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Dynamic behavior of reinforced clayey sand under cyclic loading

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ABSTRACT

Experimental investigations and modeling of linear elasticity of fiber-reinforced clayey sand under cyclic loading unloading are conducted in this paper. Experimental studies are focused on four aspects. First, a series of cyclic triaxial tests, with different confining pressures and deviator stress ratios up to 150 cycles, are performed. Impacts of fiber content, cell pressure, deviator stress ratio and loading unloading repetition that affect dynamic behavior of the composite material are discussed. It is shown that shear modulus decreases with increasing deviator stress ratio at high confining pressure and the rate of loss of shear modulus found to be much lower for fiber reinforced specimens. Other results show that increase of shear modulus with loading repetition is more pronounced at higher deviator stress ratios. Second, the optimum fiber content is experimented under cyclic loading unloading and is expressed as a power function of deviatoric stress ratio. It is shown that optimum fiber content is not constant and it is affected by deviator stress ratio. Third, a function is introduced to describe the linear stress–strain curve under cyclic loading unloading using equivalent linear analysis. The shear modulus *G* is expressed as a function of fiber content, confining pressure, deviatoric stress ratio and loading repetition. Finally constitutive coefficients of the model parameters are calibrated by the results of cyclic triaxial shear tests and using the linear regression.

1. Introduction

In recent years, many geosynthetic materials have been used as engineering materials and widely applied in geotechnical earthquake engineering. Fiber is one of many types of synthetic materials being used to improve engineering properties of soils by providing extra resistance of shear and tensile stress. Soil reinforced with geo fiber can be considered as a composite material and its mechanical behavior is comparatively new when compared to other research fields.

It is well known the roots of surface vegetation improve the stability of slopes by increasing soil strength (Wu et al., 1988; Ekanayake and Phillips, 2002; Greenwood et al., 2004; Danjon et al., 2007; Sonnenberg et al., 2012; Hejazi et al., 2012; Bourrier et al., 2013; Pollen-Bankhead et al., 2013; Wu, 2013). Soil reinforcement using tension-resisting material is an attractive method of improving the compressive and tensile strength on soils (Rowe and Taechakumthorn, 2008; Li and Rowe, 2008; Plé and Lê, 2012; Li et al., 2014; Tiwari et al., 2014). Experimental studies indicate that the soil desiccation cracking behavior was significantly influenced by fiber inclusion (Nahlawi and Kodikara, 2006. Tang et al., 2012; Lakshmikanth et al., 2012; Divya et al., 2014). Monotonic loading in shear box tests, consolidated and drained triaxial compression tests have shown that shear strength is increased and post-peak strength loss is reduced when discrete fibers are mixed with the soil (Gray and Ohashi, 1983; Maher and Ho, 1994; Yetimoglu and Salbas, 2003; Ibraim and Fourmont, 2007; Ahmad et al., 2010; Lovisa et al., 2010; Falorca and Pinto, 2011).Unconfined compression tests indicate that fiber insertion in the soil causes an increase in unconfined compression strength and axial strain at failure, and changed the brittle behavior of the soil to a more ductile behavior (Consoli et al., 2010; Fatahi and Khabbaz, 2012; Estabragh et al., 2012; Olgun, 2013; Mirzababaei et al., 2013; Starcher and Liu, 2013). The influence of anisotropic distribution of fibers on the behavior of fiber reinforced soils has been experimentally investigated in tests with controlled orientations of fibers (Palmeira and Milligan, 1989; Michalowski and Cermak, 2002; Kanchi et al., 2014). Studies on liquefaction resistance of reinforced soils have shown that the fiber inclusions increase the number of cycles required to cause liquefaction during undrained loading (Noorany and Uzdavines, 1989; Maher and Woods, 1990; Krishnaswamy and Isaac, 1994; Ibraim et al., 2010; Maheshwari

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et al., 2013). Different models and methods that address the behavior of reinforced soils was performed by various investigators (Milligan et al., 1986; Chan et al., 1989; Li and Ding, 2002; Anastasiadis et al., 2011; Javadi et al., 2012; Yang and Han, 2013; Bourrier et al., 2013; Kanchi et al., 2014; Khan et al., 2014; Liu and Won, 2014; Amir-Faryar and Sherif Aggour, 2014). Cyclic loading in triaxial tests have shown that shear modulus of reinforced soil is significantly affected by multiple factors such as fiber content, confining pressure and loading repetition and as well as shear strain (Li and Ding, 2002). Experimental studies indicate that fibers were more effective on shear strength parameters at 70% relative density (Hamidi and Hooresfand, 2013). Cyclic triaxial tests have shown that for all confining pressures, with an increase in rubber percentage, shear modulus decreases while for any percentage of rubber inclusion; shear modulus increased as the confining pressure increased (Nakhei et al., 2012). Loading tests results that the cross polypropylene fibers can be considered as a good earth reinforcement material especially at fiber content of 0.5% (Abuel-Maaty, 2010). Unconfined compression tests and California Bearing Ratio (CBR) tests indicate that the optimum amount of fiber mixed in soil/lime/rice husk ash mixtures ranges from 0.4 to 0.8% of the dry mass (Muntohar et al., 2013). Recently, various investigations on prestressed reinforced soil by geosynthetics have been conducted by some researchers (Lackner et al., 2013; Shivashankar and Jayaraj, 2014). In addition, studies on Bearing capacity of footing on reinforced sand have also been reported (Nader and Hataf, 2014; Azzam and Nasr, 2014). Reinforcing soil with flexible discrete fibers does not represent a new technique in geotechnical engineering. In spite of the numerous applications, there are no dosage methodologies based on rational criteria for dynamic behavior fiber reinforced soils, especially; reinforced clayey sand. Also, no comprehensive study has been reported concerning the undrained cyclic behavior of fiber reinforced clayey sands. This approach probably results from the fact that soil (reinforced and unreinforced) shows a complex dynamic behavior that is affected by many factors, for example the physical chemical properties of the soil, fiber content, the amount of confining pressure, deviator stress ratio and loading repetition (Li and Ding, 2002).

