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Research paper

Tensile behaviour of unsaturated compacted clay soils — A direct assessment method

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ABSTRACT

This paper presents a new method for testing the behaviour of soils placed under tensile load and demonstrates its suitability for testing a number of soil types under various conditions including saturation, compaction and stabilisation. Validation of the results obtained for the soils at relatively low saturation has been conducted using the established Brazilian (indirect) test for measuring the tensile strength of brittle materials. A fair comparison has been found and the results highlight the limited applicability of the Brazilian method to soils at very low water contents at which the tensile failure criterion has been assumed using this methodology. Optical characterisation of the performance of both testing methods has also been conducted using Digital Image Correlation. The consistent, accurate measurement of directly induced tensile strains using the proposed new method has been confirmed, verifying its capability to apply a direct tensile stress in the absence of shearing, a problem commonly associated with other tensile testing methods. The developed technique has then been used to investigate the water content–tensile strength relationship for compacted, unsaturated soils and offers significant advantages in the characterisation of clay soils subjected to variable climatic loading.

1. Introduction

There is increasing effort being put into the ability to predict the future performance of earthworks and to target resources towards resilient, sustainable maintenance. This is particularly focused in the context of adaptations to our changing climate. The implications of climate on shrink–swelling behaviour are becoming central to the effective management of infrastructure slope assets. It was reported by Jones and Jefferson (2012) that damage due to shrink–swell has cost the UK economy £3 billion in the last 10 years, surpassing that of any geo-hazard. Increased understanding of the changes in performance of engineered fills is vitally important given the wide variety of earthworks assets e.g., embankments, dams, landfill liners and other earth structures. Progressive deterioration of legacy infrastructure leads to serviceability failure and/or serious instability issues. Spatial distribution analysis has indicated that unstable slopes alone with moderate to significant hazard potential constitute up to 10% of the area of Great Britain and that 7% of the transport network is located within this area (Dijkstra and Dixon, 2010).

Desiccation induces shrinkage that when constrained, due to non-uniform moisture gradients or the presence of any restraining internal soil texture/structure or frictional boundary effect will generate tensile stresses. When these stresses exceed the tensile strength of the material, cracking is initiated (Corte and Higashi, 1960; Groisman and Kaplan, 1994; Lu et al., 2007; Peron et al., 2009). Variability in soil–water content, which governs shrinkage, is primarily the result of seasonal fluctuation in precipitation/evaporation. In addition, soil–water content is affected by the transient demands of vegetation and the infiltration potential of the soil surface. All of these influences are governed by climate. Predicted climate change scenarios are recognised to have the capacity to more frequently bring about conditions conducive to desiccation cracking because of the tendency towards the increased occurrence of warmer and drier summers (particularly in the South East of the UK) and rainfall events of shorter duration and higher intensity (Hulme et al., 2002; Jenkins et al., 2010). Cracking in geomaterials is a widely researched phenomenon due to its ability to rapidly alter the soil hydraulic properties (Anderson et al., 1982; Albrecht and Benson, 2001; Philip et al., 2002; Romkens and Prasad, 2006; Zhan et al., 2006). The rapid, preferential transmission of water through the full depth of a crack (which can be on the order of metres) is potentially a significant mechanism for strength reduction in earthworks that could lead to earth structure failure. Tensile failure is also reported in clay barriers, where differential settlement of waste material causes cracking and a reduction in liner performance as an effective hydraulic barrier (Jessberger and Stone, 1991). Chemically modified/cement stabilised materials in road and rail line sub bases can also undergo tensile cracking induced by traffic generated cyclic stresses.

Tensile strength plays a vital role in the understanding of soil cracking as it becomes increasingly unsaturated. Tensile strength is the product of

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real cohesion (natural or artificial cementation between particles) and apparent cohesion due to suction (Lakshmikantha et al., 2012). Tensile strength is often over looked and is difficult to determine using the traditional suite of standard laboratory tests. Therefore, the ability to characterise the tensile strength/stiffness behaviour of geomaterials is of great importance to engineering geologists and geotechnical engineers.

There exist a number of methodologies available for the characterisation of the tensile strength of geomaterials. These can be separated broadly into two categories; direct and indirect tests. Direct tests are classified as using an applied axial tensile load and indirect tests as exploiting the application of non-tensile loading (e.g., compression) such that the specimen fails in tension. Direct tests include modification of triaxial testing apparatus (Tang and Graham, 2000; Heibrock et al., 2005; Zeh and Witt, 2007) and modification of direct shear testing apparatus (Nahlawi et al., 2004; Tamrakar et al., 2005; Trabelsi et al., 2012). Indirect tests include the Brazilian tensile test (Frydman, 1964; Krishnayya and Einsenstein, 1974), Hollow Cylinder Triaxial test (Alsayed, 2002) and beam bending (Thusyanthan et al., 2007). Each of these approaches has advantages and limitations. The Brazilian tensile test is only suitable for relatively stiff material and therefore cannot be reliably used to test saturated clay soils that exhibit plastic behaviour. Hollow Cylinder tests require complex specimen preparation due to their hollow geometry. The preparation of beam bending specimens is relatively simple; however, results are sensitive to specimen and loading geometry in addition to strain rate. Modification of a standard triaxial testing system, such as that by Zeh and Witt (2007), requires complex specimen preparation in which a textile fabric drain is placed down the centre of the specimen, risking damage in the process. Direct testing of rectangular, bow tie or dog bone shaped prisms involves less complex specimen preparation but there is the potential for squeezing of low stiffness material by shear keys and loading jaws leading to uneven stress distributions and inaccurate measurement.

