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Technical note

Microgrid inclusions to increase the strength and stiffness of sand

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ABSTRACT

Presented within this paper are the results and analysis of a series of triaxial compression tests evaluating the mechanical properties of poorly-graded sand mixed with randomly-oriented, small grid inclusions ("microgrids"), of various concentrations and aspect ratios. Addition of the relatively stiff microgrids, coupled with frictional interaction and interlocking of the sand grains within grid apertures enabled improved strength and stiffness of the reinforced composites at low confining pressures. Microgrid reinforcement mixture increased soil internal angle of friction from 5 to 10°, as well as the secant modulus by up to 50%. Aspect ratio and grid concentration exhibited effects on mechanical behavior, presenting the most benefit for large aspect ratios and concentrations of 0.5% by weight. Concentration must be optimized since larger grid concentrations may exhibit interference with one another, realizing less granular interlock and interface friction. Interlock of the microgrids and soil grains employs frictional mechanisms similar to geogrids where large interface friction may be mobilized when grid transverse member thickness and/or aperture are of comparable size to the mean grain size of the surrounding soil. However, unlike geogrids, soil composite behavior is better realized when inclusions are mixed homogenously with random orientations throughout a soil.

1. Introduction

For thousands of years, human beings have engineered soil structures to serve various functions required for the sustained improvement of infrastructure and management of natural hazards. Like all aspects of civil engineering, earthen structures have undergone significant technological advances that have allowed for design that is more efficient, cost-effective and safe. Most notably, the development of an assortment of ground improvement techniques using man-made additives has been important in allowing for the soil performance. Relevant to this work was the introduction of discrete polymeric and metallic reinforcing elements in the past 35 years (McGown et al., 1978; Gray and Ohashi, 1983; Gray and Al-Rafeai 1986; Gray and Maher, 1989; Andersland and Khattak, 1979). These reinforcements have been used to improve earthen structure performance by adding tensile strength to soil, a material that generally has limited strength in tension (Bonaparte et al., 1987; see Fig. 1). Previous studies of soil reinforcement using discrete fibrous reinforcements have demonstrated increases in strength, stiffness and ductility in sands (McGown et al., 1978; Gray and Ohashi, 1983; Gray and Al-Refeai, 1986; Gray and Maher, 1989) and in clays (Andersland and Khattak, 1979; Maher and Ho, 1994; Freilich et al., 2010). Study of the reinforcing characteristics of this soil-fiber composite has resulted in framework for improved slope stability applications (Zornberg, 2002), enhanced fill material for earthen structures (Zornberg, 2002), improved performance of soils during dynamic loading (Maher and Woods, 1990), reduced occurrence of soil cracks (Ziegler et al., 1997), improved bearing capacity (Michalowski, 2008), increased compressive strength (Ranjan et al., 1994; Miki et al., 1994), improved resistance to erosion (Mapa, 1995) and altered hydraulic properties.

One approach for quantifying the improvement in mechanical properties due to the addition of fibrous admixtures or inclusions into a soil is evaluation of stress–strain response with controlled laboratory experimentation. Prior work to demonstrate improved mechanical performance of soil due to inclusion of fibers has included laboratory testing such as direct shear tests or triaxial compression tests (Gray and Ohashi, 1983; Ranjan et al., 1994; Michalowski and Čermák, 2003). Even at relatively low confining pressures, substantial improvements in the shear strength of granular materials can be realized from fiber admixtures (Ranjan et al., 1994).

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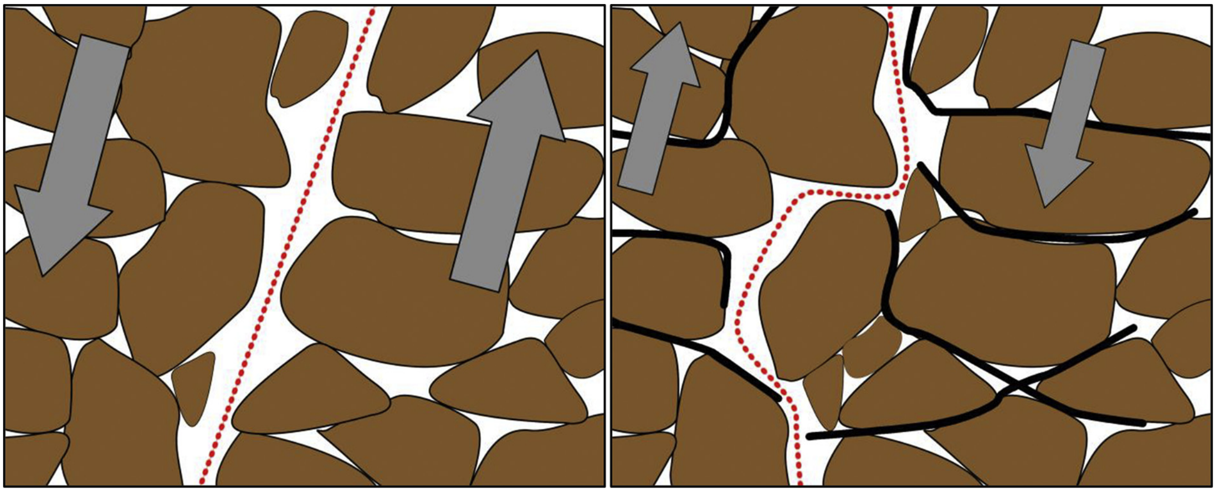

