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Review

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

Abideen Adekunle Ganiyu [a,*], Ahmad Safuan A. Rashid [a], Mohd Hanim Osman [b]

[a] *Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia*

[b] *Forensic Engineering Centre, Institute for Smart Infrastructure and Innovative Construction, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia*

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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.

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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).

* Corresponding author. Tel.: +60 149189780.
E-mail address: gabideen2@live.utm.my (A.A. Ganiyu).

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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

Fig. 1. A freshly prepared transparent soil.

such as "no smoking" from the transparent soil (Liu et al., 2003; Lo et al., 2009). A more autonomous qualitative method for assessing the transparency of transparent soils by means of modulation transfer function was presented by Black and Take (2015).

4. Factors affecting the degree of transparency

The transparency of the model (transparent soil and container) is influenced by variations in the refractive indices of the transparent soil and the containing vessel. The best material for the containing vessel is the one whose refractive index is proximate to that of the transparent soil (Ezzein and Bathurst, 2011b). The transparency is also influenced by slight variation in temperature (Ni et al., 2010; Stanier, 2011; Black and Tatari, 2015; Siemens et al., 2015), presence of impurities in the materials (Ezzein and Bathurst, 2011b), non-saturation of the transparent soil (Sadek et al., 2002; Iskander and Liu, 2010), size of the model (Sadek et al., 2003; Liu and Iskander, 2010), type of aggregate materials (Hird and Stanier, 2010; Kelly and Black, 2012), size of aggregate materials (Iskander et al., 1994; Sivakumar et al., 2007), and most importantly the imprecise matching of refractive indices of pore fluids and aggregate material (Sadek et al., 2003; Iskander and Liu, 2010; Zhao et al., 2010). The addition of reflective materials to give the needed texture for some measurements also impacts the transparency negatively (Ni et al., 2010; Stanier et al., 2012). When laser light source is being utilised in transparent soil model, the use of a dark room or temporary creation of dark background behind the testing is recommended to avoid reflection of light which also impacts negatively on the readings (Sadek et al., 2003).

5. Transparent synthetic clays

Two amorphous silica sample sizes of 1.4 μm and 25 μm with a concentration of 9% and 20% by weight, respectively, were matched with a 50:50 blend by weight of normal paraffinic solvent and colourless mineral oil to get a transparent clay with a refractive index of 1.447 at 25 °C. The density and viscosity of the pore fluid were 804 kg/m^3 and 5 mPa s, respectively. The amorphous silica was also matched with a brine mixture of calcium bromide and water to obtain a refractive index of 1.448 at 25 °C. The density and viscosity of the brine mixture were 1572 kg/m^3 and 3.6 mPa s, respectively (Iskander et al., 2003; Liu, 2009).

The fumed silica having aggregate sizes of 0.1–0.4 μm and concentration of 7% by weight was also added to pore fluid containing 30:70 blend of mineral spirit and liquid paraffin to form transparent clay. The refractive index of the oil blend was 1.456 at 20 °C. The material dubbed Trinity College Dublin (TCD) clay has been widely utilised by many researchers to model transparent synthetic clay (Lehane and Gill, 2004; McKelvey et al., 2004; Sivakumar et al., 2007; Song et al., 2009). The TCD clay mixed with sand and pea gravel in the ratio of 5:4:1 has also be used to produce "artificial rammed earth" (Beckett and Augarde, 2011).

Another transparent clay composed of fumed silica was made with pore fluid consisting of paraffin oil and white oil in the ratio of 77:23, and the fumed silica was 6% by mass (Hird and Stanier, 2010; Kelly and Black, 2012; Forlati and Black, 2014; Stanier et al., 2014; Hussin, 2015). In summary, transparent clay made from fumed silica produced superior quality to that produced from amorphous silica based on visibility of test card reported by Stanier (2011) and hence it permitted the use of a model twice the size applied for amorphous silica (Stanier et al., 2012).

