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Fibres and soils: A route towards modelling of root-soil systems

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Abstract

The addition of flexible fibres to granular, cohesionless soils, has a marked influence on the stress:strain and volumetric response. Experimental observations provide inspiration for the development of continuum models for the mechanical, pre-failure behaviour of these fibre/soil mixtures. Such generic models and the deduced mechanisms of response should be applicable to other combinations of soils and flexible fibres such as plant roots. Two features are particularly important: the distribution of the orientations of fibres (no method of preparation produces an isotropic distribution) and the allowance for the volume of void space not only occupied, but also influenced, by the presence of the fibres.

A simple shear element is used as a quasi-one-dimensional demonstrator platform for the presentation of the continuum constitutive model. Such an element represents a familiar configuration in which phenomena, such as dilation and friction, can be directly observed. A basic constitutive model for sand is adapted to this simple shear element; the fibres are added as a separate component able to withstand tension but without flexural stiffness. As the soil-fibre mixture deforms, the straining of the soil generates stresses in favourably oriented fibres. The model is used to clarify some aspects of the response of the fibre-soil mixtures: the influence of fibres on the volumetric behaviour; the existence and nature of asymptotic states; and the stress–dilatancy relationship.

Keywords: Fibres; Cohesionless soils; Ground improvement; Constitutive model

1. Introduction

It has been known, qualitatively, for many centuries that the presence of vegetation has beneficial effects on the stability and deformations of slopes through the reinforcing effect of the roots on the soil through which they are growing (Wu et al., 1988; Reubens et al., 2007). Roots, subject to the vagaries of nature, present challenges for testing and modelling. The laboratory observations presented here relate to the behaviour of cohesionless soil (sand) mixed with flexible polypropylene fibres which will be somewhat similar to the behaviour of soils containing actual plant roots. We are concerned in the present study with only the mechanical and not the hydrological effects. However, provided a model is available to describe the behaviour of the soil (saturated or unsaturated), in the absence of fibres/roots, the effect of the fibres can then be added in a systematic way.

There have been several studies of the influence of flexible fibres on the strength of soils. Failure criteria have been developed using force equilibrium considerations in a localised shear band (Jewell and Wroth, 1987; Maher and Gray, 1990; Ranjan et al., 1996); energy-based homogenisation approaches (Michałowski and Čermák, 2002); or the discrete superposition of the sand and fibre effects (Zornberg, 2002). Quantitative

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modelling of the pre-failure behaviour of fibre-soil mixtures has received less attention, and proposed models have dealt with the elastic behaviour of the material (Ding and Hargrove, 2006) or have been applied to soils reinforced with continuous thread (Texsol) (Villard et al., 1990; di Prisco and Nova, 1993). The two-dimensional DEM (Distinct Element Method) has been used to investigate the micromechanical aspects of the interaction between grains and fibres and the distribution of the tensile stresses mobilised in the fibres (Ibraim et al., 2006; Ibraim and Maeda, 2007).

Our modelling environment takes the form of an infinitesimal simple shear element (like an element at the centre of a direct shear box) (Fig. 1). There are several reasons for taking this elemental approach (Muir Wood, 2009): the direct shear box is a particularly simple pedagogic device which shows students or other users exactly what is happening in terms of linked volumetric and shearing deformations; the simple shear element is directly applicable to the deformation and sliding of a long slope and also to the propagation of shear waves in an earthquake; and there have been a number of developments in constitutive modelling over the past few decades which have endeavoured to include the influences of fabric anisotropy and the history of loading or deformation by considering the overall response to be the summation of responses of a series of shear elements distributed over all possible orientations. The microstructural model of Calladine (1971) applies to soils a framework suggested by Batdorf and Budiansky (1949) for metals, and this approach has been rediscovered in multi-laminate modelling (Pande and Sharma, 1983) and in the models of Chang and Hicher (2005).

