Model Tests with a Transparent Soil to Observe Behavior of Buried Structures due to Neighboring Constructions

Shun-ichi KOBAYASHI
Associate Professor, Department of Science and Technology, Kanazawa University, Kanazawa, Ishikawa, Japan
Email: koba@se.kanazawa-u.ac.jp
Kohei NOGUCHI
Graduate Student, School of Natural Science and Technology, Kanazawa University, Kanazawa, Ishikawa, Japan
Yuki YAMAKURI
Student, Department of Science and Technology, Kanazawa University, Kanazawa, Ishikawa, Japan
Hidekazu MAKI
Graduate Student, School of Natural Science and Technology, Kanazawa University, Kanazawa, Ishikawa, Japan
Tatsunori MATSUMOTO
Professor, Department of Science and Technology, Kanazawa University, Kanazawa, Ishikawa, Japan

ABSTRACT

Construction works in urban areas must satisfy not only the safety of a newly constructed structure itself but also the safety of existing structures adjacent to the new one. Visual observation might be a first step to understand the interaction of a newly constructed structure and existing structures adjacent to new one, if a soil would be visible. Recently, Ezzein and Bathurst (2011) reinvented a transparent soil for laboratory modelling. This technique is fundamental and versatile for geotechnical model testing. The principle of a transparent soil is to match the refractive indices of transparent grains and pore-liquid. There have been many combinations of grain-materials and pore-liquids proposed (Ganiyu *et al*., 2016). However, though the principle is simple and straight-forward, there seems to be a plenty of know-hows which should be mastered and established to conduct laboratory model tests with transparent soils. In this article, the authors would like to present such procedural know-hows and the application of them for some demonstrative experiments.

Key words: *Transparent Soil, Refractive index matching, Neighboring construction, Buried structure*

1. Background and objectives of this study

Construction works in urban areas must satisfy not only the safety of a newly constructed structure itself but also the safety of existing structures adjacent to the new one. Construction works are always accompanied by change in stresses and deformations of a ground next to the construction site. For example, change might be caused due to the loading effect, such as installing structures with pile-driving or press-in, or due to the unloading effect, such as un-installing, excavation, drilling or tunneling. This change of the soil state sometimes induces troubles of the existing buried structures, such as piles, foundations and pipelines. Visual observation might be a first step to understand the interaction of a newly constructed structure and existing structures adjacent to new one, if a soil would be transparent and visible, but it is generally impossible.

Recently, Ezzein and Bathurst (2011) reinvented a transparent soil for laboratory modelling. This technique is fundamental and versatile for geotechnical model testing. The principle of a transparent soil is to match the refractive indices of transparent grains and pore-liquid. There have been many combinations of grain-materials and pore-liquids proposed (Ganiyu *et al*., 2016). However, though the principle is simple and straight-forward, there seems to be a plenty of know-hows which should be

Table 1. Properties of silica particles

Diameter	0.2 – 1.0 [mm]
Density	2.20 [g/cm^3]
Max. void ratio	1.380
Min. void ratio	0.873
Slope of the CSL	M = 1.873
Refraction index	n = 1.4585 (24.7°C)

mastered and established to conduct laboratory model tests with transparent soils.

2. Transparent model ground

2.1. Index matching method

In general, two type of the change in direction of light occur on the boundary of two different media. One is reflection and the other is refraction. However, if the refraction index of two materials is same, no reflection and refraction occur.

This nature directly stands for the possibility of visualization inside the granular media, if a suitable combination of transparent solid particles and saturated pore liquid is selected. Early attempts of this technique for visualization experiments are summarized in the literature by Ezzein and Bathurst (2011).

After the intensive quest of a suitable combination of materials which possesses a similar mechanical properties of sands, Ezzein and Bathurst also proposed the use of fused silica as solid transparent particles and mineral oil as fill liquid.

2.2. Materials for transparent model ground

In this study, transparent silica particles are used as transparent particles, because they can be purchased easily in Japan. Physical properties of the transparent silica particles are summarized in **Table 1**. CD triaxial tests are carried out with three densely compacted samples of silica particle deposits saturated with water. Consolidation pressures and relative densities of these samples at the start of shearing are (50 [kPa] : Dr = 90.3 [%]), (100 [kPa] : Dr = 102.0 [%]) and (200 [kPa] : Dr = 85.2 [%]), respectively. Relations of axial strains and deviatoric stress q, relations of axial strains and volumetric strains (Positive in dilation) and effective stress paths are shown in **Figs. 1**, **2** and **3**, respectively.