Geotechnical tests on transparent clays, including consolidation tests, consolidated undrained triaxial tests, and consolidated drained triaxial tests, were carried out by Iskander et al. (1994). Further tests on consolidation utilising both the one-dimensional (1D) and isotropic consolidation to obtain consolidation indices, compression isochromes, pore pressure dissipation, etc., were carried out by Liu et al. (2003). The study also obtained permeability properties of transparent soil using the constant head method. The conclusions from these studies confirm that the properties of transparent soil are in congruence with those of many natural clays or sand but not of any specific clay or sand (Iskander et al., 2002a). Fig. 2 shows a transparent soil after consolidation.

6. Transparent synthetic sands

Silica gel was the first material employed for making transparent sand. The gels in two sizes of 0.5–1.5 mm and 2–5 mm were employed. The pore fluid was either a mixture of mineral oil and paraffin or brine (Iskander et al., 1994). Then, it was used in conjunction with amorphous silica in order to create two layers of

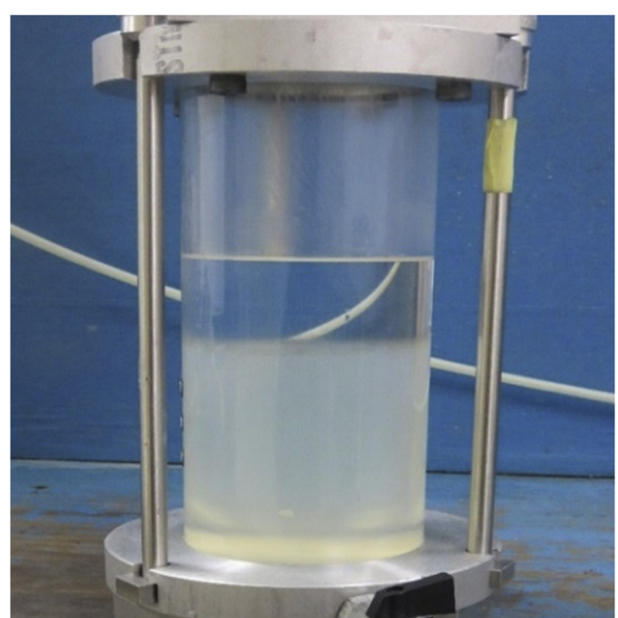

Fig. 2. Transparent soil after consolidation.

soils (sand and clay) in the same model. The resulting transparent sand has the same refractive index of 1.447 at 25 °C (Iskander et al., 2002b, 2003; Liu, 2009). The geotechnical properties of the transparent soil made from the silica gel was studied by Liu and Iskander (2010). Additionally, the dynamic properties such as damping ratio and small-strain shear modulus of transparent sand were examined by utilising resonant column tests in Zhao and Ge (2007, 2014).

Fused silica was also mixed with calcium bromide solution of 60% concentration to obtain a transparent sand with a refractive index of 1.4585. The sand was reported in a few studies (Liu et al., 2013; Liu and Sun, 2014; Sun and Liu, 2014), and the geotechnical properties of the resulting transparent soil were also studied by Cao et al. (2011).

Fused quartz has also been widely used to replicate transparent sand. It was matched with a blend of mineral oils in some studies (Ezzein and Bathurst, 2014; Chen et al., 2015; Ferreira and Zornberg, 2015) with emphasis on unsaturated applications (Siemens et al., 2011, 2012). The geotechnical properties of this material were assessed in Ezzein and Bathurst (2011b). In addition, a sucrose solution of 66.5% concentration was also added to fused quartz to produce a transparent sand with a refractive index of 1.458 at 23 °C (Guzman et al., 2014b). The sucrose solution is devoid of many setbacks of mineral oils and calcium bromide in aspects like transparency degradation, flammability, toxicity and stability (Zhao et al., 2010). The geotechnical properties of water based sucrose saturated fused quartz transparent sand were also investigated (Guzman and Iskander, 2013; Guzman et al., 2014a). Also, sodium iodide-thiosulfate solution has been recently matched with fused quartz to produce a transparent sand and its geotechnical properties were examined (Carvalho et al., 2015).

