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LASER-AIDED TOMOGRAPHY: A TOOL FOR VISUALIZATION OF CHANGES IN THE FABRIC OF GRANULAR ASSEMBLAGE

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A new experimental technique to visualize the dynamic behavior of particle assemblage is developed. According to the proposed method, a granular structure model, made of particles of crushed glass and immersed in liquid with the same refractive index, consequently becomes invisible. An intense laser-light "sheet" (LLS) is then passed through it, illuminating the contour lines of all the particles within a cross-section. Scanning the model with LLS allows a 3D image of every discrete particle's shape and motion to be obtained as well as the whole-field deformation of the model.

***Keywords** : visualization, dynamic behavior, granular structure.*

1. INTRODUCTION

Model experiments are a common and powerful tool for the study of the dynamic behavior and stability of such granular underwater structures as rockfill dams, artificial islands made of gravel and sand, the masonry foundations of offshore and near-shore structures and so on. Though they provide us with important findings about the dynamic failure mechanism through sensors placed within a three-dimensional model, it is not easy to get a clear whole-field image of the deformation, because the discrete particles that make up those structures are not strongly bonded, and thus, never behave like a continuous medium.

Visualization techniques help to overcome this problem and there are several methods available at present. These include the "x-ray technique" and the "immersion method". The former is a technique to take x-ray photographs of a soil model within which lead bullets are buried as targets[1]. According to this method, not only the bullets but also a change of density in the model material can be visualized through x-rays. Thus, it is possible to observe vague shade associated with dilatation and shear band formation. Since this technique yields only two-dimensional information, photographs taken from different angles are necessary in order to obtain three-dimensional deformation images. As this process is tedious, a computer is often utilized as an aid to analyze the graphic data (Computed Tomography).

The "immersion method" is another powerful technique. According to this method, a model made of glass particles is immersed in a liquid with the same refractive index, thus becoming transparent. Opaque or colored particles are placed in the model and serve as markers. The motion of the markers is observed. The "immersion technique", originally and independently developed by Wakabayashi, T.[4], and by Dantu P.[5] in the first half of 1950's, is well-known in the field of photo-elasticity and many researchers such as Allersma, H.G.B.[2], Ura T.,[3] have used and improved it since then.

Though these methods are useful in observing the whole-field of a model, they provide only two-dimensional stress information or the motion of the markers, which is usually not enough to define the changes in the particle assemblage perfectly.

Konagai and Tamura have developed a new

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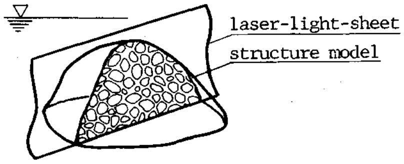

Fig.1 Visualization method.

Table.I Properties of turpentine & tetralin oils.

Property	Turpentine Oil	Tetralin Oil
Boiling Point	153 ~ 175°C	207.6°C
Specific Gravity (0 ~ 40°C)	0.815 ~ 0.850	0.960 ~ 0.996
Refractive Index (514.5nm)	1.481 ~ 1.491	1.546 ~ 1.557
Coefficient of Viscosity	1.257 cps (25°C)	2.020 cps (25°C) 1.300 cps (50°C)
Surface Tension	――――	36.30dyn/cm(13.3°C) 33.63dyn/cm(36.7°C)
Specific Heat	0.453 cal/g.deg	0.403 cal/g.deg

experimental method; Laser-Aided Tomography (LAT), which enables the visualization of all particles interlocking one another in a three-dimensional model[6),7),8)]. The first half of this paper describes in detail the proposed method and its application with reducing the grain size. The latter half describes some findings on the failure process of embankment-shaped models made in the course of performed LAT experiments.