On the contrary, there are some feasible options for

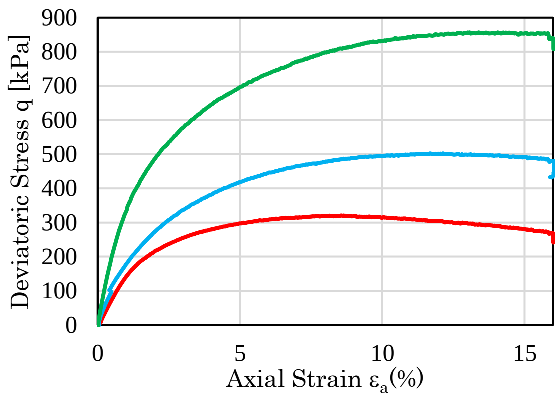


Fig. 1 Axial strain vs deviatoric stress (CD test)

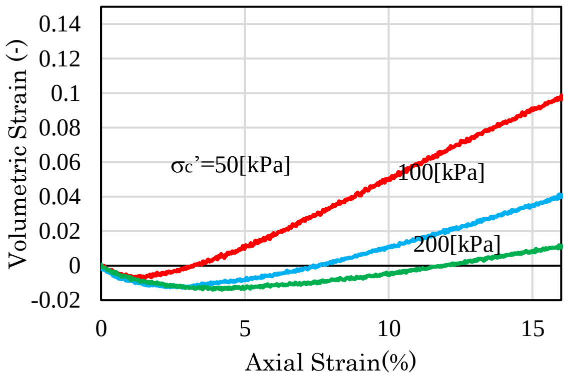


Fig. 2 Axial strain vs volumetric strain (CD test)

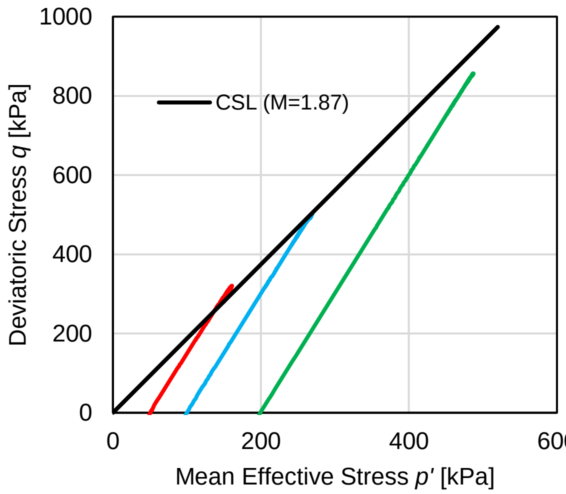


Fig. 3 Effective stress path (CD test)

pore fluids. Such fluids can be divided into two groups: oily fluid and aqueous solution.

In the oily fluid group, mineral oil refined from petroleum is cheap and easily handled. Several industrial products are available in Japan. Density, viscosity and refraction index are inter-dependent each other, and refraction index of a mixture of two mineral oils can be approximated by a linear relation of weight fraction. Mixture of "Moresco White P-40" (n = 1.4469, at 20.9

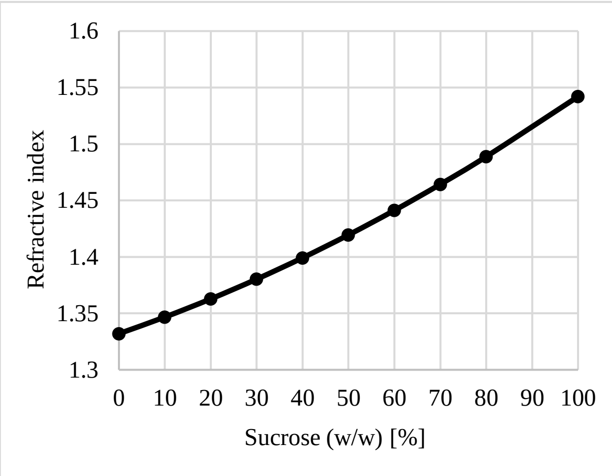


Fig. 4 Refractive index of Sucrose solution (20 Deg. C)

