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Technical Note

Visualization of tunnelling-induced ground movement in transparent sand

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ABSTRACT

This paper presents an experimental investigation of internal soil deformation ahead of a tunnel boring machine by using transparent sand and digital image correlation (DIC) techniques. Soil deformation and its control are often very critical issues for protecting adjacent properties and services during tunnel construction. Currently, most of soil deformation measurements are limited to ground surface settlement since natural soil is not transparent. The visualization of spatial deformation inside soil masses will improve the understanding on the influence in tunnelling. Transparent sand is used in this study, which is made of fused silica and a calcium bromide solution with a matching refractive index. An optical set-up is developed that consists of a laser, camera, and computer. The laser is used to illuminate the targeted traverse section ahead of a scaled shield machine. The images of laser speckles generated through interaction between the laser light and silica are captured by the camera and then transferred onto a computer. DIC is used to calculate the soil displacement between two images obtained before and after the machine movement. Two model tests are performed with an overburden cover that varies by one to two times the tunnel diameter. The results show that soil deformation changes with increases in tunnel depth. The settlement troughs at various soil depths are similar to Gaussian curves. As expected, the trough becomes narrower as the soil depth increases. The influence zone changes from a rectangle over a reversed trapezoid shape in the shallower tunnel to a bell over a trapezoid shape restrained within the soil mass in the deeper case. The limitations of this study are also discussed in the paper.

1. Introduction

One of the critical issues in urban tunnelling is the control of ground movement induced by tunnelling in order to protect adjacent properties and services. Nowadays, modern tunnel boring machines (TBMs) have been increasingly applied in urban settings because the TBMs can provide appropriate support pressure on the tunnel face, which will counterbalance the soil and water pressure ahead of the machine. Even though this is the case, inappropriate support pressure will still cause stability failure in the soil and jeopardize the safety of the adjacent properties. In order to evaluate the risk for adjacent structures, Peck (1969) proposed an empirical solution for estimating the surface settlement induced by tunnelling. Since then, there have been many modifications of Peck's method based on field measurements, for example, that by O'Reilly and New (1982). All of these studies mainly focus on the surface settlement, while only a few investigations are available on subsurface movement, like the work by Mair et al. (1993).

Many methods, including numerical, analytical, and observational methods, have been used to investigate soil deformation and address instability problems that are induced by tunnelling (Lee and Rowe, 1990; Leca and Clough, 1992; Harris et al., 1994). However, laboratory testing that includes both 1-g and centrifugal tests has played a significant role in the investigation of soil deformation and lining stresses during tunnelling. Meguid et al. (2008) provided a brief review of different modelling techniques used in the laboratory, including trap door modelling, and the use of a rigid tube with a flexible or movable face, pressurized air bags, polystyrene foam and organic solvents. Many of these laboratory tests take advantage of axisymmetric features of the tunnel and simulate the tunnel as a semi-cylinder tube or as plain strain problems. The results from these studies were inevitably influenced by the boundary conditions. In addition to soil augering and methods with a miniature shield machine to overcome the boundary effect (Nomoto et al., 1999; Lee and Yoo, 2006), a new modelling technique that uses transparent soil was recently introduced by Ahmed and Iskander (2011a,b) with a pressured air bag to visualize soil deformation and failure during tunnelling. This paper presents an

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experimental investigation on internal soil deformation by using transparent soil with a miniature shield machine.

2. Transparent soil

Ground movement occurs at the vicinity of TBMs and then propagates to the ground surface. Deformation in the soil cannot be easily observed since natural soil is not transparent. A new kind of modelling technique that uses transparent soil has been developed to overcome this limitation. Transparent soil is made of silica with pore fluids that have matching refractive indices (Mannheimer and Oswald, 1993). This has been used by many researchers in their geotechnical investigations, including in tunnelling by Ahmed and Iskander (2011a,b). Two kinds of amorphous silica had been developed to model sand and clay (Iskander et al., 2002a,b). However, amorphous silica is found to exhibit a higher secondary consolidation and a higher compressibility than natural soils due to its porous particles (Liu et al., 2003). A new kind of silica called fused silica is used in this study with grain sizes that range from 0.1 to 0.5 mm. The fused silica used in this study is obtained from Jiansu Kaida Silica Co., Ltd., China, without further processing. Compared to amorphous silica, fused silica has solid particles with no pores inside, which exhibit a better capacity to model natural sand. A calcium bromide solution is used in this study instead of mineral oils that were used in other research work due to its easy accessibility. A series of trial tests were performed for the calcium bromide solution so that it would provide the best transparency with a concentration of approximately 60%. The transparency of the transparent fused silica is shown in Fig. 1. The peak friction angle of the fused silica is estimated to be 38.4° through a series of direct shear tests on wet silica, as shown in Fig. 2. This friction angle value is within the normal range reported for natural sands (Holtz et al., 2011), but lower than the peak friction angle of 43–44° for a similar material reported by Ezzein and Bathurst (2011). The different sources of material and the pore fluids may contribute to the discrepancy. The physical properties of the fused silica are summarized in Table 1.