2. PROPOSED METHOD

According to the proposed method, particles of crushed optical glass are heaped in a water tank full of liquid. Consequently, the model becomes invisible because the liquid's refractive index has been tuned to that of the glass material. An intense laser-light "sheet" (LLS) which is then passed through the model illuminates the contours of all particles within the "cut" cross-section because the chemically active fracture surfaces of the grains change their optical properties slightly in comparison to their pre-crushing state (**Fig.1**).

The liquid should fulfill some basic requirements in order to be used in the experiments. It should be: (1) colorless; (2) transparent; (3) of low volatility and (4) of low viscosity, i.e. it is eligible for dynamic experiments where a large Reynold's number is required.

The authors used a mixture of turpentine and tetralin oils. **Table I** provides information about some index properties of the two solvents. Since the refractive index of the optical glass (BK-7) used in our experiment lies within the range formed by the two solvents' indices, it is possible to tune the refractive index of the mixture to that of glass. The refractive index of the mixture is governed by the Clausius-Mosotti's formula:

$$\frac{1}{\rho}\frac{n^2-1}{n^2+2} = \frac{1-c}{\rho_1}\frac{n_1^2-1}{n_1^2+2} + \frac{c}{\rho_2}\frac{n_2^2-1}{n_2^2+2} \qquad (1)$$

where

n, ρ = refractive index and density of the mixture,
n_1, ρ_1= refractive index and density of turpentine oil,
n_2, ρ_2= refractive index and density of tetralin oil,
c = percentage of tetralin content.

The refractive index can also be tuned by altering the liquid's temperature because both density and refractive index vary with temperature as shown in **Figs. 2** and **3**. The average rate of change of the refractive index with respect to temperature in the interval from 20°C to 30°C is about -0.00028/deg for green laser light (wavelength = 514.5 nm). Thus, the simplest way to fine-tune the refractive index is with temperature control. However, this process leads to volatilization of pinene oil which is the major ingredient of turpentine oil. Thus, turpentine oil must be added occasionally to the mixture.

As already mentioned above, the refractive index of the glass should lie between those of the two solvents. There are many kinds of glass commercially available. Among the optical glasses, BK-7 is one of the most inexpensive. Its refractive index is 1.5194 for monochromatic laser light with a wavelength of 514.5 nm. Strip blocks of the glass were broken into particles by a jaw-crusher. Two kinds of marks are seen on the grains' fracture surface; "rib marks" and "hackle marks"[9)]. Dense curved lines running in the transverse

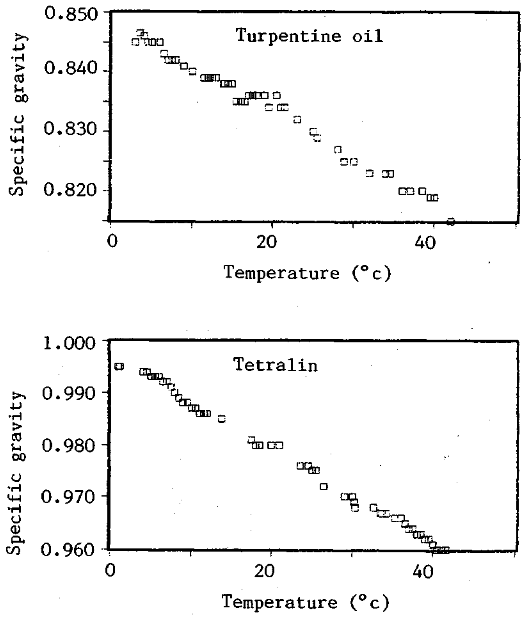

Fig.2 Variation of specific gravity of solvents with temperature.

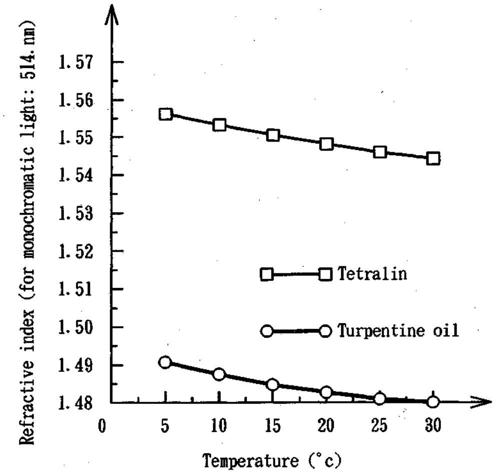

Fig.3 Variation of refractive index of solvents with temperature.