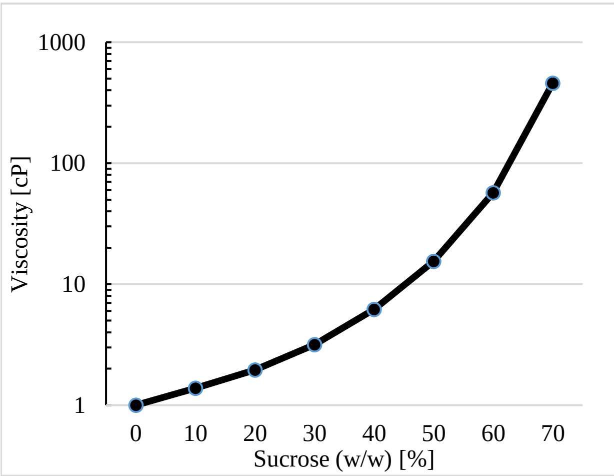


Fig. 5 Viscosity of Sucrose solution (20 Deg. C)

Deg. C, Viscosity 3.6 [cP]: Moresco Corp.) and "Cosmo White P-60" (n = 1.4540 , 21.1 Deg. C, Viscosity 7.9 [cP] : COSMO Oil Lubricants Co., Ltd.) with the weight fraction 1: 16 is used in this study. Silicon oils can be used as alternative, such as, "KF-96-10cs" (n = 1.4002 , 25 Deg. C, Viscosity 9.35 [cP] at 25 Deg. C :Shin-Etsu Chemical Co., Ltd.) and "KF-56" (n = 1.5011, 25 Deg. C, Viscosity 14.9 [cP] at 25 Deg. C: Shin-Etsu Chemical Co., Ltd.). Silicon oils are chemically synthesized and have larger variety of refraction index than mineral soils, but silicon oils are more expensive in general.

In the aqueous solution group, sucrose (roughly speaking, sugar) solution is cheap and feasible. In addition, aqueous solutions are far better than oily liquids because they are easy to handle for cleaning of testing devices and reuse/disposal of samples and to keep the laboratory environment clean.

However, it should be carefully handled, because very dense sucrose solution (67.1 % w/w) should be used to match the refractive index of silica particles (n = 1.4585) as shown in **Fig. 4**. In addition, such dense sucrose solution is highly viscous as shown in Fig. 5. Once air bubbles are trapped into a viscous liquid, it is almost impossible to remove them. A countermeasure to avoid air bubbles and to make fully saturated transparent model ground with sucrose solution are described later.

2.3. How to make a model ground

Model ground should be completely saturated with pore fluid to avoid any refraction and reflection in a specimen.

In case of mineral oil, viscosity is a little bit higher than that of water. So, liquid pluviation technique can be applied to make a model ground.

On the contrary, in case of sucrose solution, liquid is too viscous to use liquid pluviation technique, because entrapped tiny air bubbles don't disappear. Therefore, a liquid replacement method as mentioned below is proposed to make saturated model ground with sucrose solution.

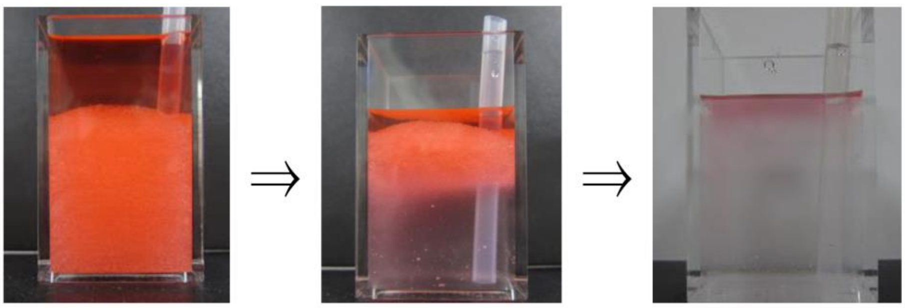


Photo 1. Preparation procedure of a transparent model ground saturated with sucrose solution (Container size: w=45mm, D=55mm, H=88mm)

