An Internal Sand Displacement Field around a Laterally Loaded Pile

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ABSTRACT
An internal sand displacement field around a laterally loaded pile is visualized in this paper by utilizing transparent soil and an image processing technique called digital image correlation. Transparent sand is made of amorphous silica gel and a pore fluid with a matching refractive index. An optical system consisting of a laser light, a camera, a loading frame, and a computer was developed to optically slice a transparent soil model. A distinctive laser speckle pattern is generated by the interaction between the laser light and transparent soil. Two laser speckle images before and after a deformation were used to calculate the displacement field. The displacement and strain fields are similar to the one for natural sand. The results show that transparent soil can be used for more advanced non-intrusive deformation measurements in geotechnical engineering.

RÉSUMÉ
Un champ interne de déplacement de sable autour d'une pile latéralement chargée est visualisé en ce document en utilisant le sol transparent et une technique à traitement d'images appelée la corrélation d'image numérique. Le sable transparent est fait du silicagel amorphe et d'un fluide de pore avec un indice de réfraction assorti. Un système optique se composant d'une lumière laser, d'un appareil-photo, d'une armature de chargement, et d'un ordinateur a été développé pour découper optiquement un modèle transparent de sol. Un modèle de tache distinctif de laser est produit par l'interaction entre la lumière laser et le sol transparent. Deux images de tache de laser avant et après qu'une déformation aient été employées pour calculer le champ de déplacement. Les champs de déplacement et de contrainte sont semblables à celui pour le sable normal. Les résultats prouvent que le sol transparent peut être employé pour des mesures non-intrusive plus avancées de déformation dans la technologie géotechnique

1 INTRODUCTION

The pile foundations have been used widely to resist horizontal loadings in many structures. The loading capacity of a laterally loaded pile has attracted the interests of engineers for more than five decades. Many methods have been developed to analyzed the laterally loaded pile, including Broms' method (Broms 1964a, b), the elastic method(Poulos 1971a,b), and the p-y curve approach (Matlock 1970; Reese 1977), and strain wedge method (Ashour et al. 2002). However, all the methods mentioned above focus on the loading capacity and deformation of the laterally loaded pile itself. There is limited information available on soil deformation around the pile due to the non-linear behaviour of soil and the complex soil-pile interaction. Finite element method (FEM) can be used to investigate soil movement around a pile under lateral loading. However, the FEM results have not been verified due to the limited field data available.

This paper is to visualize internal sand movement around a laterally loaded pile using transparent soil and digital image correlation (DIC).

2 VISUALIZATION TECHNIQUES IN GEOTECHNICAL ENGINEERING

Visualization of internal soil displacement or strain fields can significantly improve the understanding of the geotechnical engineering problems. Many visualization techniques have been used in geotechnical engineering research for more than half a century. A picture of soil movement, which occurred at failure in clay under a loaded plate, was obtained by Bergfelt (1956) by tracking the movement of embedded lead shots using an X-ray method. A similar method was used in the 1960s and 70s to study the deformation and strain fields inside soil (Roscoe et al. 1963). However, all the investigations mentioned above are intrusive measurements. The embedded lead shots also cannot follow soil movement under excessive movement conditions. Computerized axial tomography (CAT) and magnetic resonance imaging (MRI) were utilized in geotechnical experiments. Nevertheless, routine applications of these techniques are limited by their high cost and their technical limitations including a poor resolution, a low penetration depth, etc.

Transparent materials including photoelastic material or glass have been used to model natural soil (Konagai et al. 1992; Dupre and Lagarde 1997). Their studies are limited by the fact that these materials cannot accurately model soil strength and deformation behaviour and also have a poor quality of transparency.

3 TRANSPARENT SOIL

Transparent soil used in this paper is made of amorphous silica gel with a pore fluid having the same refractive index to model clay or sand.

