EXPERIMENTAL OBSERVATION AND DIRECT SIMULATION OF PARTICLE-FLUID SYSTEM

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ABSTRACT
Mechanical behavior of particle-fluid system is extensively studied in various engineering fields such as geotechnical engineering, mechanical engineering, and powder technology. Although observation of complicated behavior including interaction between particle and pore fluid is essential, few efficient techniques are available for this purpose. From this point of view, an observation technique based on LAT (Laser-Aided Tomography) and PIV (Particle Image Velocimetry) was developed. A numerical analysis method based on SPH (Smoothed Particle Hydrodynamics) is also proposed for simulating the behavior of particle-fluid system.

Keywords: LAT (Laser-Aided Tomography), PIV (Particle Image Velocimetry), SPH (Smoothed Particle Hydrodynamics)

INTRODUCTION
Mechanical behavior of particle-fluid system is widely related to various engineering problems. In the field of geotechnical engineering, boiling, piping, and liquefaction are categorized as phenomena of this system. It is substantially difficult to observe the internal behavior of such phenomena, and few visualization techniques are applicable. One of well-known ways is to use X-ray technique [1] which envisages the inside of particle-fluid system detecting the differences in material density. Although the X-ray technique is applicable to identify actual materials, i.e. sand particles and pore water, it cannot visualize the flow of pore water because of the homogeneity of its density. Thus a new technique combining LAT (Laser-Aided Tomography) [2][3] and PIV (Particle Image Velocimetry) [5] was developed for visualizing both movement of particles and fluid flow: LAT for 3-D movement of each particle, and PIV for velocity field of fluid. One disadvantage of this method is that not actual geomaterials but crushed glass is to be used as particulate media. The method, however, directly treats digitized images, which enables us to obtain higher resolution in the future with the progress in digital technology.

For simulating the behavior of particle-fluid system, an averaging concept such that based on Darcy’s law is often employed to describe fluid motion. Recently, direct simulation methods for the particle-fluid interaction have been developed in the scheme of FEM [6] and Lattice-Boltzmann Method [7]. This study also aims to develop a simulation method for the system using Smoothed Particle Hydrodynamics (SPH) [8]. SPH, a kind of meshless analysis method, has an advantage of avoiding mesh-discretization and re-meshing process. This method is also expected to yield good simulation because it deals with Navier-Stokes equation.

VISUALIZATION TECHNIQUE AND MEASURING SYSTEM
Figure 1 shows a schematic illustration of the observation system. LAT, a kind of laser-slicing method, visualizes each particle motion including rotation inside a 3-D specimen composed of crushed glass and pore fluid.

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which are of the same refractive index. PIV, also a kind of laser-slicing method, visualizes fluid motion by means of pursuing a pattern created by tracing powder mixed into the fluid. Simultaneous application of LAT to particle part and PIV to fluid part enables us to observe the interaction of particle-fluid system. A measuring system is newly developed to acquire digital images. The system consisting of a CCD camera (1 million pixels, 30 fps) and a PC (2GB RAM) is able to take photograph for about 30 seconds with 30 fps, which is almost the same performance as that of a conventional digital image processor.

EXPERIMENTAL SETUP

Figure 2 shows the setup of a test specimen. An acrylic anchor was embedded in an assembly of crushed glass grains packed in an acrylic cubic container and inundated with silicone oil. Fine nylon powder which is commonly used in PIV technique was mixed in the oil as a tracer. Table 1 lists the physical properties of the materials. In order to observe the behavior of whole specimen and the local behavior near the anchor base, a couple of tests were performed and photographed by the CCD camera with different magnifying power: Case 1 with 0.130 mm/pixel and Case 2 with 0.049 mm/pixel. Figures 3 and 4 show the initial configuration of specimens in Case 1 and Case 2, respectively. In both of the tests the anchor was pulled up at a constant rate of 0.75 mm/s.

FIG. 1. Brief overview of experimental setup

FIG. 2. Diagram of specimen

FIG. 3. Initial state of case1 (752 × 480 pixels)

FIG. 4. Initial state of case2 (800 × 800 pixels)
### TABLE 1. Material parameters

<table>
<thead>
<tr>
<th></th>
<th>Acrylic anchor</th>
<th>Silicone oil</th>
<th>Glass grain</th>
<th>Tracing powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.20 g/cm³</td>
<td>1.02 g/cm³</td>
<td>2.52 g/cm³</td>
<td>1.02 g/cm³</td>
</tr>
<tr>
<td>Diameter</td>
<td>-</td>
<td>-</td>
<td>2mm−5mm</td>
<td>40µm</td>
</tr>
<tr>
<td>Viscosity</td>
<td>-</td>
<td>20.6 mm²/s</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.490</td>
<td>1.514</td>
<td>1.514</td>
<td>-</td>
</tr>
</tbody>
</table>

