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Review

Utilisation of transparent synthetic soil surrogates in geotechnical physical models: A review

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A B S T R A C T

Efforts to obtain non-intrusive measurement of deformations and spatial flow within soil mass prior to the advent of transparent soils have perceptible limitations. The transparent soil is a two-phase medium composed of both the synthetic aggregate and fluid components of identical refractive indices aiming at attaining transparency of the resulting soil. The transparency facilitates real life visualisation of soil continuum in physical models. When applied in conjunction with advanced photogrammetry and image processing techniques, transparent soils enable the quantification of the spatial deformation, displacement and multi-phase flow in physical model tests. Transparent synthetic soils have been successfully employed in geotechnical model tests as soil surrogates based on the testing results of their geotechnical properties which replicate those of natural soils. This paper presents a review on transparent synthetic soils and their numerous applications in geotechnical physical models. The properties of the aggregate materials are outlined and the features of the various transparent clays and sands available in the literature are described. The merits of transparent soil are highlighted and the need to amplify its application in geotechnical physical model researches is emphasised. This paper will serve as a concise compendium on the subject of transparent soils for future researchers in this field.

1. Introduction

Earliest researches to visualise the interior of soils were achieved using X-ray techniques (Kirkpatrick and Belshaw, 1968; Bransby and Milligant, 1975; Kharchafi and Dysli, 1993), and later tomography X-ray and radiography methods (Desrues et al., 1996; Shi et al., 1999; Wong, 1999; Ngan-Tillard et al., 2005; Hall et al., 2010a; Paniagua et al., 2013). However, their usage is restricted because of their experimental limitations, technical sophistications and economic considerations. In addition, some of the investigations were intrusive (Bergfelt, 1956; Nemat-Nasser and Okada, 2001) and the embedded particles have distinctive features from the adjoining soils. The evolution of transparent synthetic soils which permits studying spatial behaviours and flow features inside a soil continuum non-intrusively (Mannheimer and Oswald, 1993; Iskander et al., 1994) coupled with the advances in optical technologies and image processing techniques such as particle image velocimetry (PIV) (White et al., 2001a, 2001b; Take and Bolton, 2002; Liu and Iskander, 2004) has enhanced the capability of modelling geotechnical and geo-environmental engineering problems in the last two decades (Iskander, 2010).

The transparent synthetic soil is a two-phase medium composed of both the synthetic aggregate and fluid components. Transparency is attained by using aggregate materials and pore fluids with identical refractive indices, thus permitting complete penetration of light (Iskander et al., 2002b). The refractive index is the ratio of speed of light in a vacuum to that in a medium (Iskander, 2010). The aggregate materials that have been used for transparent synthetic soils include precipitated amorphous silica, silica gel, fumed silica, fused silica, fused quartz, aquabeads and gelbeads. The materials were matched with different fluids or blends of fluids such as mineral oils, paraffinic oil, white oil, mineral spirit, brine mixture, sucrose solution and water. Previous researches investigated the geotechnical properties of transparent soils and confirmed that their properties were consistent with those of natural soils (Liu et al., 2003; Zhao and Ge, 2007, 2014; Cao et al., 2011; Guzman and Iskander, 2013).

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Today, transparent soils have been used in the laboratory to model soil-structure interaction problems (Toiya et al., 2007; Zhao, 2007; Liu et al., 2010; Lwti, 2015), including tunnelling-induced movements (Ahmed, 2011; Ahmed and Iskander, 2011c, 2011d), soil-geosynthetic interactions (Ferreira, 2013; Tatari, 2014; Bathurst and Ezzein, 2015), soil deformation measurements (Liu, 2003; White et al., 2005; Beckett and Augarde, 2011), projectile penetration in sand (Cave et al., 2014; Chen et al., 2014; Guzman, 2014; Omidvar et al., 2015a), visualisation of grout permeation in soil and rock (Liu et al., 2013; Sui et al., 2015), performance of vibrated stone columns (McKelvey et al., 2004; Kelly, 2014a), study of three-dimensional (3D) flow and geo-environmental problems (Hunter, 2012; Serrano, 2012; Siemens et al., 2014; Kashuk et al., 2015; Ma, 2015; Sills, 2015), centrifuge models (Song, 2008; Song and Hu, 2009), and those in unsaturated soils (Beckett and Augarde, 2010; Oldroyd, 2011; Siemens and Oldroyd, 2014).

Although the basic principle of modelling using the transparent synthetic soil is well established, its application is still restricted to a cluster of researchers and is not yet widely spread across the world. Hence, there is a need to further propagate its potentials and explore its abundant research values. A review of the characteristics of transparent soils and their application in geotechnical physical models is the focus of this paper.

