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A transparent material to model the geotechnical properties of soils
Matériaux transparents pour la modélisation des propriétés géotechniques des sols

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SYNOPSIS: This paper demonstrates the feasibility of producing transparent materials which exhibit macroscopic properties representative of the geotechnical properties of natural soils. The transparent “soils” discussed in this paper were made by consolidating suspensions of amorphous silica in liquids with matching optical refractive indices. The developed transparent “soils” could possibly be utilized in model studies to measure three-dimensional deformation patterns and flow paths within model transparent soil continua.

INTRODUCTION

The study of many geotechnical problems would be aided by the ability to measure the continuous spatial deformation and flow patterns within soil deposits using non-intrusive techniques. These measurements are usually limited by the fact that soil sensors do not provide a continuous image of the measured continuum. Additionally, soil sensors exhibit static and dynamic characteristics that are different from those of the surrounding soils, and therefore can change the response of the measured continuum. Tests conducted with a transparent material which has properties that closely model the geotechnical properties of natural soils can potentially circumvent these experimental problems if the response of a model transparent continuum can be measured using non-intrusive optical visualization techniques.

Several methods have been used to accomplish this goal. Computerized Axial Tomography (Cat-Scan or CT scanning), which is a technique used primarily in medicine, has been adapted to obtain non-intrusive images of soil samples (e.g. Orsi et al., 1992). However, the broad application of CT scanning in geotechnical engineering is limited by the high cost of the scanning microscopes. Optical techniques have been used in model studies to measure the response of transparent materials which model specific soil properties. For example, translucent media made of crushed glass and a matched refractive index fluid have been used to study stress distribution under simple shear (Allersma, 1982), as well as the response of saturated embankments under seismic loading (Konagai et al., 1992). The study of soil response using optical visualization techniques is limited, however, by the lack of a transparent material that can accurately model the properties of natural soils.

This paper demonstrates the feasibility of producing transparent materials that can model the macroscopic geotechnical properties of natural soils. The clarity of the produced soils is demonstrated in Fig. 1, where a 2 mm (0.08 in) mesh is clearly visible through a 7.5 cm (3 in) thick soil specimen.

PREPARATION OF TRANSPARENT SPECIMENS

The transparent soils discussed in this paper were made by consolidation from suspensions of two sizes of amorphous silica aggregates (25 μm and 1.6 μm average size) and two different liquids with matching refractive indices (mineral oil and calcium bromide brine) (Iskander et al., 1994).

Amorphous silica consists of ultra fine particles with individual diameters on the order of 0.02 μm. These particles combine to form larger spherical aggregates, which are porous. In addition to matching the refractive indices of the pore fluid and silica aggregates, the optical properties of transparent soils benefit from two additional characteristics of amorphous silica (Mannheimer, 1990). First, the particles constituting the silica aggregates do not scatter light because their diameters are shorter than the wavelength of visible light. Therefore, any defect in the particles does not affect the transparency of the synthetic soil. Second, porous aggregates are capable of adsorbing pore fluid, thus displacing air, which is a major source of transparency degradation.

The total void ratio of the consolidated specimens ranged between 4 and 8. The total void ratio is representative of the voids both within and between the silica aggregates and therefore does not correlate well with typical void ratios of natural soils. The inter-aggregate void ratio is thought to be more representative than the total void ratio for geotechnical purposes, and was estimated by Iskander et al. (1994) to be in the range of 0.2 - 0.8.
GEOTECHNICAL PROPERTIES OF TRANSPARENT SOILS

Conventional consolidation, permeability and triaxial compression tests were performed on specimens trimmed from the consolidated samples.

Consolidation Tests

A typical relationship between total void ratio and applied stress is shown in Fig. 2. The specimen was trimmed from a sample consolidated to 140 kPa (20 psi) from a slurry of 25 μm amorphous silica and oil. The change in void ratio during consolidation represents the change in both the voids within and between the silica aggregates. Substantial secondary consolidation occurred (Iskander, 1991). When a load is applied, it is likely that two consolidation processes take place, the first involves the pores between the silica aggregates, and the second involves the pores inside the silica aggregates.

