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TECHNICAL NOTE

Geosynthetics Under Cyclic Pullout and Post-cyclic Monotonic Loading

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Abstract Several real life reinforced soil structures such as traffic supporting embankments and pavements are subjected to cyclic loads. The behaviour of soil-reinforcement interface under cyclic load is different from that under monotonic load. In the investigation reported herein, cyclic pullout tests were conducted on geogrid embedded in sand. A load controlled pullout test apparatus complying with the dimensions suggested by ASTM D-6706-01 was designed and fabricated in-house. Modular units for applying both cyclic and monotonic load were also designed and fabricated. Cyclic load was applied through a pneumatic double acting air cylinder. In addition, the setup consisted of a signal generator and a filter lubricator regulator volume booster. The effect of normal stress and cyclic load on the pullout behaviour was studied. It was found that cyclic loads of a lower magnitude than the monotonic capacity could cause failure. In the case of cyclic loads of small magnitude, the displacements showed tendency to stabilize. In the case of higher magnitudes of cyclic loads, the displacements progressively increased to failure. An initial stiffness was noticed in the system due to the initial densification achieved near the interface due to the dynamic nature of the cyclic pullout forces. Normal load as well as cyclic load played important roles in the number of cycles to cause failure. Post-cyclic monotonic tests showed the effect of degradation of the soil-geosynthetic interface after subjecting the same to certain number of load cycles.

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Introduction

Soil reinforcements such as geosynthetics are commonly used for improving the strength of earth structures such as embankments, retaining walls and pavements. The reinforced soil derives its strength from the stress transfer from the soil to the reinforcement that takes place at the soil–reinforcement interface [1] and for proper utilization of the reinforcement strength, strong interfacial bond is required [2]. However, the behaviour of soil-reinforcement interface under cyclic load (such as traffic load) is different from that under monotonic load. For example, cyclic triaxial tests on reinforced clay have shown that the interfacial properties influence the behaviour of the composite mass to a large extent [3].

Figure 1 shows some of the situations where the soil-geosynthetic interface is subjected to cyclic loads (after Meyer et al. [4]). The vertical cyclic stress σ_{dyn} induces a cyclic loading F_{dyn} in the geosynthetic in addition to the static load F_{stat}. This additional strain due to cyclic loading has been recorded through in situ measurements with strain gauges by Verspohl and Gartung [5] at a geogrid reinforced railway embankment for each train axle passing. The additional vertical stress σ_{dyn} of passing trains can be measured in the upper 4–5 m of soil and its value declines rapidly with growing depth [4, 6].

The interfacial shear strength is represented by the coefficient of sliding which can be measured by performing modified direct shear tests between soil and any type of geosynthetic reinforcement [7–9]. Geosynthetics in reinforced soil structures often derive their strength from

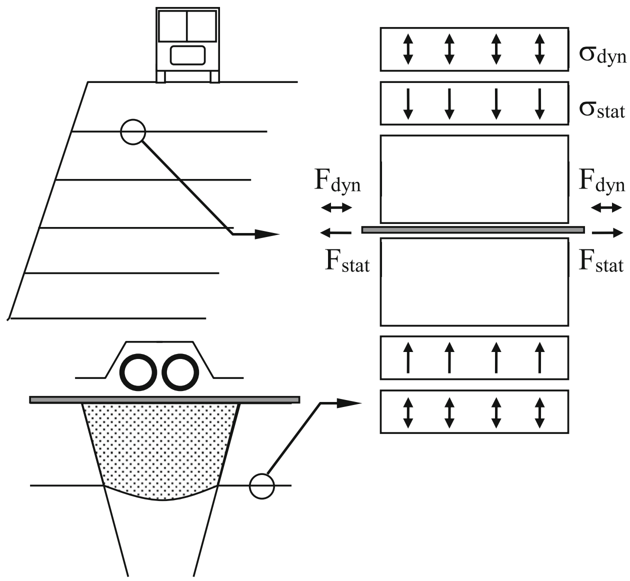


Fig. 1 Examples of cyclic loadings (after Meyer et al. [3])

anchorage. The mechanism of failure in such cases involves two sliding surfaces, i.e., one below and one above. Such conditions are ideally simulated in pullout tests in which the geosynthetic exhibits large deformation and causes the soil particles to reorient themselves into an altered shear strength mode at the soil-to-geotextile interfaces. This is considered to result in lower pullout resistance values in comparison to direct shear tests. However, for the case of materials like crushed stone, at lower normal stress values, the pullout resistance is higher in comparison to shear resistance in direct shear tests. This is due to the development of interlocking mechanism and passive resistance above sliding [10]. Furthermore, pullout tests have the advantage that they represent a combined effect of bond and shear stresses. Lopes and Silvano [11] found from the comparison of pullout tests and modified direct shear tests that the direct shear test produced erroneous results even in the case of planar reinforcements. This is due to the fact that the contribution of geosynthetic deformation to the interfacial bond is not reflected in the direct shear tests. Such contribution is relevant for planar reinforcements [12]. The bond coefficient can be measured by performing pullout tests between soil and any type of geosynthetic reinforcement [12–14].

