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Energy efficiency of fibre reinforced soil formation at small element scale: Laboratory and numerical investigation

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ABSTRACT

This paper explores the aspects related to the energy consumption for the compaction of unreinforced and fibre reinforced samples fabricated in the laboratory. It is well known that, for a fixed soil density, the addition of fibres invariably results in an increased resistance to compaction. However, similar peak strength properties of a dense unreinforced sample can be obtained using looser granular soil matrices mixed with small quantities of fibres. Based on both experimental and discrete element modelling (DEM) procedures, this paper demonstrates that less compaction energy is required for building loose fibre reinforced sand samples than for denser unreinforced sand samples while both samples show similar peak strength properties. Beyond corroborating the macro-scale experimental observations, the result of the DEM analyses provides an insight into the local micro-scale mechanisms governing the fibre-grain interaction. These assessments focus on the evolution of the void ratio distribution, re-arrangement of soil particles, mobilisation of stresses in the fibres, and the evolution of the fibre orientation distribution during the stages of compaction.

1. Introduction

Laboratory characterisation of the behaviour of fibre reinforced sand requires fabrication of small scale samples for element testing. The sample fabrication invariably includes a succession of several stages like soil-fibre mixing, deposition and compaction. Application of the use of short flexible and discrete fibres for the construction of real scale geotechnical systems will equally include mixing, deposition and compaction, but the procedure will certainly be more challenging due to the large volumes of material involved.

Mixing sand and fibres for laboratory element testing purposes is not a complex process, nor does it require highly technical skills. The amount of sand is relatively small and so is the fibre content, normally up to 1% by mass of dry soil. Fibres are added progressively to the sand which is in a moist condition and all the mixture is manually blended with the help of a little spoon until by visual inspection the operator is satisfied that the composite presents a uniform appearance. The formation of fibre reinforced sand samples commonly used in laboratory studies follows the so called moist tamping fabrication technique (Ladd, 1978). Although subjected to some criticism (Vaid et al., 1999; Eliadorani and Vaid, 2003; Frost and Park, 2003), this fabrication method, in the case of fibre reinforced sands, has the main advantage of preventing the segregation of fibres, while eventually producing a soil-fibre fabric which may resemble that of man-made compacted reinforced soils in the field.

The question of whether this soil-reinforcement technique aimed at increasing the strength and stability of sandy soils is reasonably more cost-effective than other methods that are currently being used in practice (for example, densification of granular soils by compaction) has never been investigated. As an initial attempt to assess the cost-effectiveness of the fibre reinforcement technique, this paper seeks to provide a fundamental analysis and quantitative estimation of the energy required for the compaction phase of samples formed in laboratory. A numerical assessment of the sample formation process based on Discrete Element Modelling (DEM) is also conducted to provide insight into the interaction mechanisms at the fibre and grain scale.

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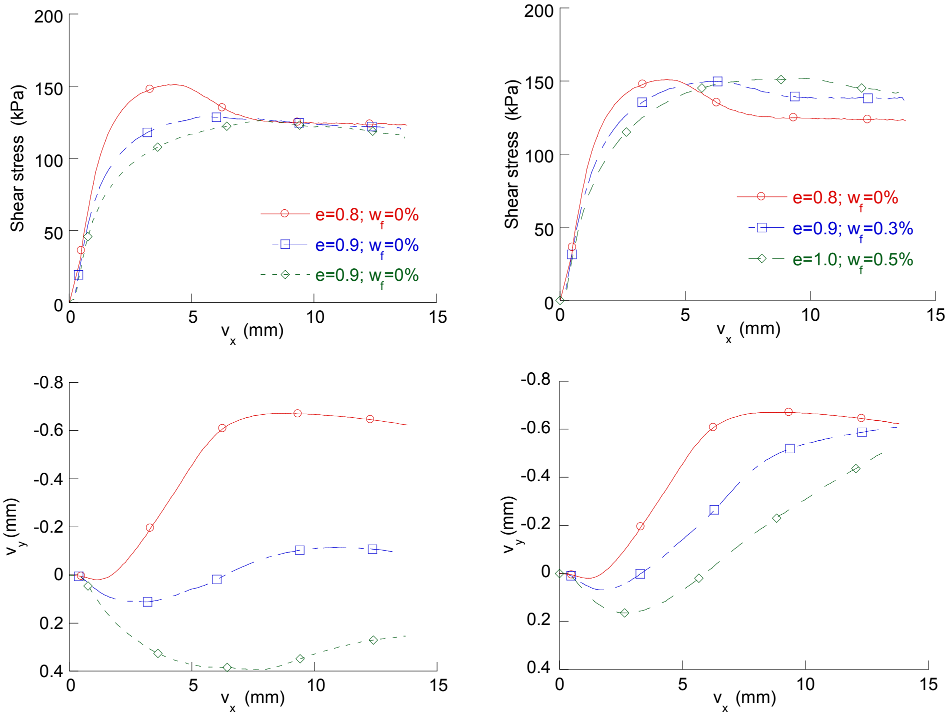

