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Shear behaviour of a geogrid-reinforced coarse-grained soil based on large-scale triaxial tests

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ABSTRACT

In China, weathered mudstone geogrid-reinforced coarse-grained soil is used extensively for road embankments. However, the microstructure and disintegration process of weathered mudstone remain unclear. Furthermore, few studies have investigated the shear behaviour of this kind of geogrid-reinforced fill through large-scale triaxial tests against grain size effects. To bridge this gap, this study reports results from large scale consolidated undrained (CU) and consolidated drained (CD) triaxial tests as well as scanning electron microscopy (SEM), energy-dispersive X-ray (EDX), and disintegration tests on weathered mudstone geogrid-reinforced coarse-grained soil. EDX spectrograms and SEM images show that coarse grains disintegrate rapidly mainly owing to the high clay mineral content and loose microstructure. Therefore, a suitable disintegration time ($\sim$15 days) is recommended for embankment sits. The shear behaviour of this geogrid-reinforced fill is investigated in detail through large-scale triaxial tests. The shear deformation tends toward strain hardening behaviour with an increase in the number of geogrid layers and the confining pressure. Geogrids significantly improve the apparent cohesive strength of coarse-grained soil. The pore water pressure is found to develop rapidly in the 0%–4% axial strain phase but dissipate slowly in the 4%–12% axial strain phase. During shear, the pore pressure coefficient *A* values of 0.2–0.4 are indicative of the partial saturation of specimens. Consequently, pore water pressure development is mainly attributed to the movement and rearrangement of coarse particles in coarse-grained soil. Experimental data show that the geogrid-reinforcement coefficients increase with the number of geogrid layers, and a 20-cm separation between geogrid layers is recommended for embankment construction sites. The number of geogrid layers influences the geogrid–soil interface's mobilization and the slip surface type. Test results revealed three types of slip surfaces related to the failure shapes of specimens. Then, based on CU experimental data, the parameters of the Duncan–Chang constitutive model are discussed.

1. Introduction

Mudstone, which is widely distributed in the southern part of China, is an extremely fine-grained sedimentary rock consisting of a mixture of clay and silt-sized particles, generally a mixture of clay minerals with any or all of quartz, feldspar, and mica. Mudstone can be subdivided into siltstone and claystone, in which more than 50% of the composition is silt- and clay-sized particles, and both of which have similar mechanical properties. Mudstone is a soft rock, commonly with uniaxial compressive strengths less than 15 MPa and density less than 2.65 g/cm^3. Therefore, it is generally too soft for construction or similar purposes. However, when naturally weathered, it breaks into blocky flakes and eventually into residual coarse-grained soil, which is often used as a fill for constructing embankments in mountainous areas in China.

In recent years, geosynthetics, especially geogrids and geotextiles, have been increasingly used to reinforce embankments. A geogrid-reinforced embankment, by preventing lateral deformation and distributing traffic loading over a larger subgrade area, can often carry higher traffic loading (U.S. Army Corps of Engineers, 2003). Therefore, when weathered mudstone coarse-grained soil are used in highway embankments subjected to traffic loading, they are usually reinforced with geogrids in top layer. In this study, the shear behaviour and influences of geogrid reinforcement on clayey mudstone coarse-grained soil are investigated in detail through large-scale triaxial test results.

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Many studies have investigated granular soil (or granular mixture) reinforcement mechanisms through laboratory and field tests. Giroud and Noiray (1981) used geogrids and woven geotextiles as reinforcements for increasing resistance to traffic load. They, along with many other studies (Berg et al., 2000; Hufenus et al., 2006; Subaida et al., 2009), concluded that geogrids mainly provide reinforcement through lateral restraint, improved bearing capacity, and the tensioned membrane effect. Giroud and Han (2004a, b) presented a design method for geogrid-reinforced unpaved roads in which the influences of the bearing capacity factor (Nc) and interlock among the geogrids were considered. Mekkawy et al. (2011) investigated the shoulder rutting performance of geogrid-reinforced granular shoulders on soft subgrade by performing laboratory and full-scale tests. They presented a design chart correlating the rut depth with the number of load cycles to subgrade CBR. This chart was used to optimize granular shoulder design parameters and better predict granular shoulder performance. Palmeira (2009) analysed the results of large-scale cyclic and monotonic loading tests of unreinforced and geosynthetic-reinforced unpaved roads. They found that the presence of a reinforcement layer significantly reduced the magnitudes of vertical stress increments transferred to and vertical strain in the subgrade. Their experimental investigations showed that geogrids were more efficient than geotextiles in restraining lateral movement of the fill material. Perkins and Ismeik (1997a, b) also noted the beneficial effects of geosynthetics on reinforced pavements and unpaved roads. Anderson and Killeavy (1989) and Cancelli et al. (1992) noted that the use of geosynthetic reinforcements could reduce pavement thickness by 20%–50%. Knapton and Austin (1996) achieved rut depth reductions of up to 50% by using geosynthetic reinforcements, especially geogrids. Raymond and Ismail (2003) noted that the reinforcement layer position influences a road's performance. Yang et al. (2012) conducted accelerated pavement tests on unpaved road sections with geocell-reinforced sand bases and demonstrated that the NPA geocell significantly improved the stability of unpaved roads with sand bases and reduced permanent deformation. Gourc et al. (1986) proposed a displacement evaluation method based on the effect of reinforcement extensibility on the mobilization of interface mechanisms of fabric-retaining walls. Skinner and Rowe (2005) studied the stability of geosynthetic-reinforced retaining walls by analysing a geosynthetic-reinforced soil wall supporting a bridge abutment and approach road constructed on clayey soil deposit. Ehrlich et al. (2012) presented a physical model study of the influence of compaction on the behaviour of geogrid-reinforced soil walls. Their results showed that the position of maximum tensile force mobilized in the reinforcements was nearer to the face in the wall with heavy compaction. Weggel and Ward (2012) presented the equations for a numerical model that describes the accumulation of filter cake on a geotextile as flow passes through and solved them numerically using an Euler finite difference scheme and an Excel spreadsheet. Sitharam and Hegde (2013) discussed the geotechnical problems at a site, the design of a geocell foundation based on experimental investigation, and the construction sequences of geocell foundations in the field. Yang et al. (2014) focused on soil-rock mixtures as the backfills of geogrid-reinforced soil retaining walls with due concern for their long-term performance and safety. Wang et al. (2014) conducted a numerical compound tensile test (in sand) with one geogrid tensile member by PFC2D to investigate the load transfer behaviour between the geogrid and sand. Moraci and Recalcati (2006) used a large-scale pullout test setup to study the factors influencing the behaviours of geogrid reinforcements embedded in granular soil and evaluated the peak and residual pullout resistance values. Fannin et al. (2005) and Chakraborty and Salgado (2010) studied the dilative behaviour of granular soil.

