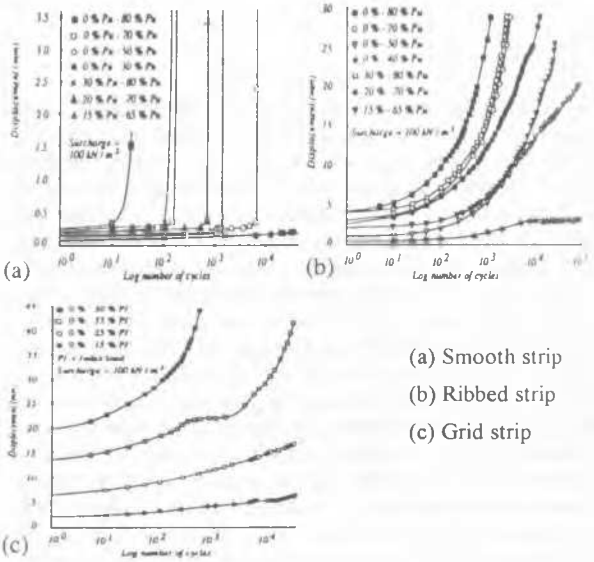


Figure 4. Axial displacement of grid strip.

4 REPEATED LOAD TEST BEHAVIOUR

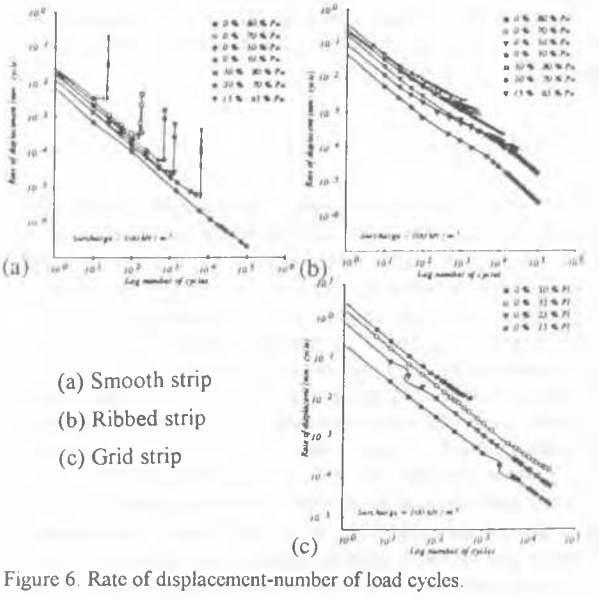
A wide range of loading levels and amplitudes was chosen to assess their effect on the behaviour and performance of the three test strip elements. In some cases the tests were taken to 10^5 load cycles. The cumulative effects of cyclic loading are shown in Figure 5. These results demonstrate clearly the complex nature of repeated loading. There are significant differences in the manner the strips behave. The smooth steel strip was characterised by an initial stable state followed by a short period with an accelerated movement leading to a catastrophic failure. The ribbed and plastic strips displaced much further under repeated loading, exhibiting a gradual movement and despite the large number of load repetitions none of these strips failed by pulling out. This observation would suggest that such strips are much more suitable to resist pull-out repeated loading than the smooth strip.

The above data were presented in semi-log form making difficulty in comparing trends between the strips because of different levels of loading, different initial displacements on load and different modes of load mobilisation. Other investigators have successfully used the rate of deformation technique to explain the behaviour of elements subjected to repeated loading.



(a) Smooth strip
(b) Ribbed strip
(c) Grid strip

Figure 5. Displacement-log numbers of load cycles.



(a) Smooth strip
(b) Ribbed strip
(c) Grid strip

Figure 6. Rate of displacement-number of load cycles.

For example, Lashine (1973) showed that an accelerated rate of displacement for repeated tests on a granular soil usually was irreversible and indicative of failure once such a stage had been reached. The present data are replotted in this form of rate of displacement/cycle against the number of cycles on a log-log scale (Figure 6). The smooth strip data clearly reflect the trends shown in Figure 5(a), namely that all strips failed by eventually pulling out although initially all rates of displacement kept decreasing with increases in the number of load cycles. An interesting feature is that the slopes of all plots are approximately the same. In general there was no indication that failure was imminent. None of the ribbed strips tests indicated failure, the rate of displacement in all cases decreasing with cycle number increase. The Geogrid data show a similar trend.

5 STATIC LOADING AFTER REPEATED LOADING

The act of subjecting a reinforcing element to a package of repeated load tests modifies the stress state along the strips and changes the locked-in stress regime. It is to be expected, therefore, that if such a strip is loaded to failure in a static mode that its behaviour will be quite different from a similar strip subjected to static loading but without any repeated loading.

