Consideration of Rate Effect on Pullout Behavior for Geogrid Reinforced Soil Structures under Dynamic Loading

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ABSTRACT
This paper presents an experimental study to investigate the effect of loading rate on the pullout behavior of high density polyethylene (HDPE) geogrids confined in compacted dry sand. A series of pullout tests were performed under different displacement rates, initial sand relative densities, and vertical stresses using a pullout device that incorporates standard elements such as roller grips, a motor for displacement-control pullout, and instrumentation for pullout force and displacement measurement. For comparison, a series of in-isolation tensile tests on single-rib geogrid specimens were also performed under different loading rates. Test results indicate that the in-isolation tensile behavior of HDPE geogrid is significantly affected by loading rate, while the pullout behavior of geogrids confined in soil shows negligible rate effects for different initial relative densities and vertical stresses considered.

1. INTRODUCTION

Geosynthetic reinforced soil (GRS) structures have been widely used in high seismicity areas. Dynamic shear forces develop on the soil-geosynthetic interface involving various loading rates and frequencies under earthquake loading, which may cause internal failure of GRS structures due to reinforcement rupture or pullout. For the design of GRS structures, the tensile properties of geosynthetics are typically measured from static in-isolation tensile tests on geosynthetic specimen at a prescribed loading rate (ASTM D6637; ASTM D4595). However, the in-isolation tensile behavior of geosynthetics is very sensitive to the rate of loading, especially for high density polyethylene (HDPE) geogrids. Results from different studies indicate that the tensile stiffness and strength generally increase with increasing loading rate (Boyle et al 1996; Sawicki and Kazimierowicz-Frankowska 2002). Research has been conducted on the cyclic response of in-isolation geogrids, and results indicate that the cyclic behavior strongly depends on the magnitude of tensile strain applied and the frequency of tensile loading (Bathurst and Cai 1994; Ling et al. 1998; Cardile et al. 2017).

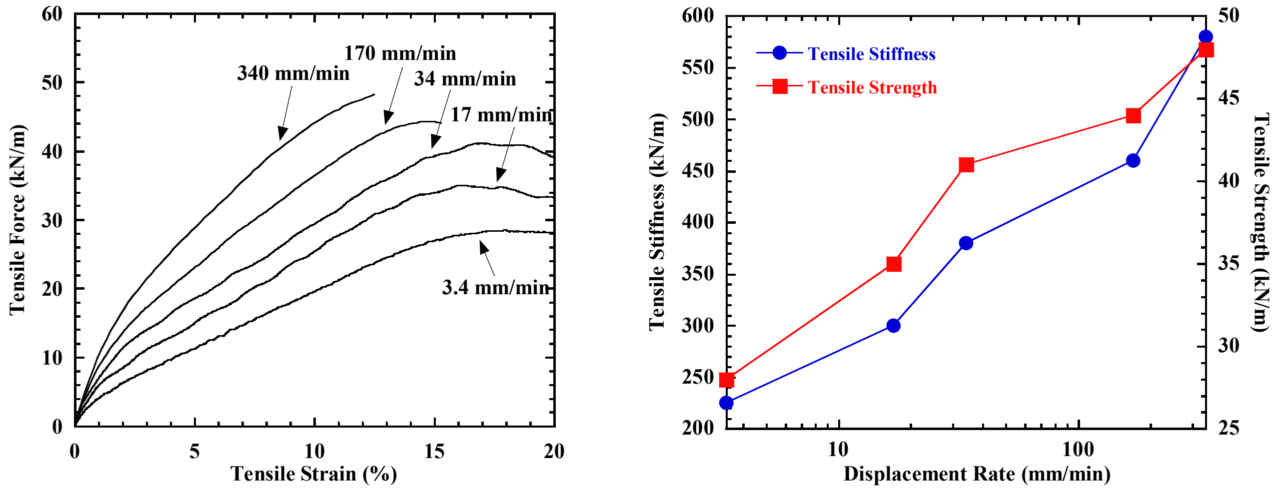
While most previous studies focused on the in-isolation tensile response of geosynthetics, the in-isolation condition does not reproduce field conditions where the geosynthetics are confined within backfill soil. Soil-geosynthetic interaction mechanisms may lead to significant differences in the behavior of geosynthetics from in-isolation conditions. Research on the tensile behavior of geosynthetics with soil confinement is limited (McGown et al. 1982; Farrag et al. 1993; Boyle et al. 1996; Sawicki and Swidzinski 1999; Franca et al. 2016; Balakrishnan and Viswanadham 2017). Farrag et al. (1993) performed a series of pullout tests on HDPE geogrids and found that the pullout resistance increases with increasing density and confining stress. Boyle et al. (1996) conducted in-isolation and in-soil tensile tests on several woven and nonwoven geotextiles and found that nonwoven geotextiles are affected by soil confinement, while woven geotextiles are affected by loading rate but not soil confinement. Balakrishnan and Viswanadham (2017) conducted a series of in-soil tensile tests on geogrids to investigate the effects of normal stress and soil type. Results indicate that the tensile stiffness increases with increasing normal stress, and the geogrid embedded in granular soil exhibited higher tensile stiffness than in marginal soil. In order to investigate the effect of loading rate on HDPE geogrids, this paper presents an experimental study on pullout behavior with soil confinement under different displacement rates.