**RESULT OF EXPERIMENTS**

By verifying the movie of experiments, it was possible to observe not only the glass grains motion including rotation but also the pore fluid motion. Then a digital image processing based on a pattern matching technique was applied to obtain quantitative velocity field. In order to decide the movement automatically, a cross-correlation value between two successive photographs are calculated so that the positions of the destination may have the maximum cross-correlation value. Figure 5 and Figure 6 illustrate a series of velocity fields of Case 1 and Case 2 with photographs at the same moment during the pull-up of anchor. Values of contour box in these figures show the norm of velocity vector normalized by the anchor speed of 0.75mm/s. The sample pattern size is 31 pixels (4.03mm) square for Case1, and 29 pixels (1.42mm) for Case 2. The interval of photographs is 0.167 seconds for Case 1, and 0.10 seconds for Case 2, respectively.

Figure 5 (a’) shows an earlier stage of the experiment. A small cavity appears just below the anchor bottom and the fluid in the cavity keeps to the anchor. The grains above the anchor board rise with almost the same speed of the anchor. This tendency is observed throughout the experiment. Figure 5 (b’) indicates a radiational movement of the fluid in the cavity below the anchor bottom, which is explained by the projection of the fluid velocity perpendicular to the laser sheet caused by a glass grain dropping. However, it is difficult to reconstruct the fluid velocity in the perpendicular direction only from in-plane velocity information. In order to comprehend the three dimensional behavior including out-of-laser sheet behavior, other means such as Stereo PIV are needed. Figure 5 (c’) delineates tumbles of glass grains at the upper left of the anchor board and the blinking flow in the cavity. Through the validation of the photographs which are used to construct Figure 5 (c’), the occurrence of tumbles can be explained as follows: since the pattern matching operation is effective for the pattern made by edges of glass grains, it is exploitable to obtain the displacement field if the photograph is shot with a magnification power of the same order as that used in Case 1.

Figure 6 (a’) also represents the velocity field at a very early stage of Case 2. At this stage, not only wrap-around of the pore fluid but also updrawing of the pore fluid below the anchor bottom is observed. Since the motion of glass grains is not observed below the anchor bottom, the velocity field detected below the anchor bottom may indicate only pore fluid movement. However, the phenomena of pore fluid updrawing are also observed in other regions. The intensity of updrawing abates steadily with the anchor rising and essentially vanishes after 8.4 seconds. At this stage, the glass grains start to drop into the cavity. Figure 6 (b’) demonstrates the droppings of glass grains on both sides which occur coincidentally. Figure 6 (c’), however, only shows the dropping on the left side. The flow caused by the dropping in the cavity is quantified with a vivid clarity. On the contrary, the movement of glass grains is smudged, which may be due to a kind of size effect: the sample pattern size (1.42mm) is smaller compared with the grain diameter (2−5mm). Some other means are required to detect the motion of glass grains precisely.

At present it is still difficult to obtain clear images of grains and fluid at the same time; the mix of grain and fluid in the same photograph prevents easy handling in terms of an automatic quantization. It may be possible to designate a certain fluid region manually by GUI (Graphical User Interface), but this is too laborious. The prospect of the digital image processing of particle-fluid system depends on how to separate images of pore liquid from particles.
FIG. 5. Results of Case 1
FIG. 6. Results of Case 2
NUMERICAL APPROACH FOR PARTICLE-FLUID SYSTEM

To develop a suitable numerical method for the above-mentioned high-density particle-fluid system, a preliminary analysis was carried out by using the SPH method. The SPH, a kind of meshless Lagrangian method, treats the fluid as an assembly of particles. In this method, the standard equation for estimating a physical quantity \( A \) at position \( r \) is represented by weighted superposition of physical quantity defined at neighboring particles position as follows:

\[
A(r) = \int A(r')W(r - r', h)dr' \approx \sum_b m_b \frac{A_b}{\rho_b} W(r - r_b, h)
\]

(1)

where the value of \( A \) for a neighboring particle \( b \) at position \( r_b \) is denoted by \( A_b \). Notations \( m_b \) and \( \rho_b \) indicate mass and density of particle \( b \) at position \( r_b \), respectively.

\( W \) is an arbitrary weighting function called "kernel function" which has a smooth and continuous first derivative and is smooth and continuous itself. Usually the second derivative is also smooth and continuous. Parameters of the kernel function are the distance between position \( r \) and position \( r_b \) and the scaling variable \( h \). The kernel function also has a restriction for normalization, then weighting function \( W \) should satisfy the following equation:

\[
\int W(r - r', h)dr = 1
\]

(2)

The smoothing formalism also provides a mean to determine gradient of a physical quantity \( A \). The gradient of a physical quantity \( A \) at position \( r \) is described by

\[
\nabla A(r) = \int A(r')\nabla W(r - r', h)dr' \approx \sum_b m_b \frac{A_b}{\rho_b} \nabla W(r - r_b, h)
\]

(3)