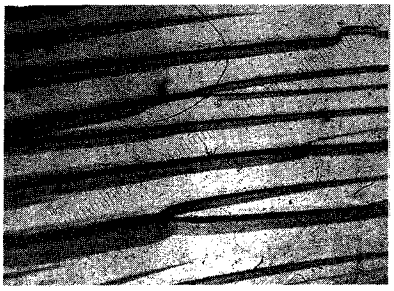

Fig.4 Hackle Marks on a surface of BK-7 (Magnification:100).

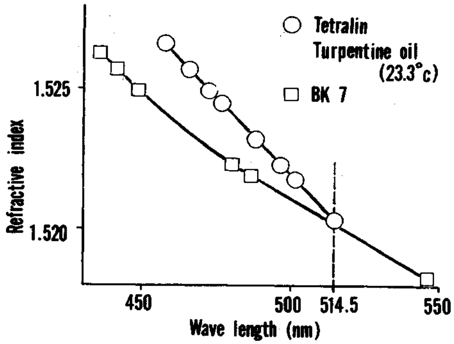

Fig.5 Variation of refractive index with wave length.

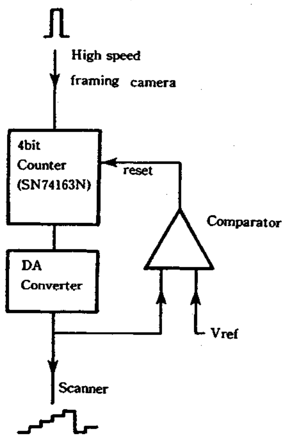

Fig.6 Step function generator.

direction of fracture travel are called "rib marks". They give a shell-like luster on fracture surfaces. "Hackle marks" appear as radial lines showing the direction of fracture travel. **Fig. 4** is a microphotograph of the hackle marks on the fracture surface of BK-7. These marks are traces of an intense strain induced at the exact time of fracture. Residual strain will be another cause of slight change in the optical properties of the surface.

The refractive indices of both the glass and the liquid vary with color as shown in **Fig. 5**. The curve showing the refractive index variation of the glass does not fit into the liquid one. Thus, monochromatic light must be used in the proposed method in order to avoid color dispersion. An Argon laser of 4 W-power type is used in the experiments. It is possible to emit several types of monochromatic light simply by adjusting the angle of the built-in prism. Green light of 514.5 nm is used in the experiments because it is the most intense and can reach a power of 1.7 W.

High-speed scanning and exact positioning of the laser-light "sheet" (LLS) is an essential part of the technique which enables us to observe the three-dimensional shape and motion of an arbitrarily chosen particle within a model. A high-speed framing camera is a powerful tool to record any sudden change in the structural configuration. The authors devised an instrument for scanning the model with LLS in unison with high-speed framing. **Fig. 6** shows the schematic wiring diagram of this instrument. A disk shutter with a slit revolves in the camera. The disk has a small mirror on it. A reflecting photo-interrupter is set close to this disk shutter, and consequently, generates pulses, the number of which coincides with the number of frame advances. Thus, counting the pulses by a digital counter and converting the number into an analogue voltage, a step function is obtained with which a galvanic mirror is rotated to scan the model with the laser-light "sheet". This voltage, increasing step by step, is compared with the reference voltage V_{ref}, and the counter is reset when the stepped-up voltage exceeds V_{ref}. Thus, we can change the number of cross sections only by changing the reference voltage. **Fig.7** is a photograph taken with an ordinary reflex camera. The picture shows a cross section of an embankment model with a cylinder in it. The model is scanned with LLS at intervals of 2 mm by means of this instrument (200 frames/s). Three cross-sections are photographed and superimposed on one film frame. We can observe the spacial variation of the grain shape of all particles on the LLS.