Fig. 1. Shear failure for no fiber reinforcement (left) and fiber reinforcement (right). Note increased shear strength from indirect failure surface (red dashed line) due to fiber inclusions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The magnitude of shear strength increase has been shown to be a function of the size and quantity of fibers (Maher and Ho, 1994; Freilich et al., 2010; Michalowski and Čermák, 2003; Consoli et al., 2009; Dos Santos et al., 2010) and the placement of quantities of fibers in evenly spaced layers (Gray and Al-Refeai, 1986). The comparison of total weight or volume of different types of fibers has generally been up to approximately 5% (Maher and Ho, 1994; Ranjan et al., 1996), but some studies have indicated reduced efficiency or even detrimental effects when fiber content exceeds 2% of dry weight of the soil (Santoni et al., 2001). The impact of fiber length on the strength of the composite has also been studied. Experiments by Maher and Ho (1994) show that increasing the length of polypropylene fibers mixed in a clay soil from 2.5 to 20 mm increases ductility but decreases tensile strength.

There has been significant research performed involving application of discrete fiber reinforcements to soils for increased composite behavior, but there is little work involving the unique benefits of grid-shaped inclusions at the granular scale despite their promise in other applications. At the large scale, prior experimental work has demonstrated that use of geogrid reinforcements can increase soil mechanical behavior by means of granular interlock and surface friction. Geogrids have demonstrated significant improvement for reinforcement of slopes (Yoo, 2001; El Sawwaf, 2007), walls (Bathurst et al., 2000; Tatsuoka et al., 1997), roads (Giroud and Han, 2004), and foundations (Han and Atkins, 2002, Khing et al., 1993), but function only as a planar reinforcement and do not apply the composite behavior produced by randomly oriented fibers mixed with soil. Morel and Gourc (1997) used large-aperture (10 mm × 10 mm) grids that were randomly-oriented to reinforce sandy soils, finding that addition of the mixed grid significantly improved shear strength. On the granular scale, the addition of "mesh" inclusions, typically comprised of extruded patches of small textiles, were demonstrated to increase the strength of poorly-graded sands in a series of triaxial compression tests under a variety of confining pressures (Al-Refeai, 1991). However, there are no existing studies evaluating the reinforcing behavior of small grids (i.e. aperture less than 2.5 mm), or "microgrids", on the mechanical performance of soils having a mean grain size comparable to the grid aperture.

As with other grid reinforcements, potential benefits in soil frictional strength and stiffness resulting from microgrid mixing present a potential means of ground improvement for applications that employ low confining pressures, like remediation of slopes that have failed surficially, backfill of retaining structures, and roadway subgrade stabilization. A series of triaxial tests was performed to evaluate the mechanical properties of soil–microgrid composites under low confining pressures.

2. Materials and methods

2.1. Triaxial testing

A series of 99 consolidated-drained (CD) triaxial tests were performed to evaluate the mechanical behavior of microgrid-reinforced sands under low confining pressures. Each triaxial specimen was confined by vacuum at confining pressures of 5, 10, and 15 kPa, each created anew and tested in three separate iterations, subsequently averaged when consistency was exhibited under each specific confinement. The confining pressures were constrained by the testing system capacity, but deemed appropriate for representative stresses for microgrid application as surficial ground improvement. Specimens were sheared to approximately 6–7% axial strain (ε_1), which was consistent with the deformation required to develop post-peak softening behavior in the unreinforced sand. The triaxial specimens had a diameter of 70 mm and a height of 180 mm. The dry sand was tested under triaxial compression with or without microgrid reinforcement.

Testing was performed on specimens with fibers oriented randomly in space and distributed uniformly. Dry sand or a dry sand-grid mixture were air pluviated in 36-mm lifts and mechanically compacted to air-dry densities of approximately 1614, 1597 and 1565 kg/m^3 for microgrid concentrations of 0.25%, 0.5% and 1%, respectively (relative density of 100%). Throughout each lift, care was taken to ensure that distribution of microgrids was even and compaction did not create weak, unconnected seams between lifts from exposed microgrids or cause granular convection of inclusions to the surface. Although relative densities of 100% may be impractical for field implementation (unless vibratory compaction techniques or small compaction lifts are implemented), the density of the sand-grid composite was deemed suitable for facilitating consistent specimen conditions for comparison and analysis. Specimen preparation included air pluviation of the sand or sand-grid mixtures through a funnel with an exit diameter of 60 mm placed directly upon a mesh with an aperture size of 12.8 mm. The dry pluviation technique in combination with the use of a 12.8 mm sieve at the specimen entrance was deemed to provide a random