Aquabeads is a water-based material utilised to model transparent sands, and its pore fluid is 100% water (Lo et al., 2008a; Serrano et al., 2011). Its superiority over previously mentioned materials includes the ability to model large-scale models without degradation and suitability for multi-phase flow and geo-environmental problems (Lo et al., 2008b; Tabe et al., 2011). The hydraulic properties of aquabeads-based transparent sand have been investigated by Lo et al. (2008a, 2009). Gelbeads is another water-based material that has been recently utilised to model transparent fine gravel (Ma et al., 2014). A new synthetic material commercially termed LAPONITE RD has also been discovered to hydrate and swell upon dispersal in water to form a transparent slurry. A comprehensive description of the material and its geotechnical properties have been carefully described by Wallace and Rutherford (2015). The material was employed in Chini et al. (2015) and Wallace et al. (2015b). Table 1 shows the aggregate material, pore fluid composition, and physical properties of transparent synthetic soils.

7. Displacement measurement using PIV in transparent synthetic soils

PIV was originally developed in the fluid mechanics field to determine the velocity of a fluid flow that is seeded with small particles (White and Bolton, 2004; Zhang et al., 2005). In recent years, the method has been utilised in geotechnical modelling using the terms such as block matching (Guler et al., 1999; Michalowski and Shi, 2003) and digital image correlation (Hall et al., 2010b; Houda et al., 2014; Suleiman et al., 2014). In PIV, successive images are compared through a precise identification of several minute parts in image space (pixel) and later converted to object space (in millimetres) (Sadek et al., 2003). Accurate calibration of PIV algorithm and the camera is essential in order for the system to process the images perfectly (Yuan et al., 2012; Zhao and Ge, 2008).

Internal deformations in a transparent soil slurry are measured by relating images of speckles generated both before and after soil deformation. This is obtained by employing the PIV combined with advanced photogrammetry and the use of laser light source to optically slice the soil. The speckle is the interface between the laser and the soil matrix (Kong et al., 2015).

GeoPIV is a MATLAB-based module developed specifically for geotechnical applications. In GeoPIV, image processing algorithms are written to apply the PIV principle to the images of soil. It correlates a time-lapse sequence of images to a reference image, and a grid of discrete patches is added to each image to track the displacement of these patches (White and Take, 2002).

In transparent soils, PIV along with close-range photography has been used to examine the spatial displacement field under a model footing (Iskander and Liu, 2010), effect of pile geometry on the interior displacement of soil surrounding the laterally loaded pile (Liu et al., 2010), deformation and failure behaviour of vibrated stone columns (Kelly and Black, 2012), movement of soil

Table 1
Composition and typical properties of transparent synthetic soils.

Aggregate material	Pore fluid composition	Properties			Reference
		Refractive index	Viscosity (mPa s)	Density (kg/m^3)	
Precipitated (amorphous) silica	Mineral oil Paraffinic oil	1.447 at 25 °C	5	804	Iskander et al. (1994)
	Calcium bromide solution	1.448 at 25 °C	3.6	1572	Iskander et al. (1994)
Silica gel	Mineral oil Paraffinic oil	1.447 at 25 °C	5	804	Sadek et al. (2002)
	Calcium bromide solution	1.448 at 25 °C	3.6	1572	Sadek et al. (2002)
Fumed silica	Paraffin Mineral spirits	1.456 at 20 °C	8	817.1	Gill and Lehane (2001)
	Paraffin Technical white oil	1.467 at 20 °C	7.7	[a]942	Black (2015)
Fused silica	Calcium bromide solution	1.4585 at 25 °C	2.8	1590	Liu et al. (2015)
	Mineral oils	1.4585 at 30 °C	7	1170	Sui et al. (2015)
Fused quartz	Mineral oils	1.4586 at 22 °C	10	838	Ezzein and Bathurst (2011b)
	Sucrose solution	1.458 at 23 °C	201	1340	Guzman et al. (2014b)
	Sodium iodide solution	1.458 at 22 °C	2.2	850	Carvalho et al. (2015)
Aquabeads	Water	1.333 at 20 °C	[b]0.9	980	Tabe et al. (2011)

[a] The datum comes from Stanier (2011).
[b] The datum comes from Carvalho et al. (2015).

particles in two layers of soils under compaction (Beckett and Augarde, 2011), and some aspects of tunnelling (Ahmed and Iskander, 2011a, 2012; Sun and Liu, 2014). A comprehensive review on the implementation of PIV in geotechnical engineering is presented by Take (2015).