At the end of testing, the opportunity was taken to load statically all specimens which had been subjected to repeated loading. Test data are given in Figure 7. In general, the smooth strip gave a significant reduction in pull-out capacity. The ribbed strip gave a significant increase, whilst there was little change in the performance of plastic Geogrid strip. For this strip, it was not possible to pull it out of the sand. These findings would suggest that a smooth strip is not efficient under cyclic loading. The significant changes in the static performances of the smooth steel strips demonstrate the importance of the sand densification in the vicinity of these strips. The ribbed strip is a much more reliable reinforcement if the applied loading is of a slow cyclic form. The Geogrid, because of the very large reserve length unloaded, behaved in a similar manner to first time loading.

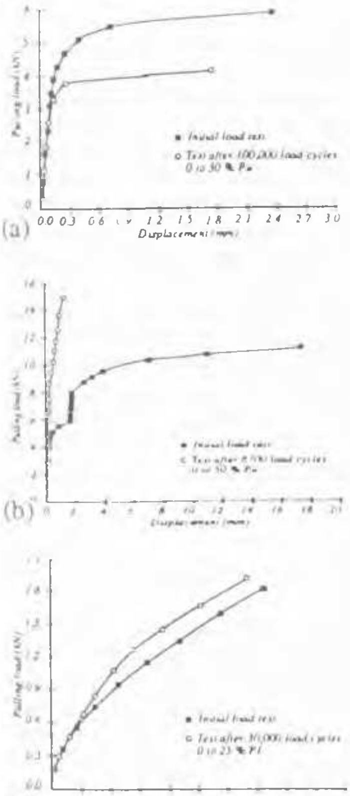


Figure 7. Load displacement relationships before and after repeated loading. (a) smooth strip. (b) ribbed strip. (c) Tensar Geogrid strip

6 DISCUSSION OF THE FINDINGS

The test data clearly demonstrate the complex nature of repeated loading response of foundation element. From a fundamental point of view the deterioration in the performance of a strip appears to be related to several partly understood factors including, (i) changes in load transfer along the strip length, (ii) Changes in the locked-in stress after each load cycle, (iii) compaction of the sand due to local shear reversals causing breakdown of particles, (iv) changes in the normal confining stress along the strip with increase in the number of load repetitions leading to a significant deterioration of the skin friction resistance.

With the relatively inextensible steel strips the applied load is mobilised over the full length of the strip. In contrast, the relatively extensible Tensar Geogrid strip under load deformed much further than the steel but even at the highest test load, 50%P.I., the resistance to load was mobilised over the front quarter length of the strip, the remaining three-quarters of the strip being unstressed. The load was resisted primarily by the bars of the grid acting as a series of anchors or footings. On unload large residual loads were locked in the steel strips. It was not possible to measure load distributions in the Tensar Geogrid strip but the evidence, as obtained from the longitudinal movement of this strip under load change, suggests that that the locked-in loads on unload were small. It is clear that the mechanics of load mobilisation for the steel strip (primarily in side friction) are different from those of the Tensar Geogrid (primarily in bearing against the individual bars of the grid). Direct comparison of load carrying capacity between the steel strips and the Tensar Geogrid is unwarranted because, in use, the grid reinforcement covers the plan area of the ground whereas the individual strips cover a small area only. From knowledge of strips spacing the relative load efficiencies of the grid versus the strip may be established. From a simple consideration it will be found that the Tensar Geogrid has at least the same load capacity as the steel reinforcement. Also, at reasonable depths of embedment the Tensar will fail structurally rather than pull out.

Under load the Tensar Geogrid moves much further than the steel reinforcement but, for a given load, has a much greater reserve of pull-out capacity. In design allowance can be made for the larger movements. In contrast to the movements of the strips under static loading, the application of repeated loads generated quite complex trends. The smooth strips strained very little further under repeated loading for all load levels but suddenly started to pull out leading to catastrophic failure. The ribbed strips displaced much further under repeated loading showing a gradual movement with the number of load applications. None of the strips failed by pulling out, the rate of displacement per load cycle decreasing. Clearly this strip is much more suitable to resist pull-out repeated loading than the smooth strip. None of the Tensar Geogrid strips failed during repeated loading. In no case did any of the applied load reach the distal end of the strip. The behaviour of these grid strips was even better than the ribbed steel strips. From all of the test data generated to date it is impossible to predict when the onset of failure by pull-out starts. There is a need to develop further a degradation curve for repeated loading and apply it to the reinforced earth strip. All indications are that grid and ribbed reinforcements are suitable for cases of repeated loading. The grid is a more efficient element than a ribbed strips.

CONCLUSION

The results of the large-scale tests demonstrate the complex nature of repeated loading response of reinforcing elements. The act of subjecting a reinforcing element to a package of repeated loading modifies its static pull-out capacity. The rate of accumulation of reinforcement movement increases with increase in the number of load repetitions, load amplitude and load level being controlling variables. The large numbers of load cycles can lead to a significant deterioration in the skin friction resistances mobilised and the evidence to date suggests that compaction of the sand in the immediate vicinity of the reinforcing element with cyclic strain is responsible. A particular features was the inability of the Geogrid to pull out of the sand, failure being by rupture of the reinforcement material. In general, under repeated loading a Tensar Geogrid reinforcing element is safer and more efficient than either the smooth or the ribbed steel elements.

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