Mannheimer and Oswald (1993)and Iskander et al. (1994) demonstrated that transparent substances made of amorphous silica powder and a pore fluid with a matching refractive index exhibit macroscopic geotechnical properties similar to natural clay (Iskander et al. 2002a). Later a different kind of transparent soils made of silica gel was developed to model sand (Iskander et al. 2002b). Both materials have the same refractive index, which permits transparent soil in modelling the stratum conditions in the field. Transparent soil has been used to model natural soil in scaled experiments by other researchers(Welker et al. 1999; Gill and Lehane 2001; Toiya et al. 2007). Transparency of this material is shown in Fig. 1.

The matching liquid used in this research was a 50:50 blend by weight of colorless Drakeo® (item# K7041) mineral oil and a Magiesol® 47 (item# K7544) normal-paraffinic solvent supplied by Penreco (*2780 Waterfront Pkwy. E, Indianapolis, IN 46241, USA*). Silica gel used was a commercial product of Multisorb Technologies Inc. (*325 Harlem Road, Buffalo, NY 14224, USA*) without further processing. The silica gel is an angular fine silica gel with an aggregate diameter of 0.5-1.5 mm. The grain size distribution of silica gel is shown in Fig. 2. The direct shear tests are performed on loose silica gel, as shown in Fig. 3. The angle of shearing friction is 33^{o} from these tests. It was used to model loose saturated sand condition in this study.More details regarding the geotechnical properties can be found in Iskander et al.(2002b).

Fig. 1 Transparency of a transparent soil sample

4 DIGITAL IMAGE CORRELATION

The image processing technique used in this research is called digital image correlation (DIC), which is also called particle image velocimetry (PIV). It is a classic pattern recognition technique where two images are compared to obtain the relative displacement between them. DIC is widely used in many engineering fields to obtain spatial deformation patterns. In geotechnical engineering, DIC has been recently used to measure soil deformation during shear (Gudehus and Nubel 2004; Guler et al. 1999; Horii et al. 1998; Rechenmacher and Medina-Cetina 2007; White et al. 2003).

In this paper the PIVview2c software programmed by PivTec GmbH (*Stauffenbergring 21, D-37075 Göttingen, Germany*) is used to calculate the displacement field. This software has features to allow users to select the window size, cross-correlation algorithm, peak function, etc. Unless noted, the features used in this research are final window size 64 X 64 pixels, the multiple-correlation algorithm, and the multi-grid interrogation method. More details about these options can be found in PIVTEC (2006).

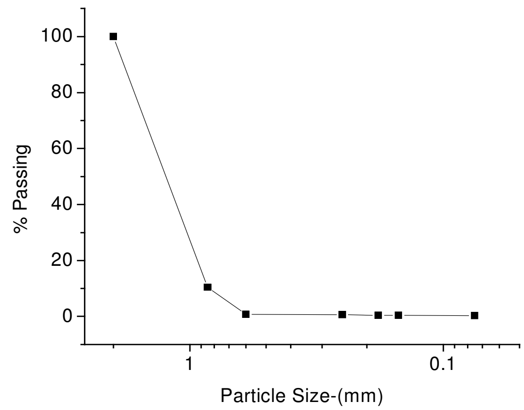


Fig. 2 Grain size distribution of used silica gel

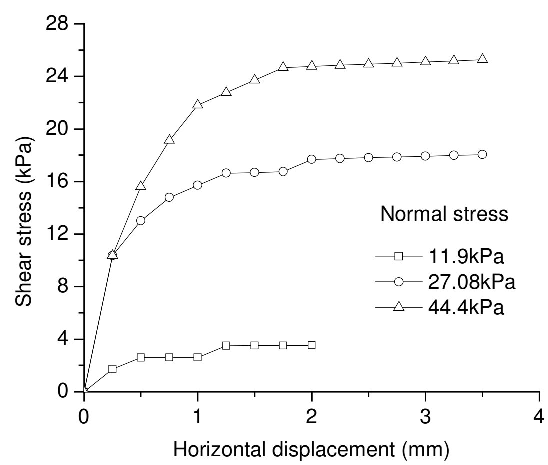


Fig. 3 Typical direct shear test results

5 AN OPTICAL SYSTEM FOR INTERNAL DEFORMATION MEASUREMENT

The optical test set-up consisted of a mono Complementary metal–oxide–semiconductor (CMOS) camera, a laser light source, a line generator lens, a loading frame, and a PC, as shown in Fig. 4. The camera is PixeLink PL-B741E model camera with a resolution of 1280 x 1024 pixels from PixeLink (*3030*