8. Applications of transparent soil in geotechnical physical models

8.1. Soil-structure interaction

Song et al. (2006) utilised the transparent synthetic clay to investigate the pullout bearing capacity and rotational behaviour of vertically driven plate anchor (VDPA) under different loading stages. Liu et al. (2010) also employed the synthetic transparent soil to study the effect of pile shape on the displacement of sand surrounding a laterally loaded pile. Stanier et al. (2012, 2014) studied the failure process of helical screw piles in the transparent clay, while Hird et al. (2011) investigated the vertical displacement field in the vicinity of piling auger using transparent clay. A model test using transparent soil to investigate the influence of a driving shoe and surface body ribs on the resistance during press-in installation of a tubular pile was presented by Forlati and Black (2014). Kong et al. (2015) studied the internal deformation in transparent sand caused by a pile moving under oblique pullout loads. Also, the strain path brought about by tube sampling in clay was examined in transparent soil (Hover et al., 2013a; Hover, 2014). The failure mechanism, surface heaving, internal field of deformation, load–displacement behaviour and ultimate oblique pulling resistances were obtained and the results are analogous with previously measured values in natural soils.

8.2. Tunnelling-induced movements

Experimental studies on the internal soil deformation ahead (Sun and Liu, 2014) and around (Liu and Sun, 2014) a tunnel boring machine were carried out by using transparent sand with an overburden cover of one and twice the tunnel diameter. Ahmed and Iskander (2011b) also focused their research on the subsurface settlement profiles above tunnels in transparent soil. The surface settlement profile and the dispersal of soil deformation within transparent soil mass near a tunnel were studied by Ahmed and Iskander (2011a). It was observed that the data obtained are in line with field measurements in which the trough width parameter is directly related to the depth of the tunnel and independent of the volume loss. Ahmed (2013) also presented the result of a study using a transparent soil to detect 3D deformations resulting from submerged cavities that led to a sinkhole.

8.3. Soil-geosynthetic interaction

Ezzein and Bathurst (2011a, 2014) developed a pullout box apparatus and a test method to investigate soil-geosynthetic interaction during pullout test using transparent synthetic soil. The apparatus possesses a glass bottom and the transparent soil permits real life photographs of the inserted geosynthetic specimen to be taken. The apparatus was embedded with a geogrid specimen up to 2 m in length and the specimens subjected to constant rate-of-displacement in-air testing and in-soil pullout testing under a range of normal stress. The results confirmed that the transparent soil is an excellent replica of natural soil for the investigation of soil–geogrid interaction (Bathurst and Ezzein, 2015). Ferreira and Zornberg (2015) also presented another transparent pullout testing device envisioned with the aim of investigating soil–geogrid interaction under small displacements and strains using transparent synthetic soil.

8.4. Soil deformation measurements

Transparent synthetic soils were used to observe the displacements generated during the installation of cylindrical model piles in clay (Ni et al., 2010) and the undrained penetration of penetrometer in clay (Lehane and Gill, 2004). The results were compared favourably with those of already established shallow strain path method. Also, transparent soil was employed in the observation of soil deformation patterns around penetrometers (Gill and Lehane, 2001) where it was observed that the relocation of soil particle spread furthest in a ring surrounding the penetrometer and was not directly under its base (Toiya et al., 2007). An investigation into the effect of tube sampling using transparent soil was carried out. The centreline strain path of the sample during tube penetration was obtained and it was comparatively similar to that of an existing analytical model (Hover et al., 2013b). The transparent clay was also employed to determine the failure zone in a laboratory vane shear test (Hussin, 2015; Hussin et al., 2015; Wallace et al., 2015a).

The displacements and spatial deformation of soil under a model strip footing (shallow foundation) were examined in Liu (2009), Iskander and Liu (2010), and Liu and Iskander (2010). Creep was more pronounced in the resulting load–displacement performance of the footing (Iskander and Liu, 2010). The strain fields and deformation observed from the footing are similar to those from the natural soil (Liu, 2009; Liu and Iskander, 2010) and also the results from finite element modelling using Plaxis software (Iskander et al., 2003).