Fig. 8(a) shows a model of a rock mound made of fairly coarse particles set in the water tank. An expanded aluminum plate (very porous), whose rough surface enhances frictional resistance, underlies the model. The height and slope of this model are 20 cm and 1:1.5, respectively. After filling the tank with the liquid, three different cross sections A, B and C on **Fig. 8(a)** are photographed (**Fig.8 (b),(c)** and **(d)**). The shapes of all particles on the LLS are clearly seen in these prints. There are some particles whose contours are not in contact with the others. It goes without saying that the points where there is contact are out of the LLS plane.

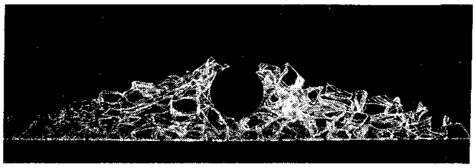

Fig.7 Overlapped cross-sections of embankment model.

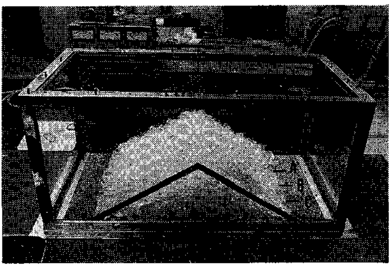

Fig.8,a Embankment model.

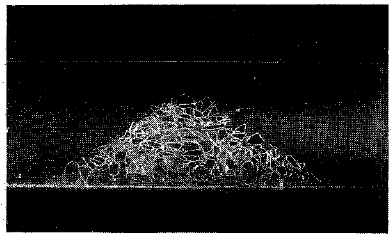

Fig.8,b Cross-section A.

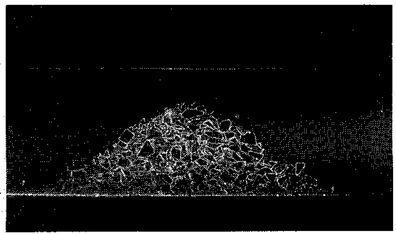

Fig.8,c Cross-section B.

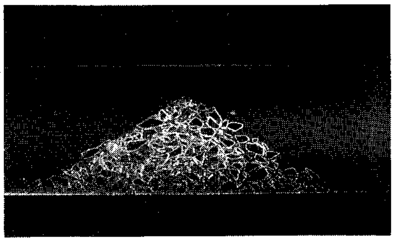

Fig.8,d Cross-section C.

Fig.8 Cross-section of embankment.

3. VISUALIZATION OF DEFORMATION OF FINER PARTICLE ASSEMBLAGE

Utilizing this method for smaller particle sizes will expand its application to analyses of structures made up of finer grains such as sand. However, the finer the glass particles are, the more difficult it is to obtain a clear picture of the cross-section. Glass beads with various sizes are commercially available. However, since they are made by dripping melted glass into cold water, they contain entrapped air bubbles and their surfaces are optically deteriorated. Consequently, they can not be used in the proposed method, and crushing glass blocks is, at present, the only sure way to obtain fairly high-quality, fine particles. The glass, BK-7 used in the experiments, is not so brittle as tempered glass. Thus it is liable to break into thin sharp-pointed pieces, and sometimes, cracks are observed in the grain's interior. These cracks are hardly permeated by the liquid, and air remains in them. This leads to a serious reduction of transparency of a grain assemblage. Thus, an increase of crushing power improves their optical quality[10]. Based on empirical knowledge gained, we were able to reduce the grain size of the employed glass material to 1 mm or smaller in our experiments. **Fig. 9** shows the particle-size accumulation curve for the crushed glass together with those for Silver Leighton Buzzard (SLB)[11] and Toyoura sand[11]. **Fig. 10** shows a micrograph of the glass grains at a magnification of 10 times. They are angular in shape. After close examination, one can again find the "rib marks" and "hackle marks" even on these small surfaces. It goes without saying that the grain shape and the surface roughness greatly affect the mechanical properties of the grain assemblage. **Table 2** provides information about some index properties of the above mentioned materials. The glass material shows relatively high values of minimum and maximum void ratios.