(a) (b)

Fig. 1. Direct shear test results: (a) unreinforced samples and (b) one unreinforced and two reinforced samples.

2. Motivation

Standard laboratory compaction tests on fibre-reinforced sands indicate that fibre reinforcement provides resistance to compaction causing, for a given compaction energy, a less dense packing compared with unreinforced sand (Hoare, 1979; Murray et al., 2000; Ibraim and Fourmont, 2007). The maximum dry density of the reinforced sand also decreases with increasing fibre content. Although these observations may question the ability of the fibre-reinforcement technique to provide a cost-effective alternative to soil densification if, for example, the matrix density of the reinforced soil is to be preserved, the design process of fibre-reinforced soils may consider alternative approaches, such as using less sand material (loose state) reinforced with fibres that would provide strength properties like that of an unreinforced dense sand. Therefore, the assessment of cost-effectiveness should focus on the comparison between the compaction energy required for the formation of dense unreinforced sand and the compaction energy for the formation of less dense fibre-reinforced soils, providing that the mechanical characteristics of the latter are better than or at least similar to the former.

Fig. 1a shows the direct shear test results of three unreinforced sand samples (Hostun RF sand, Flavigny et al., 1990) of three void ratios, e (ratio between volume of voids and volume of solids) of 0.83, 0.94, 1.01 sheared under a normal stress of 208.5 kPa (Ibraim and Fourmont, 2007). Fig. 1a presents the variation of both the shear stress and vertical displacement (v_y) with the horizontal displacement (v_x) and reveals typical responses for a medium-dense, loose and very loose sand material. Fig. 1b shows similar direct shear test responses, but this time the loose and very loose sand samples are reinforced with polypropylene fibres (Loksand™) 0.3% and 0.5% fibre contents (w_f) by mass of dry sand, respectively. While the volumetric responses of the samples presented in Fig. 1b reflect the differences in the sample densities, with higher dilation for the dense unreinforced sample, the particularity here is that all samples present a similar peak shear stress response, around 150 kPa. If the densification process of the unreinforced medium-dense sand sample requires compaction energy, how does this compaction energy compare with the energy required to construct the fibre reinforced samples? An experimental procedure was devised to assess the compaction energy for these unreinforced and fibre-reinforced sample types. Parallel DEM simulations of analogue systems were equally conducted.

3. Experimental set up

The moist tamping fabrication method consists of compacting a wet soil by applying a monotonic load to successive layers of pre-definite height in a rigid mould using a light tamper (Ladd, 1978). The area of the tamper represents a fraction of the total cross-sectional area of the sample and, therefore, the compaction of a layer involves sequential horizontal re-positioning of the tamper once the soil underneath is vertically compressed. The tamper is attached to a rod and the verticality of the rod is assured by a guiding linear bearing system rigidly attached to a horizontal plate. The plate could be either supported by the sample's mould or by any other external prop, which in our set up consists of a transparent plexi-cylinder as shown in Fig. 3a. The compaction process does not use any mechanical loading system other than that provided by the human force. While the density of the sample is initially fixed, its control is performed by choosing the right amount of dry soil required for each successive layer and by ensuring that the soil is fully compacted within the desired layer volume.

The assessment of the compaction energy employed for the formation of each layer and for the whole sample requires the measurement of both compaction forces applied in each tamping effort and the corresponding vertical travel of the tamper. While the former measurement is provided by a load cell located between the tamping rod and the tamper, which eliminates the effects of parasitic rod friction of the rod/guiding bearing system, the latter is measured using a Linear Variable Differential Transformers (LVDTs) sensor attached to the reference collar as shown in Fig. 2a. The maximum capacity of the load cell is 5 kN and the measurement range of the LVDT is ± 20 mm. A