8.5. Projectile penetration in sand

A physical modelling approach of studying projectile penetration in sand was developed to quantify the response of granular soils to non-intrusive, high-speed penetration using transparent soil (Chen et al., 2014; Guzman et al., 2015). Rapid penetration into soil was studied using transparent soil in 1g model tests. Penetration tests were carried out by accelerating a conical rod into the transparent soil, and the images from the penetration were taken and analysed to obtain the soil velocity in the soil–projectile interaction zone (Chen et al., 2015). Another approach for quantitative analysis of dynamic penetration into granular media was also formulated using transparent synthetic soils (Omidvar et al., 2015b). A series of 80 penetration tests was carried out by shooting spherical projectiles at speeds of up to 200 m/s into dry and saturated transparent sands to determine the terminal depth of penetration (Guzman et al., 2014b). The penetrations were analysed using existing empirical and physical models and the results agreed with those of previously published models.

8.6. Grout permeation in soil and rock

Transparent synthetic soil was employed to visualise the permeation process in soil (Liu et al., 2013). A grout injection station with a constant pressure head was used to inject grout into the transparent soil model. Image processing techniques were utilised to separate the front of grout body. At the end, it was observed that the radius of grout body varies directly with the grouting time and this confirms Maag's permeation grouting formula. Transparent soils were also utilised to model saturated fractured rock mass (Sui and Qu, 2015), and the grout permeation process was visually observed (Liu et al., 2015; Sui et al., 2015).

8.7. Vibrated stone columns

Laboratory reduced scale test on vibrated stone column in transparent clay model was investigated (McKelvey et al., 2004; Sivakumar et al., 2007). It was discovered that bulging was prominent in long columns while punching was dominant in short columns. The bearing capacity of the transparent clay bed was enhanced by the existence of the columns. In another research, it was observed that isolated stone column fails via an end bearing, bulging and compressive failure in transparent clay soil (Kelly and Black, 2012).

8.8. 3D flow and geo-environmental contamination problems

One of the earliest uses of transparent soil in geotechnical physical model tests was to study the flow of prefabricated vertical drain (PVD) (Welker et al., 1999, 2000). Both full size and reduced size PVDs with diameters between 100 mm and 300 mm were utilised and the results closely matched those obtained from mathematical models and electrical analogue. Different types of aqueous-based aquabeads have been employed to simulate two-dimensional (2D) flow, contaminants separation and surfactant flushing (Lo et al., 2008a, 2008b, 2009; Tabe et al., 2011) and the conclusion was that it is the best transparent soil aggregate to visualise multi-phase systems. Transparent soils were also employed to visualise contaminants in different non-aqueous phase liquid (NAPL) systems, i.e. light NAPL (Serrano et al., 2011), and dense NAPL (Kashuk et al., 2014; Kashuk and Iskander, 2015). The overall results indicated that the transparent soil technique is adequate for visualising pollutant transport in porous media (Liu et al., 2005; Kashuk et al., 2013).

8.9. Centrifuge models

Transparent soils have been employed to observe the pullout bearing capacity and rotation of VDPA in a centrifuge (Song et al., 2006), also the loss in anchor embedment during keying with a suggestion of a simple relationship to assess the loss (Song et al., 2009). In addition, the loss in anchor embedment during keying of suction embedded plate anchors was investigated using transparent soil in a centrifuge study (Song and Hu, 2009). Black (2015) recently developed an experimental method incorporating transparent soil and laser aided imaging technology in a centrifuge modelling and validated it with a test on a strip foundation using the principle of “modelling of models”.

8.10. Unsaturated soils

Siemens et al. (2012) investigated the accuracy of unsaturated conductivity estimations for an unsaturated transparent soil which permits exact measurement of degree of saturation along the soil profile as well as the spatial measurements of conductivity. Transparent soil was also utilised to track the movement of the air–fluid interface during a drawdown test (Siemens et al., 2011) in a 2D infiltration experiment (Siemens and Oldroyd, 2014), to assess the influence of air entrapment on infiltration (Siemens et al., 2013, 2014). It was also used to accurately measure the moisture content in unsaturated soil column experiments (Peters et al., 2011).