The modelling framework has been described by Diambra et al. (2013) and Muir Wood et al. (2014); it will be summarised briefly here and used to illustrate some aspects of the response of fibre-soil mixtures: the influence of fibres on the volumetric behaviour; the existence and nature of asymptotic states; and the stress-dilatancy relationship for the mixtures.

2. Experimental observations

Inspiration for the modelling has come from an extensive experimental study on the behaviour of mixtures of Hostun sand (d_{50}=0.38 mm, C_u=1.9) with short flexible polypropylene fibres (length 35 mm, diameter 0.1 mm) (Ibraim and Fourmont, 2007; Diambra et al., 2010). It is hypothesised that the behaviour of soil containing flexible plant roots will be broadly subject to the same characteristics of mechanical interaction. Fibres can be mixed with the soil in carefully monitored proportions: attention to detail of the sample preparation techniques encourages the formation of somewhat repeatable samples. On the other hand roots grow through the soil, feeling their way between the soil particles or the packets of particles, and developing bonding by a process of cavity expansion as the root expands within its chosen tortuous void space and develops restraining confinement stresses as it grows. The detailed fabric of soil root mixtures is expected to be more variable, whether in the laboratory or in the field, so the tests on polypropylene fibre mixtures are consequently more useful for the initial development of constitutive models.

Direct shear tests with constant vertical stress σ_z=55.3 kPa (Fig. 2) and with values of specific volume between 1.8 and 2.0 (corresponding to relative densities of approximately 60% and 0%) show increased shear stress and increased dilatancy as a result of the addition of flexible fibres (Ibraim and Fourmont, 2007). Fig. 2a, b, d, e show the variation in shear stress and vertical displacement or volume change (u_z) with horizontal displacement u_x. The rate of change in vertical displacement with horizontal displacement, equivalent to an angle of dilation $\tan\psi = -\delta u_z/\delta u_x$, is plotted against externally measured values of mobilised friction τ/σ_z in Fig. 2c, f. The effect of fibres on dilatancy is confirmed in undrained triaxial compression tests on loose fibre-sand mixtures which show reduced and even negative pore pressures; the presence of fibres produces a significant reduction in liquefaction potential (Ibraim et al., 2010a; Diambra et al., 2011).

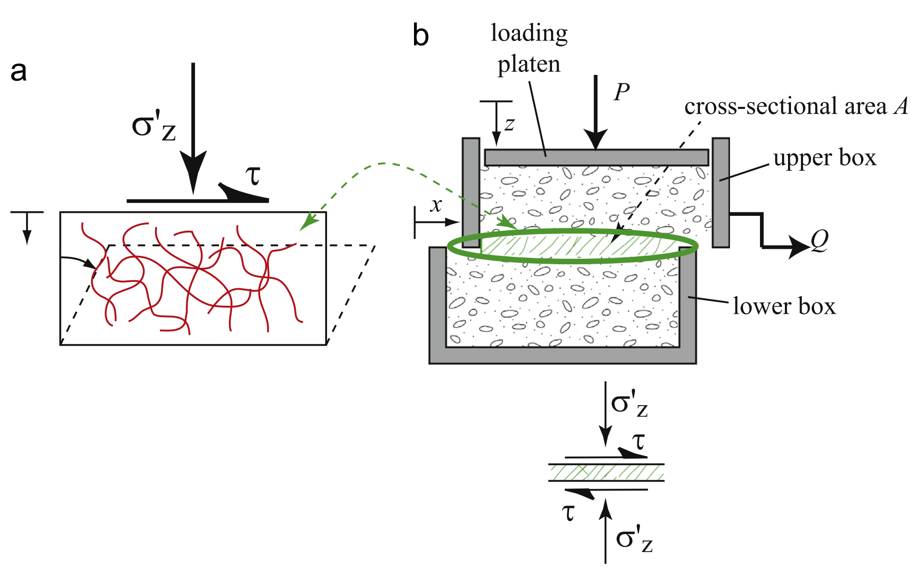

Fig. 1. (a) Simple shear element of soil with fibres; (b) corresponding to central region of shear box.