Conroy Road, Ottawa, ON K1G 6C2 Canada). It was controlled by the PC through a in-house developed software driver using Matlab Simulink commands. The laser system was model-1145AP-3340 laser with a wavelength of 632.8 nm and an output power of 35 mW from JDS Uniphase (*430 North McCarthy Boulevard, Milpitas, CA 95035 USA*)

The line generator lens from Edmund Optics (*101 E Gloucester Pike, Barrington, NJ 08007, USA*) was utilized to create a laser light sheet from the laser beam in order to slice the sample. The lateral loading arrangement consisted of a load cell (loading capacity of 100 N) attached to a linear variable differential transducer (LVDT) with a linear strike of ±25 mm. A data acquisition system was developed to acquire the loads and displacements in the anchor during uplifting, which consisted of a NI-6011E PC card and a SCB-68 shielded connector from National Instruments (*11500 N Mopac Expwy, Austin, TX 78759, USA*) and an in-house developed driver in Labview.

A Plexiglas mould with dimensions of 150 mm (wide) × 300 mm (long) × 200 mm (height) was used in the investigation. The model piles are made of acrylic. A cylindrical pile with a diameter of 12.7 mm is used in this study. The pile was embedded 160 mm deep to the bottom of transparent soil model. The pile is connected to the loading frame through a string at a loading point, which was about 30 mm above the sample height. The camera was set 15 cm above the model with its optical axis perpendicular to the horizontal plane. A built-in zoom lens in the camera is adjusted to select the right of region of interest. .

Load was applied through a screw mechanism by manually rotating a handle. The load cell and LVDT were used to measure load and deformation during the test.

6 SAMPLE PREPARATION

For the sample preparation of silica gel, first, silica gel was immersed in the pore fluid. Second, a vacuum was applied to de-air the mix until it turned transparent. Time required for applying vacuum depends on the amount of silica gel and the power of the vacuum pump. A time period of 48 hours was used in this study. Third, silica gel was packed into the Plexiglas mould to form a transparent soil sample. The mould was partially filled with pore fluid at the beginning and de-aired silica gel was slowly poured into the box. At the same time, the sample was stirred to release any air bubble entrapped during pouring. In this test, loose condition was modeled where no compaction was involved during sample preparation. Fourth, the pile was manually driven into the sample to the desired depth and the string was attached to the pile and adjusted to provide a horizontal loading to the pile.

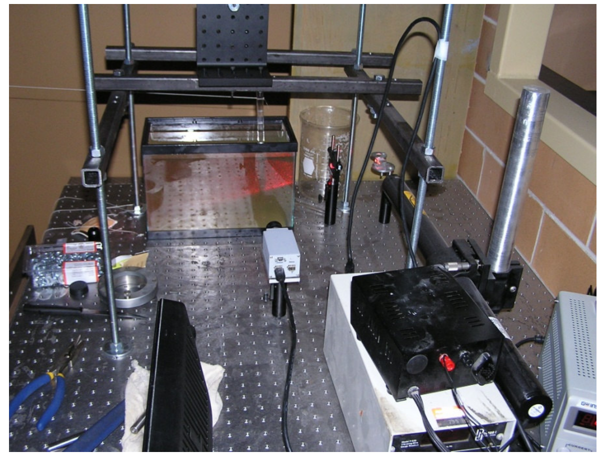


Fig. 4 The experiment setup

7 2-D INTERAL DISPLACEMENT AND STRAIN FIELDS AROUND A LATERALLY LOADED PILE

7.1 Laser Speckle Images

The laser light sheet was used to target an interested cross-section inside a transparent soil model. The interaction between the transparent soil and the laser light sheet produced a distinctive laser speckle pattern. The speckle pattern created by a coherent light beam, such as a laser, scattered from a rough surface or from particles in a liquid, has a well-defined spatial structure(Goodman 1975). The speckle properties typically depend on both the roughness and reflectance of the surface. Laser speckle techniques used in this study have been used intensively in many engineering fields, especially in surface deformation(Erf 1978).