The shear behaviour at the geotextile–granular soil interface influences the stability of a geotextile-reinforced embankment. Many studies conducted direct shear tests on various geotextile interfaces to study their shear stress–shear displacement relationships (Gilbert et al., 1996; Triplett and Fox, 2001; Zornberg et al., 2005; Bergado et al., 2006; Nye and Fox, 2007; Sharma et al., 2007; Suksiripattanaponga et al., 2013). Tran and Meguid (2013) developed a coupled finite-discrete framework to investigate the behaviour of a biaxial geogrid sheet embedded in granular material and subjected to pullout loading. Esmaili et al. (2014) presented the descriptions and results of multi-scale pullout and interface shear tests on a woven polypropylene geotextile reinforcement material in a marginal quality soil. Khoury et al. (2011) presented the results of a laboratory study on the mechanical behaviour of unsaturated soil–geotextile interfaces using a specially modified direct shear apparatus. Belén et al. (2011) studied the frictional behaviours of geosynthetics used in municipal solid-waste landfills and developed an analytical model to describe the shear behaviour and simulate progressive geomembrane–geotextile interface failure from direct shear tests. Sayeed (2014) used large-size direct shear tests to determine the interfacial shear characteristics of sand–geotextile under three different normal stresses. They investigated the surface morphology of sand particles based on SEM images and quantitatively analysed it using the Wadell roundness and degree of angularity methods. Pitanga et al. (2009) investigated geogrid-reinforced granular soil and found very low dilatancy values between 1/300 and 1/50 of the maximum shear displacement in addition to a nonlinear failure envelope in the normal stress ranges. Stark et al. (1996) and Hebeler et al. (2005) studied the geogrid interface interaction mechanisms based on shear tests and found that interbedding and hook control the interface shear strength. Gilbert et al. (1996) and Sharma et al. (2007), among others, developed interface interaction models to fit experimental data. Indraratna et al. (2006, 2007), among others, demonstrated the effectiveness of geogrid reinforcements on restricting ballast deformation through field tests and simple laboratory tests. Coleman (1990) and Shukla and Yin (2006) evaluated the effects of interlocking between railway ballast and geogrid apertures on shearing resistance. Indraratna et al. (2011) described how the ballast–geogrid interface copes with fouling by coal fines. They investigated the stress–displacement behaviours of fresh, fouled, and geogrid-reinforced ballast by performing a series of large-scale shear tests. Dombrow et al. (2009) conducted a series of large-scale shear tests with fresh ballast and ballast fouled by coal to varying degrees. They found that the shear strength decreased steadily as the fouling percentage increased. Tutumluer et al. (2012) studied the shear behaviour of ballast under monotonic and cyclic loading. Chen and McDowell (2012) used the discrete element method to simulate the cyclic loading of geogrid-reinforced ballast under confined and unconfined conditions. Leshchinsky and Ling (2013), based on prior large-scale laboratory tests of ballast embankments with geocell confinement and relevant numerical modelling, validated an acceptable material model for a parametric study using finite element analysis to investigate the effects of geocell confinement on ballasted embankments when encountering a soft subgrade, weaker ballast, or varying reinforcement stiffnesses. Indraratna et al. (2013) described a novel large-scale process simulation test (PST) apparatus that can capture the lateral strain variation upon loading. They conducted laboratory tests to explore the deformation and degradation response of both unreinforced and reinforced ballast under high-frequency cyclic loading.

For coarse-grained soils, Pitman et al. (1994) focused on the effect of the coarse grain content on soil porosity. Lade et al. (1998) investigated the effect of the coarse grain content on the