This paper investigates the various aspects of fiber reinforcement through a number of cyclic triaxial tests. A large number of triaxial tests were carried out by varying the fiber content, confining pressure, deviator stress ratio and number of cycle loading unloading. Effects of these parameters on the secant shear modulus of the reinforced soil are studied. As well as, a function is introduced to describe the optimum fiber content under cyclic loading unloading. Finally, a deviatoric stress–strain relation is featured and introduced.

2. Experimental program and procedures

The experimental program was carried out in two parts. First, the geotechnical properties of the soil and fibers were characterized. Then a series of triaxial cyclic shear tests for both the fiber-reinforced and unreinforced specimens under different confining pressure and deviator stress ratio were carried out as discussed below.

2.1. Materials

The soil used in this study was sand and was obtained from the bed of the dried river in the region of Kermanshah, west of Iran. The sample was collected in a disturbed state, by manual excavation, in sufficient quantity to complete all the tests. The results of the characterization tests are shown in Table 1. This soil is classified as clayey sand (SC) according to the Unified Soil Classification System.

Monofilament polypropylene fibers were used throughout this investigation. The fibers were 12 mm in length and 0.023 mm in diameter, with a specific gravity of 0.91, tensile strength of 500 MPa, elastic modulus of 7.4 GPa and linear strain at failure of 80%.In this paper, the concentration of fibers included in a composite is defined as a proportion of dry weight of sand $\chi = W_f / W_s$, where W_f is the weight of fibers and W_s is the weight of the dry sand. The fiber content χ was 0, 0.5 and 1 percent by weight of the dry soil. For all the specimens presented in this study, the quantity of clayey sand, W_s, was kept unchanged when different proportions of fibers were added. Distilled water was used both for molding specimens for the triaxial tests and for the characterization tests.

2.2. Methods

2.2.1. Specimen preparation

For the triaxial tests, cylindrical specimens, 70 mm in diameter and 140 mm high, were used. Samples prepared at moisture content of 10% (wet side of OMC) with wet unit weight 19.8 kN/m^3.The fiber-reinforced and unreinforced compacted soil specimens used in the tests were prepared by hand-mixing dry soil, water and polypropylene fibers (when appropriate). During the mixing process, it was found to be important to add the water prior to adding the fibers, to prevent floating of the fibers. The amount of fibers for each mixture was calculated based on the mass of dry soil. Visual and microscope examination of exhumed specimens showed the mixtures to be satisfactorily uniform. After mixing sufficient material for one specimen, the mixture was stored in a covered container to avoid moisture losses before subsequent compaction. Two small portions of the mixture were also taken for moisture content determination. The specimen was statically compacted in three layers inside a cylindrical split mold, which was lubricated, so that each layer reached the specified dry density. This fabrication method is commonly used in laboratory studies of fiber reinforced soils and it has the advantage of a good control of specimen density while preventing the segregation of fibers. The sample preparation method followed in this study led intensively to the construction of dense specimens. It eventually produces a soil-fiber fabric which resembles the compacted reinforced soils in the field. After the molding process, the specimen was immediately extracted from the split mold, and its weight, diameter and height were measured. The samples were then placed within plastic bags to avoid significant variations of moisture content before testing.

2.2.2. Dynamic shear tests and stress shear strain curves

The cyclic triaxial shear test is a reliable method for study dynamic behavior of soils and could be used to determine important

Table 1
Physical properties of the soil sample.

Value	Properties
28%	Liquid limit
11.5%	Plastic limit
2.68	Specific gravity
86%	Sand
14%	Clay & silt
0.0043	D_{10} (mm)
0.4	D_{30} (mm)
1.5	D_{60} (mm)
8.5%	Optimum moisture content (standard Proctor compaction)
10.5%	Water content of samples
21.44 kN/m^3	Maximum dry unit weight (standard Proctor compaction)
19.8 kN/m^3	Wet unit weight of samples
100 kPa	Cohesive strength C_{uu} (at OMC with standard compaction)

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