The compression index, \( C_C \), and recompression index, \( C_r \), were found to be 2.35 and 0.23, respectively. The coefficients of consolidation, \( C_v \), ranged between 0.001 and 0.002 cm\(^2\)/sec (0.1 and 0.2 ft\(^2\)/day). These values are in the range typically reported for Swedish and Canadian clays (e.g. Holtz and Kovacs, 1981). The ratio of \( C_r \) to \( C_C \) is 0.1 which is within the range typically reported for natural clays (Carter and Bentley, 1991).

Permeability Tests

Constant head permeability tests were performed before extracting the soil samples from the consolidometer (Mannheimer and Oswald, 1993). Hydraulic conductivities ranging between \( 2.3 \times 10^{-7} \) to \( 2.5 \times 10^{-5} \) cm/sec were measured, which corresponds to intrinsic permeabilities in the range of 1.5 to 160 milli Darcy. Natural soils with intrinsic permeabilities in this range usually exhibit a hydraulic conductivity to water at room temperature ranging between \( 1.5 \times 10^{-6} \) and \( 1.6 \times 10^{-4} \) cm/sec. These permeabilities are in the range typically reported for clays and silts.
Triaxial Tests

Consolidated-undrained (Fig. 3 & 4) and consolidated-drained (Fig. 5 & 6) triaxial tests were performed on normally consolidated specimens trimmed from the consolidated samples. Generally, no strain softening was observed. Large volumetric strain occurred in drained tests due to the continuous shear deformation of the silica aggregates as shear stress was applied (Fig. 6). The stress-strain curves are typical of normally consolidated clays and very loose sands. The triaxial tests shown in Figs 3-6 were used to construct the failure envelopes shown in Fig. 7. The strength of the specimens consolidated from suspensions of fine silica is similar to the strength reported by Bishop (1971) for the Boston, Horten, Massena, Wiener Tegel, Studenterlunden, and Boulder clays. The strength of the specimens consolidated from suspensions of coarse silica is similar to the strength reported by Kenny (1959) for the Drammen, Bersimis, and Boston Blue clays.
The measured behavior of transparent soils appears to be consistent with the properties of many soils but not any one soil in particular. For example, the strains during shear are characteristic of soft normally consolidated clays, while the strength is consistent with the properties of stronger clays. This discrepancy should be viewed in the context of the testing program. The triaxial tests discussed in this paper were performed on normally consolidated samples, which resulted in large strains as well as strain hardening during shear. Overconsolidated transparent soils may exhibit stress-strain properties that are more consistent with the properties of natural clays, which are typically overconsolidated. Overconsolidated transparent soils may also exhibit strain softening during shear, which is very desirable considering the difficulty in the numerical modeling of strain softening.

The peak strength of transparent soils was defined at 20% strain, which is larger than strain corresponding to the peak strength of most natural clays. This discrepancy would limit the use of existing transparent soils in modeling limit equilibrium problems. Deformational problems, which are of more interest, are however unaffected by this discrepancy since the strength corresponding to the strain of interest is comparable to that of natural soils.

**Visualization Experiments**

The development of transparent synthetic soils with mechanical and hydraulic properties characteristic of natural soil properties is a first step toward the use of optical techniques in geotechnical engineering. Optical techniques would provide an inexpensive method to obtain non-intrusive images of the spatial characteristics of model soil continua. At this time, visualization techniques for measuring spatial deformations in transparent soils are not yet developed. However, when such techniques are developed, transparent soils could be used to study many geotechnical problems such as deformations of embankments and deformations adjacent to foundations, retaining structures and tunnels. The use of transparent soils in scaled model tests is considered a particularly promising application. Transparent soils can also be used to visualize the effects of controlled geologic features, such as layering, on three-dimensional flow problems such as pollutant transport, remediation of contaminated aquifers, recovery of leaking and spilled petroleum products and performance evaluation of waste disposal facilities.

Optical tomography is a potential visualization technique in which laser light is used to illuminate cross sections of a transparent soil mass. Multiple video cameras are used to capture the reflected light. Computer based digital image processing can be used to analyze the reflected light and construct continuous images of the spatial deformation patterns within the transparent mass.