Glass particles whose properties are cited in **Figs. 9, 10** and **Table II** and which serve as a model for surface deposit, were submerged in a water tank (W390×D140×H150) containing a mixture of tetralin and turpentine oils. The deposit consists of 7 layers. They were heaped one upon another to a total depth of 90 mm after each layer had been compacted with a weight of 15 kgf. When particles with a representative size of about 1 mm or smaller are used, it is not easy to have a clear look at each particle on the LLS. Thus, 6 thin strips of very fine glass powder were sandwiched between the layers[10] for better visualization.

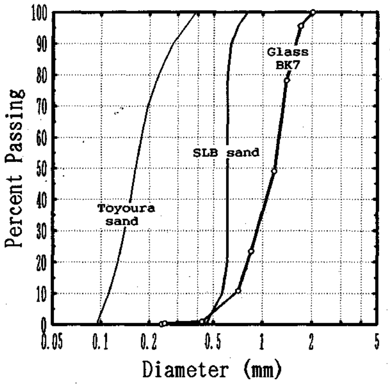

Fig.9 Particle size distribution curves.

A glass cylinder (diameter=50 mm) was driven at a speed of 5 mm/min as shown in **Figs. 11(a),(b),(c)** and **(d)**. The thin strips sandwiched between the particle layers were brightly illuminated by the diffused laser light and contribute to a better visualization of the deformation process. These thin strips were gently bent without drastic dislocation, and no clear shear band was observed. The observed surface heaving represents a large volume increase in the granular assemblage.

Formation of shear band is closely related to its thickness. In order to study shear band formation in the glass grain assemblage, a plane strain compression (PSC) test was conducted. It is desirable that the glass particles are saturated with the same liquid used in the LAT model experiment. However, this is impossible because the mixture of tetralin and turpentine oil is chemically active and would damage the rubber membrane used in the PSC test. Thus, under dry conditions, a rectangular specimen (W75×D160×H200) of glass particles was isotropically consolidated to the stress level of 0.05 kgf/cm^2 and steadily compressed at a constant axial straining of 0.125% per minute. Confining pressure σ_c was set at 0.05 kgf/cm^2 taking into account the low confining pressure in the LAT model experiment. At the end of the PSC test, at an axial strain level of ε_a=12%, a shear band, shown in **Fig. 12**, was observed. The shear band had a width of about 23 mm or approximately 20 times as thick as the

Fig.10 Micrograph of the glass grains at magnification of 10 times.

particle's size. This width will differ in different conditions of packing, boundary conditions and so on. However, since the observed width was not small and not negligible when compared, on one hand with the depth of the particle deposit, and on the other hand with the diameter of the glass cylinder, this thickness should be considered when the deformation process of the grain deposit is studied.

4. DYNAMIC FAILURE IN EMBANKMENT-SHAPED MODEL

Dynamic failure tests of embankment-shaped models were conducted using the proposed technique. **Fig. 13** shows the experimental apparatus. If the water tank with the model in it is shaken, the liquid within it sloshes. In order to avoid the effect of the sloshing on the model's behavior during a study on the structural response to an earthquake, the model, not the water tank, should be shaken. Thus, the model was put in a basket which was immersed in the water tank. This basket was hung from a steel frame which moved with the shaking table, while the water tank spanning the shaking table did not move, i.e. only the basket was shaken in the liquid. The front and rear of the basket are glazed, while both lateral sides are open. Thus, the motion of the basket does not stir the liquid much. A reflex camera with a successive-film-advance function was put on the floor with its optical axis parallel to the excited direction as shown in the figure. Since the basket sways during shaking it is rather difficult to take a clear picture of the model. In order to overcome