Although several investigators have used the pullout test for studying the soil–geosynthetic interaction [1, 15–28], limited studies have been carried out on the behaviour of geosynthetics under cyclic pullout [29–33]. In the investigation reported herein, cyclic pullout tests were conducted on geogrid embedded in sand using an in-house fabricated test apparatus and influences of some of the participating parameters were studied.

Materials and Methods

Uniformly graded sea sand (refer Table 1) at low relative density was used to fill the pullout box. The properties of the geogrid reinforcement used are given in Table 2.

Pullout Test Setup

A load-controlled pullout test apparatus complying with the guidelines given in ASTM D-6706-01 [34] was designed and fabricated in-house (refer Fig. 2). The pullout box was made of timber planks stiffened by steel members with the internal dimensions of the box being 0.61 m (length) × 0.45 m (width) × 0.305 m (depth). The slit in front of the box provides a clearance of 5 mm between the specimen and the sidewall of the apparatus. A grip, which is made of mild steel plates and hexagonal rods, connects the pneumatic cylinder to the test specimen. The design of grip was a unique one that not only provides adequate grip for the experiment to proceed, but also prevents the geosynthetic from failing by tearing at the line of grip. Modular units for applying both cyclic and monotonic load were also provided. Cyclic load was applied through a pneumatic double-acting air cylinder controlled through a solenoid valve and repeat cyclic timer. Pullout load was controlled by adjusting the input pressure through a filter

Table 1 Physical properties of the sea sand

Property	Value
Specific gravity	2.67
Effective particle size (D_{10}) (mm)	0.19
Mean particle size (D_{50}) (mm)	0.35
D_{85} (mm)	0.54
Minimum density (g/cc)	1.52
Maximum density (g/cc)	1.78
Uniformity coefficient	1.89
Coefficient of curvature	1.40
Placement relative density (%)	19
Angle of internal friction at placement density (degrees)	28

Table 2 Properties of the geogrid

Property	Value/Type
Polymer	HDPE
Mass per unit area (g/m^2)	265
Nodal thickness (mm)	4.1
Opening size (mm × mm)	39 × 39
Ultimate tensile strength (kN/m)	11.35
Strain at ultimate strength (%)	25
5 % secant modulus (kN/m) without seam	17

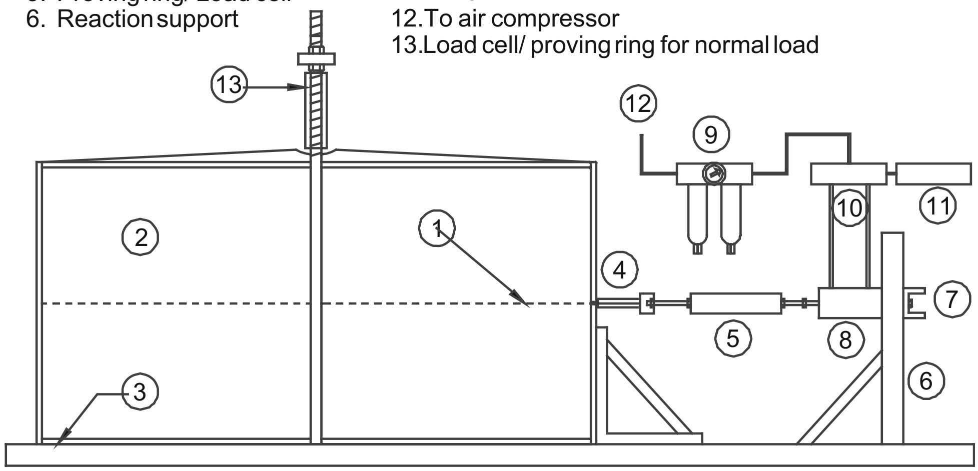


Fig. 2 Schematic of cyclic pullout test apparatus

cum regulator cum lubricator. In addition, the setup consists of a signal generator and a volume booster. The versatility of the setup allowed the conduct of monotonic pullout tests, cyclic pullout tests and post-cyclic monotonic pullout tests. Instrumentation was provided to measure pullout force, pullout displacement at the clamped end and embedded end of the test specimen, lateral pressure on the front wall of the apparatus, and the strain in the geosynthetic specimen.