2. TEST PROGRAM

2.1 Materials

A clean angular sand was used in the pullout tests reported in this study. The sand has a coefficient of uniformity of 6.1 and a coefficient of curvature of 1.0 and is classified as well graded sand (SW) according to the Unified Soil Classification System (USCS). The specific gravity for this sand is 2.61 and the fines content (passing No. 200 sieve) is 2.5% (Zheng et al. 2019). Triaxial test results on dry sand specimens at a relative density of 70% indicate a peak friction angle of 51.3°. This sand satisfies the AASHTO and FHWA backfill material requirements for GRS walls and abutments (AASHTO 2012; Adams et al. 2011).

A uniaxial high-density polyethylene (HDPE) geogrid manufactured by Tensar International Corp. (LH800) was used in this study. In-isolation tensile tests was conducted according to ASTM D6637 on a single-rib specimen with a length of 340 mm at a displacement rate of 34 mm/min (strain rate of 10%/min). The results from this test indicate that the geogrid has a secant stiffness of 380 kN/m at 5% tensile strain and an ultimate strength of 38 kN/m in the machine direction. Additional tensile tests were conducted on single-rib geogrid specimens at displacement rates of 3.4, 17, 170, 340 mm/min. Results of these tests are presented in Figure 1 and indicate that the tensile behavior of HDPE geogrid is significantly affected by loading rate for in-isolation condition. Tensile stiffness and strength increase with increasing displacement rate, which is consistent with observations from previous research (Boyle et al 1996; Sawicki and Kazimierowicz-Frankowska 2002).



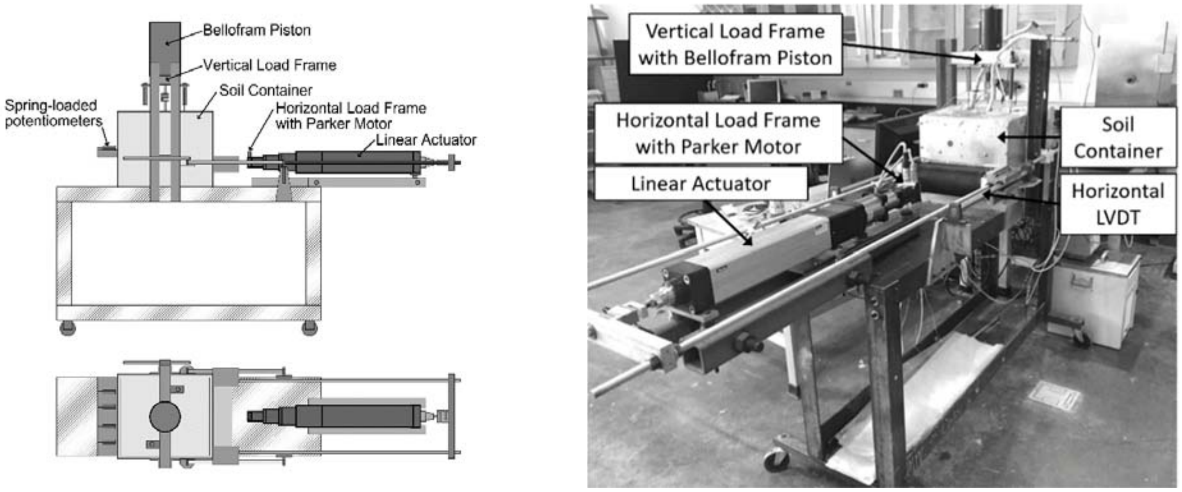
a) Tensile force-strain behavior

b) Rate effects on tensile stiffness and strength

Figure 1. In-isolated tensile tests for single-rib HDPE geogrid under different strain rates.