The research presented in this paper describes the development of the Newcastle Direct Tensile Test (NDTT) methodology that is based on a simple reversible modification of existing standard geotechnical laboratory equipment. The results have been validated against those obtained using classical tests for (brittle) geomaterials. The Brazilian test was developed for the assessment of brittle materials and has been shown to be applicable for soils in limited, low saturation conditions (Frydman, 1964; Krishnayya and Einsenstein, 1974). Furthermore, full-field strain distribution across specimens have been monitored using Digital Image Correlation (DIC) during testing to investigate the generation of inferred tensile stresses. The application of this technique to assess tensile strain development has been established in direct (Divya et al., 2014) and indirect (Stirling et al., 2013) tensile testing.

2. Method

2.1. Materials

Three soils at a range of moisture contents were selected for testing in order to assess the direct and indirect tests across a range of applications. These consisted of commercially available kaolin–bentonite–sand (KBS) mixture, remoulded glacial till and cemented silty sand. Table 1 shows the classification properties of these materials; liquid limit, L_l, plastic limit, P_l, plasticity index, PI, optimum moisture content (at which maximum dry density is achieved) and the Particle Size Distribution (PSD) coefficients of uniformity (Cu) and curvature (Cz).

The KBS soil was used in evaluation of the NDTT loading jaw design and the applicability of indirect testing on specimens at relatively high water content through the use of Digital Image Correlation. The composition by dry weight was kaolin 47.5%, sodium carbonate activated bentonite (mainly sodium and calcium montmorillonite) 2.5% and sharp sand 50%. The kaolin mineralogy is described as kaolinite with minor amounts of mica, quartz and feldspar or illmenite, chemical analysis by X-ray fluorescence showed SiO_2 50% and Al_2O_3 35% by dry mass (IMERYS, 2008). An artificial, cemented soil comprising silica sand 67.5%, kaolin 27.5% and CEM-1 5%, was used to demonstrate the range of applications for which the direct test may be used and to aid in the comparison of test methods. The remoulded glacial till represented a common engineering fill material used in the construction of, among other applications, infrastructure slopes. As this material originates from a natural deposit, XRD analysis was conducted. The following composition was established: quartz 63.5%, feldspar 7%, phyllosilicates/clay minerals including undifferentiated mica species 18.2%, kaolinite 7.1% and chlorite/smectite 0.7%.

Table 1
Material classification parameters (conducted in accordance with BS 1377 Parts 2 and 4 (British Standard Institute, 1990a, 1990b)).

	L_l (%)	P_l (%)	Plasticity index (%)	[a]Optimum moisture content (%)	[a]Maximum dry density (mg/m^3)	PSD	
						Cu	Cz
KBS	34	16	18	16	1.76	17.3	6.1
Glacial till	45	24	21	15	1.82	9.6	1.2
Cemented silty sand	23	11	12	11	2.00	18.7	5.8

[a] Conducted using the 2.5 kg rammer method (British Standard Institute, 1990b).

2.2. Direct tensile testing

The fundamental principle behind the apparatus is that direct tensile stresses are measured via a simple, easily reversible modification to the standard direct shear strength test, BS1377-7 (British Standard Institute, 1990c). In this way, the means of both generating and measuring load are already established. The rig chosen for modification was a conventional Wykham Farrance 60 mm square direct shear testing rig.

Several designs of jaws/platens have been proposed by previous authors including internally or externally glued fixings (Heibrock et al., 2005) and friction based designs such as truncated cylinders (Tamrakar et al., 2005) and truncated triangular prisms (Rodriguez, 2002; Kim and Hwang 2003; Trabelsi et al., 2012). In order to induce tension, a pair of loading jaws was designed between which the soil specimen is mounted. No adhesive was used in an effort to avoid the introduction of any additional media as it is thought that this may influence the measurement of tensile stress and complicate the quick and easy production of test specimens. A friction based system was selected and is shown in Fig. 1. Specially designed rigid PVC jaws that grip the specimen (Fig. 1a) were constructed and mounted together into the standard direct shear carriage (Fig. 1b). An interior jaw angle of ~20° was used in accordance with Arslan et al. (2008) and Kim and Sture (2008), as reported by Divya et al. (2014). This angle is recognised to be greater than the potential dilatancy of any material tested in this work and is thought to prevent the relative displacement of soil particles with respect to the confining jaw surface resulting in a uniform distribution of compressive stress.

Crucially, the jaws are made to separate in a uniaxial manner at an adjustable, constant rate. To achieve this, the jaws are placed within the carriage that is propelled by the motor; however one jaw is restrained by a brace (restrained jaw, Fig. 1a). Hence, the carriage jaw is made to move along greased bearings relative to the restrained jaw. As the carriage jaw is propelled, load is transferred evenly through the cross-section of the specimen to the restrained jaw. A brace element allows the load to be transmitted to the load gauge positioned at the opposite end of the rig. The specimen possesses a mirrored isosceles trapezium plan cross-section (38 × 54 × 50 mm (78.3 ml volume)) that aids the constraint of the specimen and induces failure at the centre due to the reduced cross-sectional area.