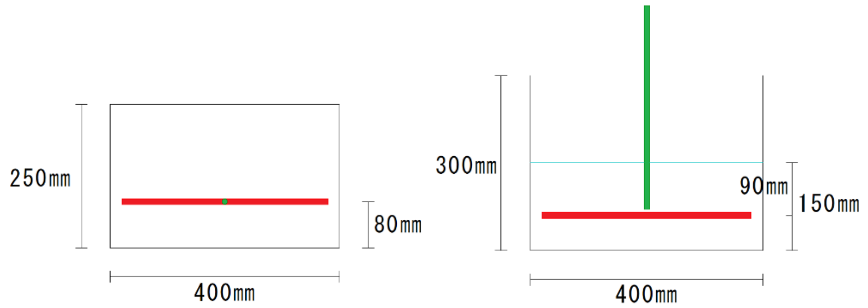


Fig. 6 Plan (Left) and section (Right) views of the testing box, the embedded pipe (Red) and the installed pile (Green)

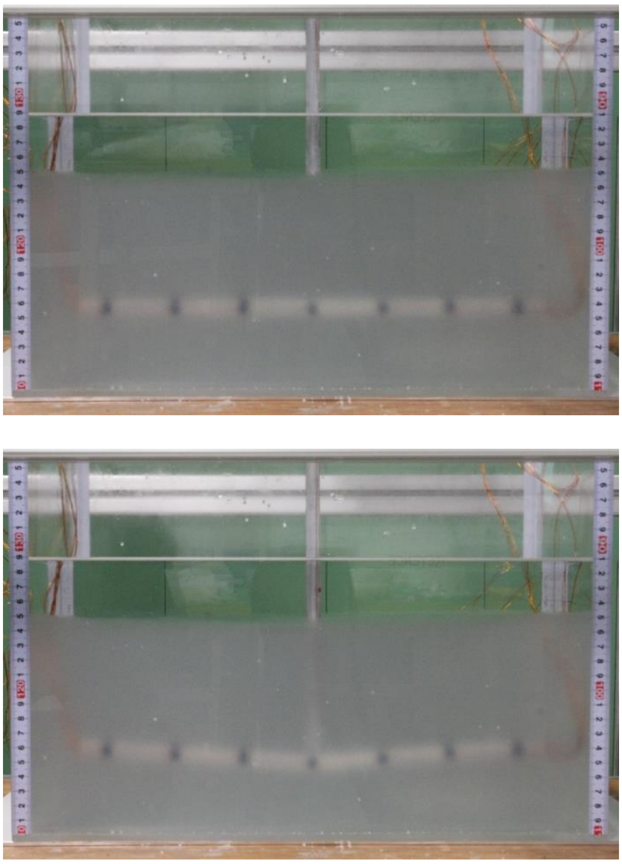


Photo 2. Deformation of the embedded pile observed through the transparent model ground. Before pile installation (Top) and after 90 mm-pile installation (Bottom)

A liquid replacement method consists of two steps. Firstly, a model ground is saturated with water by liquid pluviation technique. Secondly, heavy sucrose solution is slowly injected from the bottom of a container to make upward permeable flow and replace water with sucrose solution. During the second stage, sucrose solution was warmed to about 60 degrees Celsius to lower the viscosity and to shorten a preparation period. **Photo. 1.** illustrates the above mentioned preparation procedure of a transparent model ground saturated with sucrose solution. Water is dyed with red-coloring to monitor the replacement process easier.

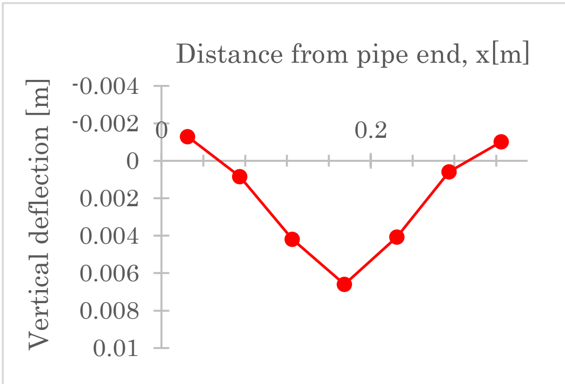


Fig. 7 Deflection distribution of the embedded pipe estimated by image analysis

3. Demonstrative experiments

3.1. Behavior of an embedded pipe subject to pile installation in a near field

In this series of tests, behavior of a horizontally embedded pipe subjected to pile installation in a near field is observed. The embedded pipe is made of ABS (Acrylonitrile Butadiene Styrene) with length of 350 mm, outer diameter of 10.0 mm, thickness of 2 mm and bending stiffness $EI = 1.02 \times 10^6 [N \cdot mm^2]$. 7 pairs of strain gauges attached to the pipe to measure the bending moment. A model ground is a mixture of silica particles and mineral oil prepared by liquid pluviation and compacted to around $Dr = 80[\%]$. A close-ended aluminum pipe pile with outer diameter 10 mm, thickness 1mm and Young's modulus $E = 59.0[GPa]$ is vertically installed.