2. Characteristics of aggregate materials

2.1. Precipitated amorphous silica

Amorphous silica powders are inert and insoluble in water but are hygroscopic. They consist of micro-particles in the order of 0.02 μm which coalesce to form larger particles with the specific gravity of 2–2.1. The unit weight ranges from 0.4 kN/m^3 to 1 kN/m^3 with a moisture content of 6–7% and aggregate sizes ranging from 1.4 μm to 175 μm (Sadek, 2002). The internal porosity of the aggregates led to their lower bulk densities in comparison with the majority of natural soils, and most of their physical properties are dictated by their aggregate sizes. They absorb pore fluids and dislodge air and are highly suitable for making transparent clays (Iskander et al., 2002a).

2.2. Silica gel

Silica gel is a colloidal form of silica and is obtained by partial dehydration of H_2SiO_3. It consists of a massive network of interconnected microscopic pores with diameters ranging from 5×10^{-10} m to 300×10^{-10} m and is characterised by a high apparent total void ratio as a result of the internal porosity of the aggregates (Zhao and Ge, 2014). It is inert and porous, obtainable in different sizes between 0.5 mm and 5 mm with a specific gravity of 2.2. The dry unit weight of the silica gel is 6–9 kN/m^3 and varies with its grain size, shape and packing. The particle shapes are the angular and rounded beads, while the saturated unit weight depends on the pore fluid. Silica gels are best utilised to model medium to coarse transparent sands (Sadek et al., 2002).

2.3. Fumed silica

Fumed silica is obtained from silica heated to high temperature and condensed from the vapour state in a powdery form (Gill and Lehane, 2001; Stanier, 2011). Its particle size is 0.014 μm with a surface area of (200 ± 25) m^2/g; the bulk density is 36.8 kg/m^3, and the particle density is 2200 kg/m^3 (Kelly, 2014b). The average compression index C_c of fumed silica is 10.5 and the swelling index C_s is 0.86 (Hird and Stanier, 2010).

2.4. Fused silica

Fused silica is a typical glass calcined by high temperature. It contains more than 99.9% of SiO_2 with a specific gravity of 2.21 and pH value of 6. The refractive index of fused silica varies from 1.55 to 1.4 through the transmission range of 0.16 μm–3 μm. The fused silica is available in different grades (Cao et al., 2011), consisting of solid particles without any pores inside it. It is colourless in appearance and suitable to model transparent sands (Sun and Liu, 2014).

2.5. Fused quartz

Fused quartz is a non-crystalline form of quartz sand manufactured by melting natural quartz crystals at 2000 °C and then cooling. The crystals become fused together and non-porous. The particles are hard, fractured and chemically resistant, and have good optical transmission (Ezzein and Bathurst, 2011b). The fused quartz has the shape, structural and chemical properties comparable to those of natural silicate sand (Guzman and Iskander, 2013). Its particles are angular with a void ratio range of 0.65–0.97 and refractive index of 1.458 at 25 °C (Kashuk et al., 2014).

2.6. Aquabeads

Aquabeads is a water absorbent polymer produced from a resin which is capable of absorbing water up to 200 times its own weight. The aquabeads is primarily designed for ground improvement purposes. It retains the absorbed water under pressure provided that the prevailing stress remains constant. It has a good stability under varying temperatures and excellent durability against heat (Tabe, 2009). Its refractive index is exactly that of water, i.e. 1.333, with a density of 980 g/L, and a pH value of 8.5–10. Although it appears yellowish when dry, it becomes very transparent after absorbing water (Lo et al., 2008a, 2009). It can be applied to modelling transparent clays, silts or fine sands depending on the type of aquabeads used (Lo et al., 2008b; Tabe et al., 2011).

2.7. Gelbeads

Gelbeads is also a water absorbent polymer produced from a resin. It has a porosity of about 0.45 and a hydraulic conductivity of 4.6–6.8 cm/s. It possesses a higher strength when compared to aquabeads (Ma et al., 2014).

3. Preparation and physical properties of transparent soil

After mixing the aggregate materials and the pore fluid, the resulting material is then put under vacuum for a period of time not less than 4 h to de-air the mix and improve its transparency. The soil becomes homogenous with invisible particles permitting the flow of light particles and internal visualisation within the soil upon saturation (Iskander, 2010). Fig. 1 is a freshly prepared transparent soil.

Transparent synthetic clay specimens display a high apparent void ratio because of the internal porosity of the aggregates. Interaggregate void ratio, e_i, which takes into account only the volume in between the aggregates, is more appropriate for geotechnical intents. In addition, the pore fluid does not completely evaporate in normal moisture content tests due to the higher boiling point. Hence, a correction factor j is often applied for this purpose (Iskander et al., 2002a, 2002b).

Some researchers have utilised test cards (Ni et al., 2010) or ophthalmic chart (Guzman et al., 2014a) to measure the degree of transparency of the soils while others simply viewed written signs