3. Experimental set-up and test procedures

3.1. Test set-up

The test mould was made of transparent Plexiglas with a thickness of 5 mm and inner dimensions of 12 cm × 10 cm × 12 cm (length × width × height). The shield machine was made of a Plexiglas tube with an inner diameter of 2.5 cm and a wall thickness of 5 mm. A solid glass bar was used to support the soil in the front. A helium–neon laser with a power of 150 mw was used to illuminate the cross-section of interest. A Canon 500D digital camera with a resolution of 4752 × 3168 pixels was used to capture the images. The glass bar was manually retracted from the tunnel to trigger soil movement, which is similar to the method used by Kirsch (2010). The schematic arrangement and a picture of the test set-up are shown in Fig. 3.

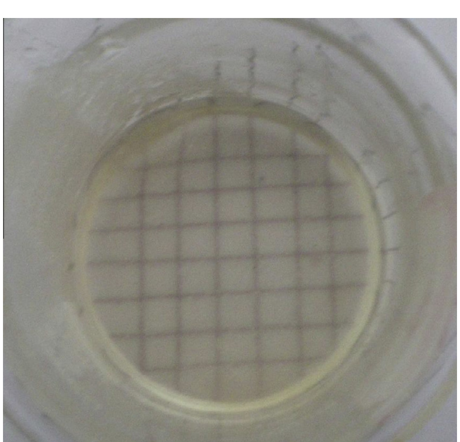

Fig. 1. Transparency of a soil sample made of fused silica (The grids are shown through a 5 cm thick transparent soil sample).

3.2. Sample preparation and test procedure

The use of a calcium bromide solution as the pore fluid causes degradation in transparency for a large sample since air is easily entrapped in high viscosity pore fluids (Zhao, 2007). A transparent sample had to be prepared layer by layer with saturated silica to avoid the entrapment of air inside. The fused silica was first immersed into the pore fluid. Then, a vacuum was applied to de-air the mixture until it turned transparent after approximately one hour. Following that, the silica was packed into the Plexiglas mould to form a transparent soil sample. The mould was partially filled with pore fluid at the beginning and the de-aired silica was slowly poured into the box. At the same time, the sample was stirred to release any air bubbles that were entrapped during the pouring. After the sample preparation, the TBM model was screwed into its position about 50 mm inside the sample.

After the sample was prepared, the camera was set approximately 280 mm away from the illuminated cross-section with its optical axis perpendicular to the mould. The focus and light intensity were then adjusted to achieve a better image quality. Since images are sensitive to changes in ambient light, the laser light source was the only light source during the test. Then, the camera was set to auto mode with the desired frame rate. After that, the TBM was manually retracted while images were acquired by the camera before and after each movement. The test was terminated when an apparent failure rupture was observed in the sample. Finally, the images were transferred to a desired folder in the computer for further DIC analyses.

3.3. Digital image correlation

DIC is a classic pattern recognition technique, where two images are compared to obtain the relative displacement between them. The DIC has been successfully used by several researchers in their geotechnical engineering research over the last decade. The DIC is used to calculate the internal sand deformation during tunnelling in this study. The accuracy of the DIC is limited by the pixel resolution of the camera and different cross-correlation algorithms (Raffel et al., 2007). PIVview2c software is used in this study, which contains features that allow the user to select the window size, algorithm, peak function, etc. More details can be found in PIVTEC (2006). Unless specified, the following are the features used in this research: initial interrogation window size of 96 × 96 pixels, final window size of 30 × 30 pixels, step size of 15 × 15 pixels, a multi-grid interrogation algorithm, and the least square Gaussian fit (3 × 3 points) for sub-pixel estimation.

4. Test result analyses

4.1. Internal sand displacement field in traverse section

The sand displacement fields analyzed by PIVview2c are shown in Fig. 4, where C is the overburden soil cover above the tunnel crown, D is the tunnel diameter, and H is the depth from the ground surface to the tunnel axis level. Fig. 4a is a typical laser speckle image captured during the test, Fig. 4b is the soil displace-