9. Merits and prospects of transparent synthetic soils

The primary merit of transparent synthetic soils is the ability to substitute real soil in model tests with additional functionality of transparency which allows for the study of 3D deformation and flow in the soil continuum non-intrusively. Water-based transparent soils are excellent materials for teaching geotechnical engineering to undergraduates and even elementary school students (Suescun-Florez et al., 2013). Aquabeads are specifically suitable for NAPL transport features in educational settings (Lo et al., 2009). The suitability of transparent soils in explaining triaxial test to students was emphasised by Sadek et al. (2002). When applied in conjunction with advanced photogrammetry and PIV (White et al., 2003; Take, 2015), transparent synthetic soils enable the quantification of the spatial deformation to be evaluated and provide a major break-through in geotechnical engineering physical model tests (Sadek et al., 2003; Ni et al., 2010; Peters et al., 2011; Stanier et al., 2012).

All the above-mentioned applications of transparent soils in geotechnical physical models are widely open for exploration of future researches. In addition, it is highly probable to adopt transparent soils in many other areas of geotechnical engineering researches based on their versatility and many of their excellent attributes earlier highlighted. The present authors are currently exploring soil-structure interactions by observing the spatial deformation of soil surrounding differently shaped axially loaded piles using transparent soil, PIV and close range photogrammetry.

10. Conclusions

Efforts to obtain non-intrusive measurement of deformation and spatial flow within soil mass prior to the advent of transparent soils have perceptible limitations. These limitations were overcome by the sterling qualities of transparent soils which facilitate real life visualisation of soil continuum and, at the same time, mimicking the geotechnical properties of natural soils. Many materials, mostly of silica background, have been matched with different pore fluids to obtain transparent clays and sands. The advent of transparent soils also catalysed the development of image measurements techniques and their adoption in geotechnical physical models. Transparent synthetic soils have found numerous applications in geotechnical physical models including soil–structure interaction, soil deformation measurement and multi-phase flow problems. The merits of transparent soil also include its appropriateness for teaching geotechnical engineering to undergraduate students.

This paper provides a concise compendium of previous researches in the field of transparent soils in order to enable prospective researchers to grasp the substance of past researches and possible future direction for relevant applications of transparent soils to attain their optimum applications in geotechnical physical models.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Abideen Adekunle Ganiyu is a PhD candidate in Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM), Johor, Malaysia. His research covers unit gravity modelling of pile foundation, visualisation of pile penetration in transparent synthetic soil using advanced photogrammetry and particle image velocimetry, and 3D numerical modelling of pile foundation. He had both Diploma and Bachelor degrees in Civil Engineering from the Polytechnic Ibadan, Nigeria and Ladoke Akintola University of Technology, Ogbomosho, Nigeria, respectively. He obtained his Master degree in Construction Engineering and Management from King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia. He is a certified Project Management Professional (PMP), a corporate member of the Nigerian Society of Engineers (NSE), and a registered Engineer with the Council for the Regulation of Engineering in Nigeria (COREN).

Dr. Ahmad Safuan A. Rashid joined UTM as an academic staff in December 2005 after completing his Master degree in the same institution. He obtained his PhD degree from the University of Sheffield in the UK in September 2011. His expertise is on small-scale physical modelling and he has conducted a study on behaviour of failure on Deep Mixing (DM) Method as a foundation. He teaches Soil Mechanics and laboratory subjects for undergraduates. He has also supervised more than 40 students cutting across Undergraduate, Master and PhD levels.

Dr. Mohd Hanim Osman is a professor at the Faculty of Civil Engineering, UTM. He is active in research and consultancies in specialised areas related to construction, in particular analysis, design and assessment of building. Currently, he is the Director of the Forensic Engineering Centre, and fellow member of the Construction Research Centre, UTM. He holds B.Eng. (Civil) (Hon.) from UTM, M.Sc. (Struct.) from University of Surrey, and PhD (Struct.) from University of Wales, Cardiff, UK. He is an active member of Malaysian Structural Steel Association, a member of the Institute of Engineers Malaysia and Professional Engineer with Board of Engineers Malaysia. He was the Deputy Dean (Academic), and the Technical Manager of Civil Engineering Testing Unit, Faculty of Civil Engineering. He is a qualified internal auditor for Laboratory Accreditation ISO 17025, and also for EAC-BEM Academic Programme Accreditation. His current major researches are on affordable building construction system, and the design of cocurriculum programme for student holistic development.