2.2 Test Setup

In this study, a pullout device is developed to investigate rate effect of geogrid for in-soil condition. Schematic view of the pullout box is shown in Figure 2(a), and a picture is shown in Figure 2(b). The pullout load is applied to the geogrid using an actuator through a horizontal load frame. A roller grip on a sliding frame is used to grip the geogrid and to apply uniform horizontal pullout loads. A Bellofram pneumatic piston is used to apply vertical loads. The Bellofram piston permits vertical stresses to be applied in load-control conditions through the aluminum loading plate. A linear variable differential transformer (LVDT) is used to measure the horizontal displacements of the grip.



a) Schematic view

b) Picture

Figure 2. Pullout device.

2.3 Test Procedures

The sand was compacted in seven lifts in the pullout box using dynamic compaction with an impact hammer to the target relative density. Three 50 mm-thick lifts were first compacted in the lower part of the soil container. The geogrid was carefully leveled on the soil surface and wrapped around the roller grip. A thin lift with a thickness of 12.5 mm was then compacted on the geogrid to ensure good contact between the soil particles and geogrid ribs. Three 50 mm-thick soil lifts were then compacted in the upper part of the soil container. After compaction, the top surface was carefully leveled so that the top plate would apply as uniform of vertical stress to the soil layer as possible. Considering the loading capability of the actuator, displacement rates of 0.1, 1, 5 mm/min were used to apply the pullout load. These displacement rates are much lower than those from the in-isolation tests (Figure 1a) because the reinforcement reaches the peak strength at much lower levels of strain in the pullout tests than in the in-isolation tests (Farrag et al. 1993). Additional tests were conducted for different relative densities and vertical stresses to evaluate the effects of these factors.

3. TEST RESULTS

The first set of pullout tests were conducted to evaluate the effect of displacement rate under low confining stress conditions. The soil specimens were compacted at a target relative density of 70%, and then geogrid pullout was performed at displacement rates of 0.1, 1, 5 mm/min. In this case, the vertical stress on the geogrid is only that associated with the overlying soil and top cap (approximately 3 kPa). The pullout force per unit width as a function of the horizontal pullout displacement for these tests is shown in Figure 3. All three curves are almost identical, with pullout forces increasing to 2.4 kN/m at a horizontal displacement of approximately 15 mm, and then remain nearly constant. The curve under a displacement rate of 0.1 mm/min shows a slightly milder slope in the early stage than those under the rates of 1 and 5 mm/min, but this difference may be to experimental variability. In general, displacement rate shows a negligible effect on the pullout behavior for the condition investigated, contrary to the strong rate effect observed in Figure 1 for tensile testing of geogrids in in-isolation condition. This is consistent with the experimental results reported by Farrag et al. (1993) that the displacement rate effect is minor when smaller than 6 mm/min. This observation may be due to the likelihood that the geogrids did not extend significantly during pullout under this low level of confinement for the displacement rates investigated and failed only due to frictional slip at the soil-geosynthetic interface. This frictional behavior appears not to be rate-dependent.