7.2 Load vs. Displacement Curve

The load vs. displacement curve of the model pile at the loading point is shown in Fig. 5. This curve resembles the typical load vs. displacement curve for a laterally loaded pile in loose sand. The load increases linearly at the initial stage to represent the elastic behavior of soil and then the rate of load increase gradually reduces with increasing displacement due to the plastic behaviour of soil. It is worth noting that there is a fluctuation in the load after the peak of load is reached. It is believed the high compressibility of silica gel due to a two-pore system and the particle breakage under stress contribute to this phenomenon.

7.3 2-D Displacement Field

A pair of images, which were captured approximately at the peak loading stage labeled A in Fig. 5, were taken at about 20 mm inside the sample. Fig. 6a shows the first image and Fig 6b shows the second image taken before and after a small relative displacement occurred in the pile. The speckles in the images are from the interaction between the laser light and transparent soil. The soil displacement field from this relative displacement was calculated using PIVview software and shown in Fig. 7, where the image background was removed in order to show clearly the vectors.

As expected, the soil moves away from the pile during pile movement. Because the pile blocked the view behind the pile, the movement behind the pile was not detected in current configuration. The region mobilized by the pile movement is extended first from the edge of the pile with an almost straight line from horizontal line and then curved toward the middle to form a bell shape.

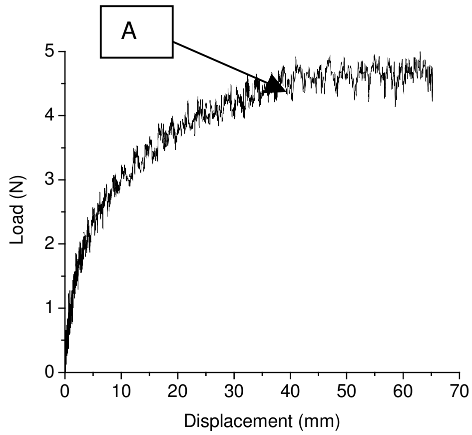
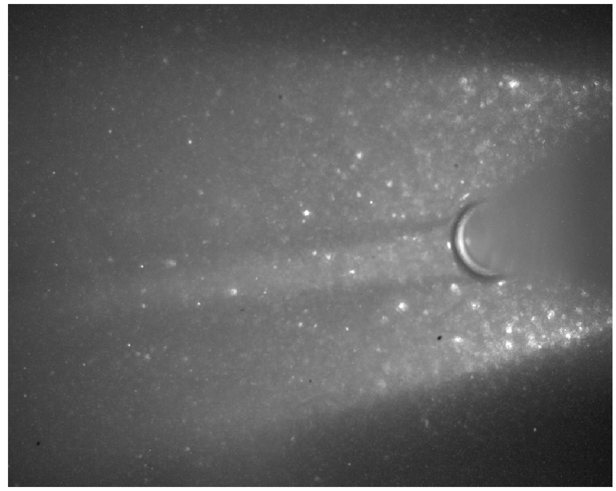


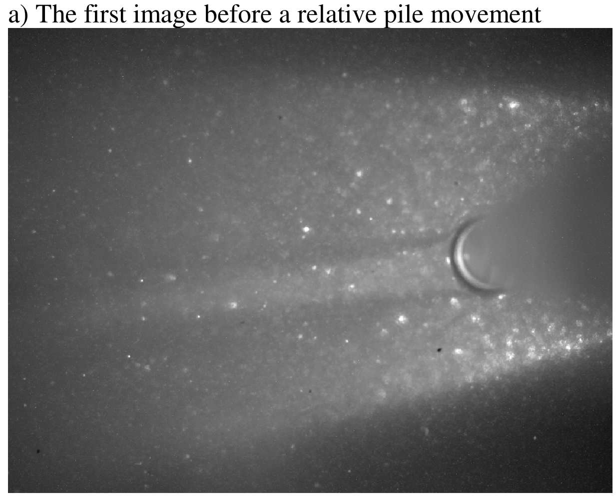
Fig. 5 The load vs. displacement curve of the laterally loaded cylindrical pile