In this way, the SPH representation of the hydrodynamic governing equations (i.e. Navier-Stokes equations) is empowered. The Gaussian function or the spherically symmetric \( \beta \)-spline function is often used as the kernel function, and the later function given by the following equation is employed in this study.

\[
W(r, h) = \frac{\sigma}{h^d} \left\{ \begin{array}{ll}
1 - \frac{3}{2}s^2 + \frac{3}{4}s^3 & 0 \leq s \leq 1 \\
\frac{1}{4}(2 - s)^3 & 1 \leq s \leq 2 \\
0 & s \geq 2
\end{array} \right.
\]

(4)

where \( r \) is the distance, and \( s \) equals to \( r/h \), \( \nu \) is the dimensional number, and \( \sigma \) is a normalization constant with the values of \( \frac{2}{3}, \frac{10}{7\pi}, \) and \( \frac{1}{\pi} \), in one, two, and three dimensions, respectively.

In the SPH, the conservation law of mass is satisfied implicitly. The SPH requires ternary processes, i.e. calculation of the density for each particle, evolution for the equation of motion, and calculation of the state equation. The density is given by

\[
\rho_a = \sum_b m_b W_{ab}
\]

(5)

where the index \( a \) represents the focused particle and the index \( b \) denotes a nearby particle. \( W_{ab} \) is the kernel value between particle \( a \) and particle \( b \). The equation of motion is expressed as:

\[
\frac{dv_a}{dt} = f - \sum_b m_b \left( \frac{P_a}{\rho_a^2} + \frac{P_b}{\rho_b^2} \right) \nabla_a W_{ab} + \sum_b \frac{m_b(\mu_a + \mu_b)r_{ab} \cdot \nabla_a W_{ab}}{\rho_a \rho_b (r_{ab}^2 + 0.01h^2)} v_{ab}
\]

(6)

where \( \mu = \rho \nu \) is the dynamic viscosity. \( P \) denotes pressure defined on the particle position and \( r_{ab} \equiv r_a - r_b \), \( v_{ab} \equiv v_a - v_b \). The state equation is given by

\[
P_a = c^2(\rho_a - \rho_0)
\]

(7)

where \( \rho_0 \) is the reference density and \( c \) denotes the coefficient constant.
SIMULATION OF FLOW PASSING CYLINDERS

Simulations of flow passing cylinders were performed as simple preliminary analyses for the particle-fluid system. Figure 7 shows schematic diagrams of two models. Model 1 has a fixed solid cylinder and Model 2 has five fixed solid cylinders in the middle of domain. Each cylinder is expressed by an assembly of the fluid particles. The vertical and horizontal boundaries of these models are periodic ones. Both of the models are wholly saturated with 2500 fluid particles which are subjected to the body force (0.01 m/s$^2$) as a driving force, and have no velocity in the initial configuration. The density and dynamic viscosity of the fluid were defined as 800 kg/m$^3$ and 1.0 Pa·s, respectively.

![Schematic diagrams of Model 1 and Model 2](image)

FIG. 7. Schematic diagrams of Model 1 and Model 2

RESULT OF SIMULATIONS

Figure 8 shows the results obtained after 12 seconds from the beginning of the simulation for Model 1 and Model 2. Figure 8 (a) and (a’) represent the configurations of the fluid particles in Model 1 and Model 2, respectively. As shown in the disturbance pattern in terms of particle configuration, Model 2 is more charged compared with Model 1, which may result from the effects of analysis boundary and neighboring cylinders. Wrap-around motion of the fluid particles is observed at each stagnation point in both models. Figure 8 (b) and (b’) shows the velocity field of Model 1 and Model 2, respectively, using color contours. The effect of periodic boundary scarcely recognized in Model 1, meanwhile Model 2 indicates the periodic nature explicitly. Figure 8 (c) and (c’) show the pressure field in terms of color contour. Model 1 shows the symmetric pressure distribution between upstream and downstream regions. In Model 2, however, the pressure in upstream region becomes high due to a kind of choke caused by the neighboring cylinders effect.

The SPH is an adaptable numerical method for expressing fluid behavior as described above, and the coding is rather easy. However, it is still difficult to treat the interaction between solid and fluid due to the occurrence of penetration on solid surface. There are some suggestions to solve this problems, but each has both advantages and disadvantages. Further investigation on the treatment of boundaries based on physical low will make SPH more powerful in analysing particle-fluid systems.
FIG. 8. Result of simulations
CONCLUSIONS
A new visualization technique based on LAT and PIV was developed and applied to experiments of particle-fluid system. The technique is distinguished by its ability to visualize particle motion and pore fluid motion simultaneously. However, it still needs resourceful image processing technique and a contrivance for separation of pore fluid from particle to attain quantitative data of high accuracy. To investigate the applicability of the SPH for the particle-fluid system, simple preliminary calculations were also performed and proved to be effective for analyses of a particle-fluid system with complicated configuration. However there remains a handling problem of particle-fluid boundary which is to be solved on the basis of physical law.

REFERENCES