Monotonic and Cyclic Pullout Tests

The pullout box was initially filled with sand up to the level of slit. Sea sand was placed through air pluviation technique [35] using a funnel for controlled placement of the sand to a targeted density. The geogrid was placed on the half-filled box and drawn out through the slit and connected to the grip. Sand was further poured on the top of the geogrid by air pluviation up to the top level and the lid was placed on top. A stiffened MS plate was placed on the top of the lid and the proving ring was installed above the plate and normal load was applied by screw jacking. The grip was connected to the air cylinder and pressure was applied using an air compressor. Following this, the experiments were conducted at different cyclic pressures ranging from 0.2 to 0.5 MPa and at different normal stresses of 3, 4 and 5 kPa. The application of normal stresses was limited by the thickness of the plate and screw jacking system and hence only low normal stresses could be applied in this initial study. Displacement of the geogrid for 5, 10, 15, 20, 30, 40 and 50 cycles and the number of cycles leading to the failure of the geogrid were noted. Furthermore, monotonic pullout tests were conducted after subjecting the geosynthetic to different load cycles.

Results and Discussion

Figure 3 shows the variation of displacements with the number of load cycles for various normal loads. It can be observed from the figures that as the cyclic load increases, the displacements also increase. The incremental displacements (displacements in between two successive cycles) were relatively less for the initial few cycles and subsequently increased. At larger number of cycles, the incremental displacements increased substantially leading to large accumulated displacements. The initial stiffness noticed in the system may be due to the initial densification developed near the interface due to the dynamic nature of the cyclic pullout forces. Furthermore, the repeated loads might have resulted in the interfacial zone achieving a constant relative density, not altered by further vibrations. Nimmesgern and Bush [36] have observed a similar slight compaction in reinforced soil after applying cyclic loads. As the accumulated deformations increased, the length of geogrid under pullout also reduced, resulting in reduced resistance and leading to faster accumulation of displacements. At higher normal loads and lesser cyclic loads, the displacements showed a tendency to stabilize without much increase in the accumulated displacements. In other words, the incremental deformations stabilized to a near zero value as observed in the experiment with a normal load of 5 kPa and cyclic load of 1.02 kN/m (refer Fig. 3c). Incremental deformations are presented in Fig. 4 for various normal loads. These figures clearly show the