7.4 2-D Strain Field

The strains can be deduced from the displacements. The failure plane can be identifying the maximum shear strain, since soil is normally assumed to failure due to shearing stress. Fig. 8 shows the shear strain contour of the displacement field in Fig. 7. It can be seen that the failure plan is curved outward from the pile edge, which is similar to that reported by natural soil. The straight line normally used in practice represents approximately the failure plane inside soil. The angle between the failure plane and the horizontal line drawn from the pile edge was measured at approximately 26 ^{o}, which was approximately ¾ ϕ (internal friction angle ϕ=33^{o} in this study). It is worthy noting that the extent of the failure plane cannot be clearly identified from the planar shear strain field, which can be identified from the strain field in the vertical plane. More research can be done in the future to address this issue.



a) The first image before a relative pile movement



b) The second image after a relative pile movement

Fig. 6 A pair of images with a relative displacement between them

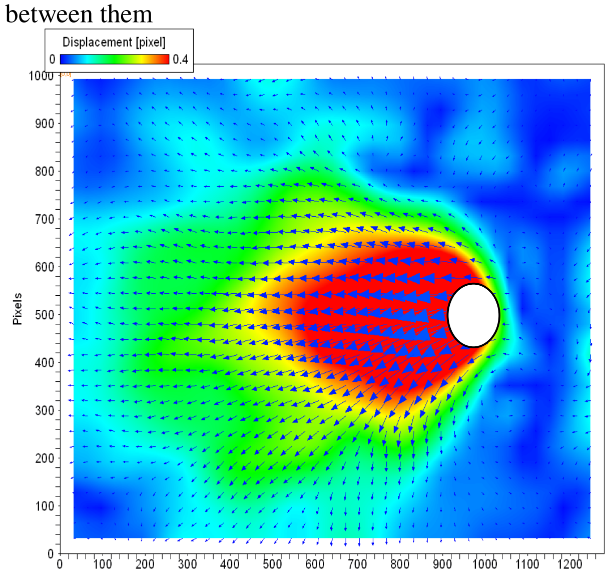


Fig. 7 The internal soil displacement field calculated from two images above

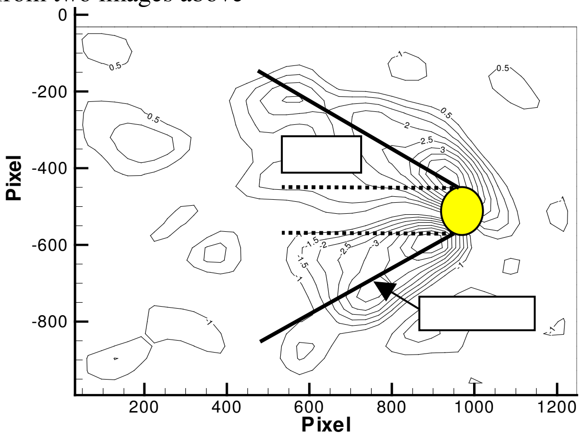


Fig. 8 Shear strain contours and potential failure plane

8 CONCLUSIONS

An internal soil displacement and strain field around a laterally loaded pile in loose sand condition is modeled in this research. Transparent sand made of amorphous silica gel and a pore fluid with a matching refractive index was used in the study. An optical system consisting of a laser light, a camera, a loading frame, and a computer was developed to optically slice a transparent soil model. The displacement from a pair of images was calculated using DIC. The failure plane in transparent soil is similar to the ones reported for natural soil. The results show that transparent soil can be used to model natural soil. Transparent soil and the developed optical system explore opportunities for more advanced non-intrusive deformation measurements for various soil-structural interaction problems.

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