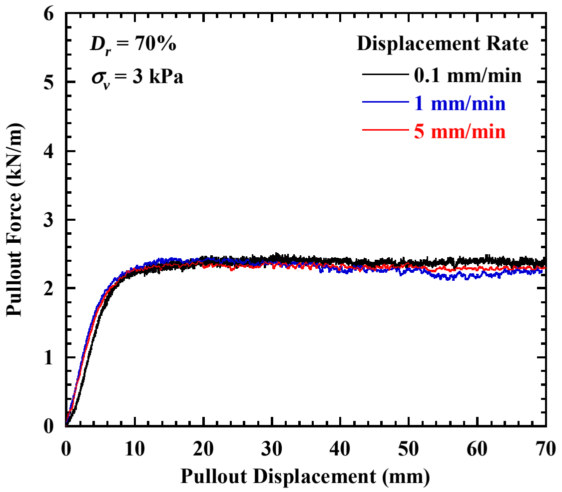
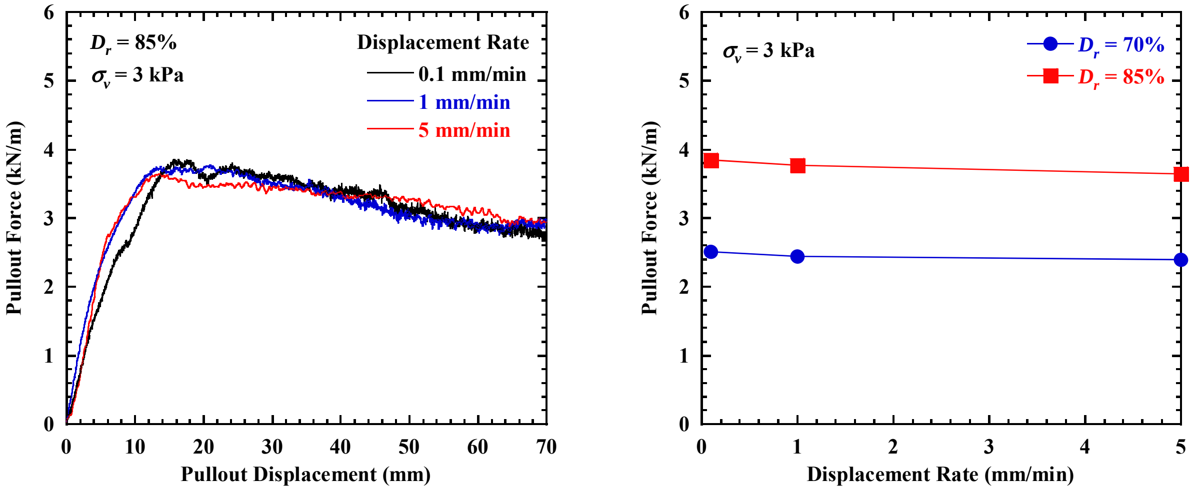


Figure 3. Pullout tests under different displacement rates.

Pullout tests were also conducted on geogrids in soil specimens compacted at an initial relative density of 85% under a vertical stress of 3 kPa. Results shown in Figure 4(a) indicate that the three curves show similar response with pullout force increasing to a peak value of 3.8 kN/m at a horizontal displacement of approximately 15 mm. Different from the results in Figure 3, a strain softening behavior was observed with increasing displacement. A comparison of the pullout capacity of geogrids in soils with relative densities of 70% and 85% under different displacement rates is presented in Figure 4(b). Results show an essentially flat line for the two relative densities and confirm that the pullout capacity is not affected by displacement rate for the conditions investigated.

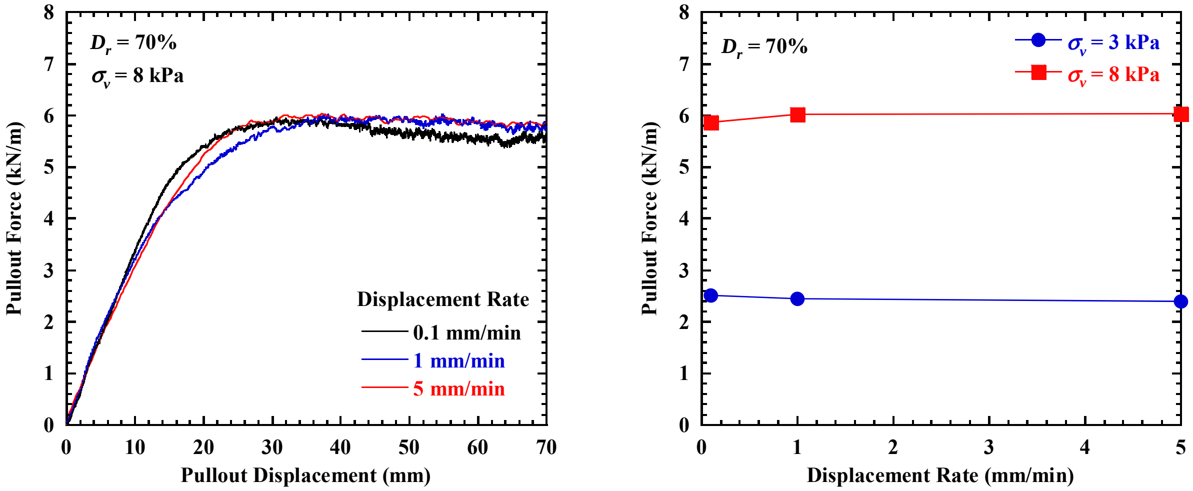


a) Results for relative density of 85%

b) Results for different relative densities

Figure 4. Rate effects on the pullout response for different relative densities.