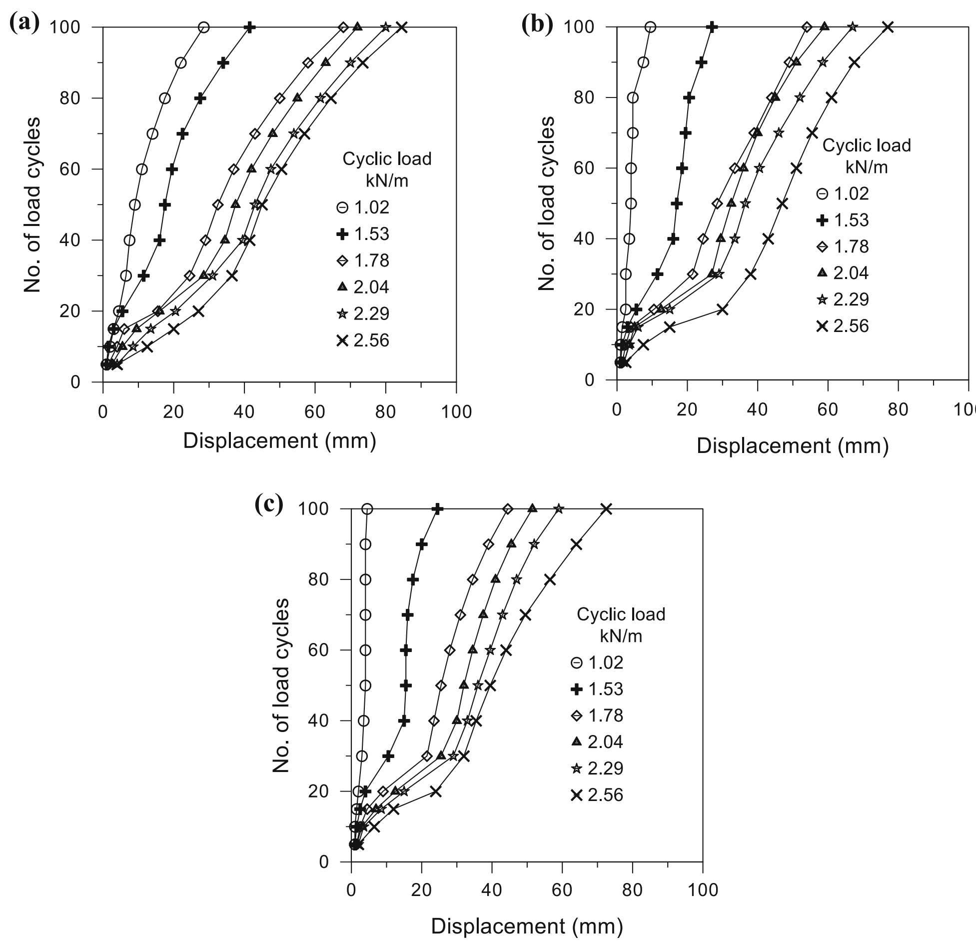


Fig. 3 Variation of number of load cycles with displacement at normal loads: **a** 3 kPa, **b** 4 kPa and **c** 5 kPa

increase in the incremental displacements in the early stages and subsequent tendency to stabilize due to the possible densification near the interface due to vibrations.

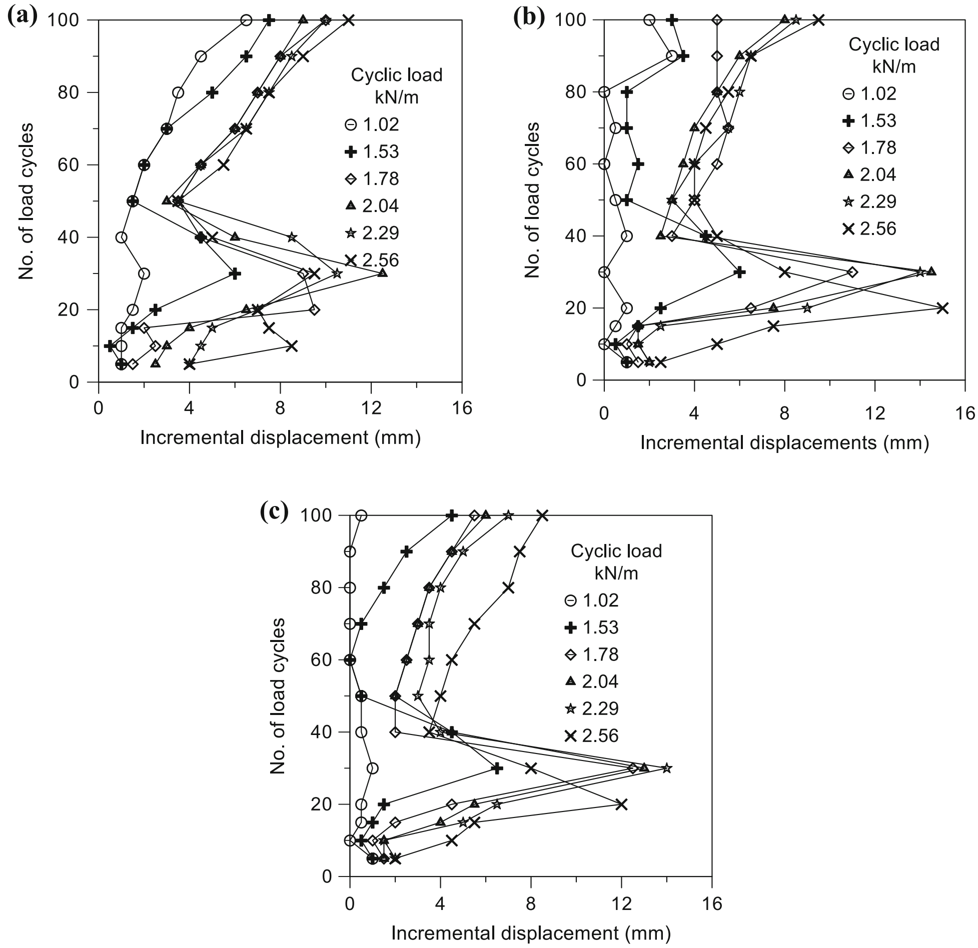
For the purpose of discussion, 50 mm displacement (which is 8 % of initial geosynthetic length under pullout) is treated as failure condition. As inferred from Fig. 5, the number of cycles to failure reduces with increase in the magnitude of cyclic loading. Furthermore, normal load as well as cyclic load plays important role in the number of cycles to cause failure. At higher normal loads, the specimen can withstand a much higher number of load cycles before reaching the specified pullout of 50 mm. However, the number of load cycles drastically reduces as the normal load reduces. Interestingly, larger cyclic loads influence failure more than the normal load and beyond a critical magnitude of cyclic load, the decisive factor is the cyclic load alone.