One demonstrative case is shown here. Plan and

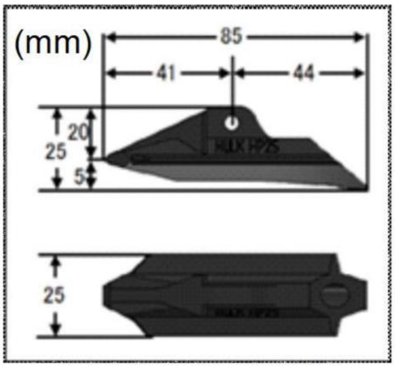


Fig. 8 Anchor head

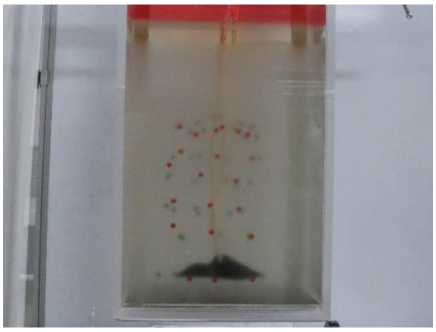


Photo 3. Embedded anchor head before pull-out

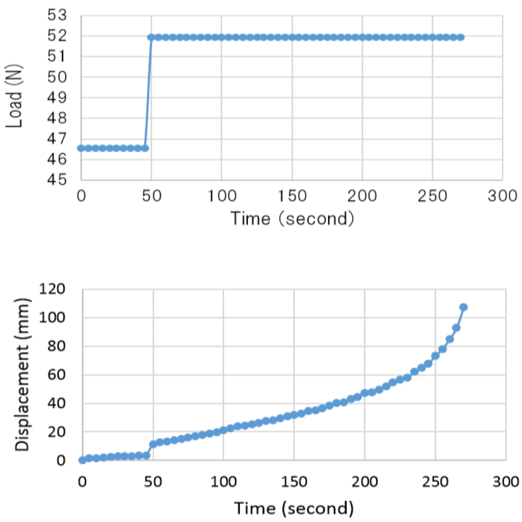
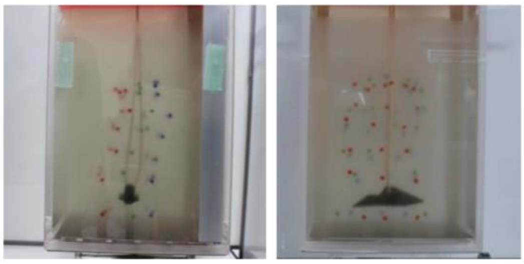
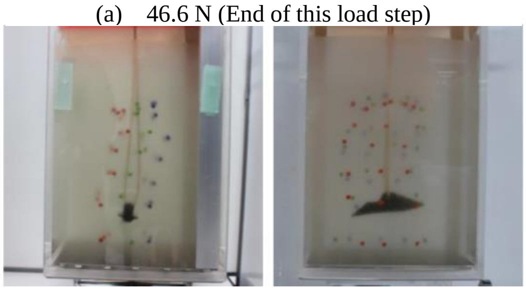


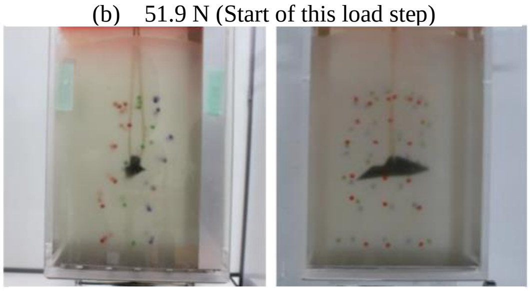
Fig. 9 Time-Anchor Load, Displacement relations



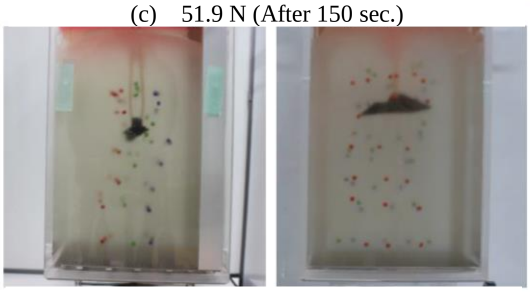
(a) 46.6 N (End of this load step)



(b) 51.9 N (Start of this load step)



(c) 51.9 N (After 150 sec.)