Pullout tests were also performed on geogrids in sand layers under a higher applied vertical stress of 8 kPa for different displacement rates. Results in Figure 5(a) and indicate three essentially identical curves, especially for horizontal displacement smaller than 10 mm. This is attributed to the stronger soil confinement due to greater vertical stress, which restricts the relative movement between the soil particles and geogrid ribs. Therefore, the rate effect would be expected to be smaller for larger vertical stress. Similar to the pullout results for geogrids in sand with different relative densities in Figure 4(b), the pullout force for different displacement rates under two vertical stresses in Figure 5(b) indicates a negligible rate effect for the conditions considered.

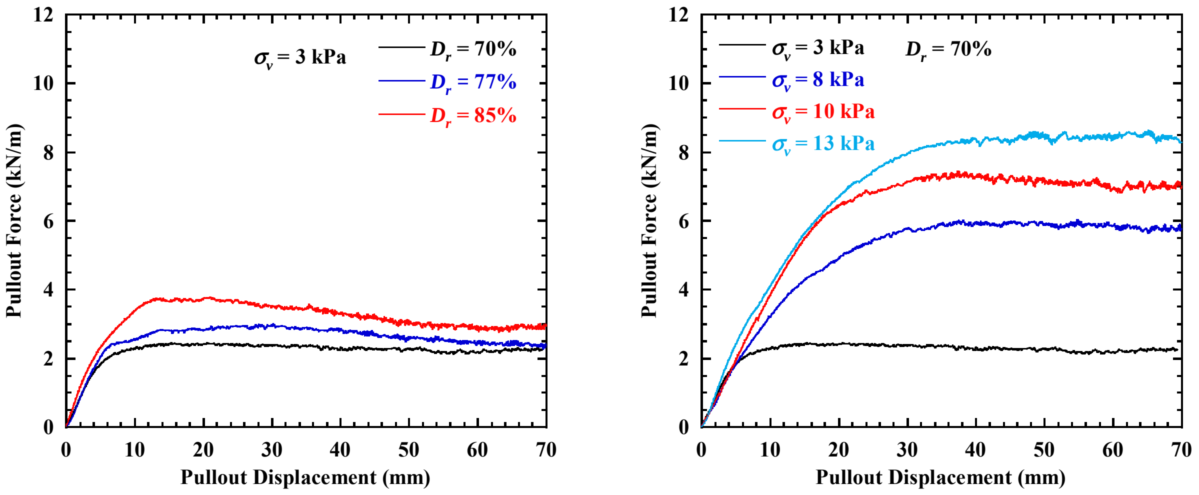


a) Results for vertical stress of 5 kPa

b) Results for different vertical stresses

Figure 5. Rate effects on the pullout response for different vertical stresses.

Additional pullout tests were conducted for more initial relative densities and vertical stresses under a displacement rate of 1 mm/min to evaluate the effects of relative density and vertical stress on the pullout response. Results presented in Figure 6 show that the pullout capacity increases with increasing relative density and vertical stress, as expected. Both factors tend to restrict the relative movement between the soil particles and geogrid ribs. In addition, vertical stress shows a stronger effect on the pullout behavior compared to the relative density.



a) Effect of relative density b) Effect of vertical stress

Figure 6. Effects of relative density and vertical stresses on the pullout response.

4. CONCLUSIONS

This paper presents an experimental study to investigate the effect of loading rate on the pullout behavior of an HDPE geogrid confined in compacted dry sand, along with a comparison with in-isolation tensile tests on single-rib geogrid specimens under different loading rates. Although the in-isolation tensile behavior of HDPE geogrid was found to be significantly affected by loading rate, the pullout behavior when confined within soil showed negligible rate effects for the different initial relative densities and vertical stresses considered. It is possible that negligible extension of the geogrids occurred during pullout, and that the soil-geosynthetic interaction mechanisms are not dependent on the displacement rate. This implies that rate effects may only need to be considered in the simulation of GRS retaining structures under earthquake loading when tensile strains are mobilized in the geogrid.

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