The post cyclic pullout behaviour of the geogrid after subjecting the same to load cycles is presented in Fig. 6. The case of pure monotonic pullout (without prior load cycles) is also shown for comparison. It can be seen that there is significant change in the behaviour of the system after undergoing the load cycles. A comparison of the curves for pure monotonic and post cyclic pullout test shows a change in the stiffness of the system. Geogrid under pure monotonic pullout shows greater peak resistance when compared to the post cyclic pullout. Furthermore, the peak pullout resistance reduces with increase in number of cycles. The stiffness of the system, represented by the slope of the initial straight-line portion of the curves, increases with increase in load cycles. Comparison of cyclic pullout with post cyclic monotonic pullout (Figs. 3, 6) indicates that cyclic loads of a smaller magnitude and monotonic pullout load of higher magnitude can cause similar displacement patterns. In other words, under similar operating conditions and under higher loads, even when the monotonic load may not cause a failure of the geosynthetic reinforcement, a cyclic load of the same magnitude may lead to failure.

Conclusions

A pullout test apparatus complying with the ASTM D-6706-01 was designed and fabricated in-house and cyclic pullout tests under a single relative density were conducted on

Fig. 4 Variation of number of load cycles with incremental displacement at normal loads: **a** 3 kPa, **b** 4 kPa and **c** 5 kPa



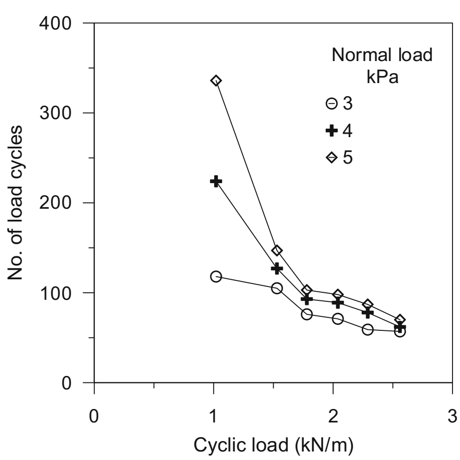


Fig. 5 Number of load cycles to reach 50 mm settlement (2.56 kN cyclic load)

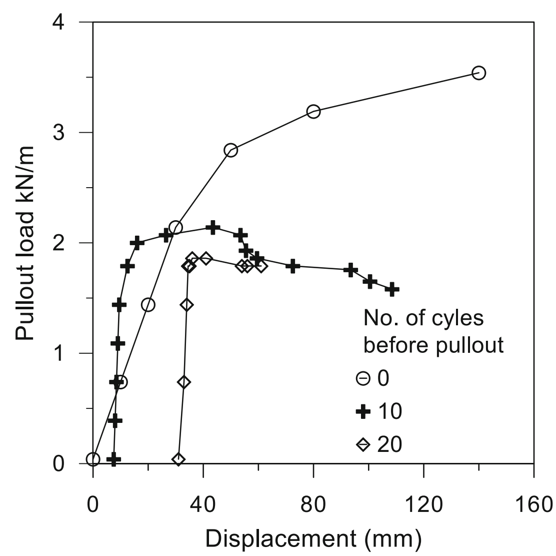


Fig. 6 Post cyclic monotonic pullout tests (2.56 kN cyclic load)

geogrid embedded in sand. The versatility of the setup allowed the conduct of monotonic pullout tests, cyclic pullout tests and post-cyclic monotonic pullout tests. It was found that cyclic loads of a lower magnitude than the monotonic capacity could cause failure. In the case of cyclic loads of small magnitude, the displacements showed tendency to stabilize. In the case of higher magnitudes of cyclic loads, the displacements progressively increased to failure.

In all the cyclic pullout tests, the geosynthetics showed a tendency to stabilise in the initial stages of pullout owing to the vibration-induced compaction achieved near the interface. However, at larger displacements, the magnitudes of incremental displacements increased, resulting in failure. Normal load and cyclic load were found to influence the number of cycles to cause failure. At higher normal loads, the specimen can take a much higher number of load cycles before reaching failure or stabilizing to zero incremental deformations and this drastically reduces as the normal load decreases. Above a critical magnitude of cyclic load, the cyclic load rather than the normal load controls the failure.

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