(d) 51.9 N (After 180 sec.)

Photo 4. Anchor failure observed from both sides; (a) End of 46.6N load step, (b) Start of 51.9 N load step, (c) After 150 sec., (d) After 180 sec.

sectional views of a testing box, an embedded pipe and a vertically installed pile are illustrated in **Fig. 6**. The embedded pipe is horizontally placed at the depth of 90 mm from the surface. Boundary conditions of the Both ends of the pipe are free. Deformation of the embedded pipe can be observed through the transparent model ground as shown in **Photo. 2**. Transparent thickness from the side wall to the embedded pile is about 80 mm. Deflection distribution of the embedded pile after the pile installation is shown in **Fig. 7**. It should be noted that a rigid motion of the embedded pipe cannot be estimated by strain distributions measured with strain gauges. In this sense, the use of a transparent model ground crucial to understand the behavior of the embedded pipe.

3.2. Behavior of an embedded anchor head subject to pull-out

In this series of tests, behavior of an embedded flip-type anchor head subject to pull-out at a constant load is observed. A dimension of a testing box is w=200 mm,

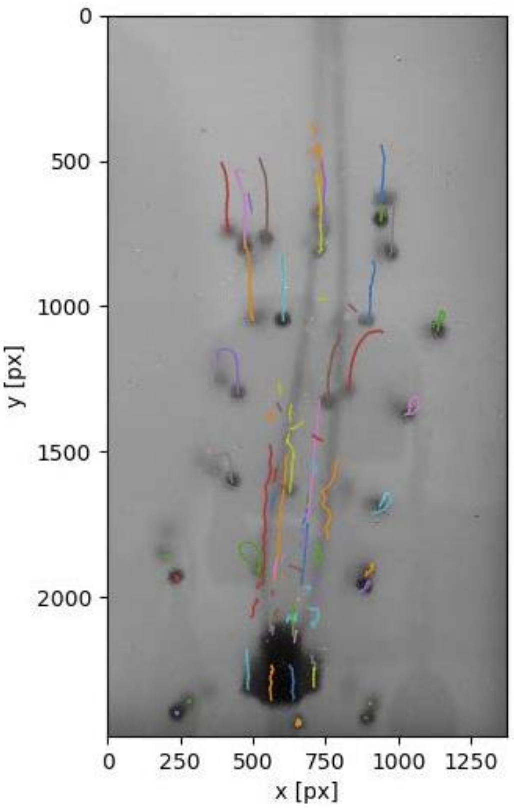


Photo 5. Trajectory of feature points during the experiment

d=200mm and h=400mm. A model ground is a mixture of silica particles and sucrose solution with height of about 250mm. An anchor head made of hard synthetic resin plastic as shown in **Fig. 8**. This anchor head is horizontally placed in the transparent model ground at the depth of 217 mm from the surface as shown in **Photo. 3**. The anchor head is subject to constant pull-out loads step by step. Creep-like behavior is observed just before the pull-out failure as shown in **Fig. 9**. Photos of anchor movement from both sides of the testing box are summarized in **Photo. 4**. Trajectory of feature points using tracking software “Trackpy” is shown in **Photo. 5**. This tracking result is preliminary because real 3D movement is not correctly evaluated. However, the movement of the anchor can be clearly detected.

4. Concluding remarks

In this article, a transparent soil based on the refractive index matching technique and its application to geotechnical model testing are presented and briefly discussed. There are various combinations of solid transparent particles and pore fluids to make a transparent soil. Among them, combinations of transparent silica particles and mineral oil / sucrose solution are used in this study. As the laboratory environment, re-use and disposal of testing materials are concerned, an aqueous solution might be better than oily fluids. However, if such an aqueous solution with high viscosity is used for index matching, special attention should be paid for complete saturation of a model ground. To tackle this difficulty, the authors propose a liquid replacement method. Some experimental applications to investigate the interactions of buried structures/objects and surrounding soils are also presented to demonstrate the advantage of a transparent soil.

5. Acknowledgements

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Trackpy: Fast, Flexible Particle-Tracking Toolkit, URL https://soft-matter.github.io/trackpy/v0.3.2 [Accessed: 15- March- 2018]