Table.II Index properties of materials

Material	Grain Shape	D_{50} [mm]	U_c	G_s	e_{max}	e_{min}
SLB sand	rounded	0.620	1.107	2.660	0.780	0.490
Toyoura sand	angular	0.160	1.500	2.645	0.977	0.605
Glass BK7	very angular	1.080	1.850	2.520	1.190	0.770

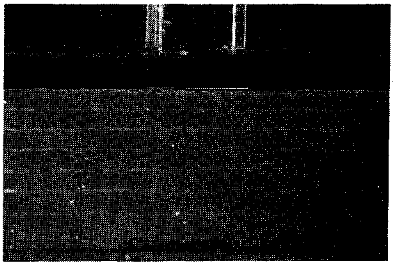

Fig.11,a Settlement, s = 0 mm.

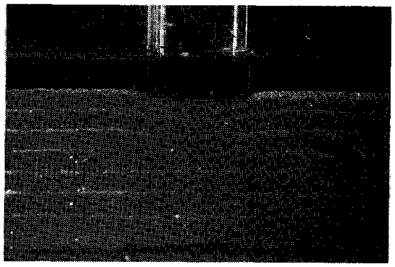

Fig.11,b Settlement, s = 5 mm.

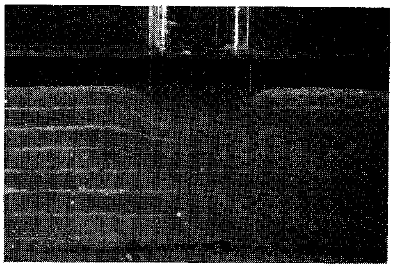

Fig.11,c Settlement, s = 10 mm.

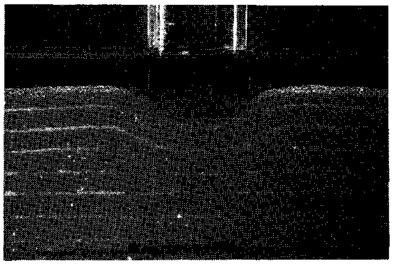

Fig.11,d Settlement, s = 15 mm.

Fig.11 Penetration of cylinder into particles deposit.

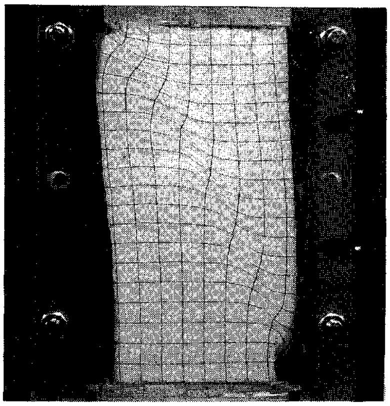

Fig.12 Failure pattern of the glass particles in PSC test, at $\varepsilon_a = 12$ %, $\sigma_c = 0.05$ kgf/cm^2 and e = 0.840.

this problem a flat mirror was mounted on the shaking table at an angle of 45° with respect to the camera's optical axis. By doing so the mirror on which the model's image is portrayed oscillates in a direction parallel to the camera's axis. This oscillation does not deteriorate the image quality and so it becomes possible to take a clear picture of the particle assemblage moving within the basket. The dynamic change in configuration was photographed as streaks. The shutter time of the camera was set at 1 s.

Screened particles (2 mm <grain< 5 mm) serving as a model were heaped to a height of 90 mm. The slope of this isosceles embankment model is 1:2.72. The model was shaken sinusoidally in the horizontal direction normal to the embankment axis. The amplitude of oscillation was increased linearly with time using a personal computer with a D/A converter. This computer also generates trigger pulses to operate the shutter of the camera.

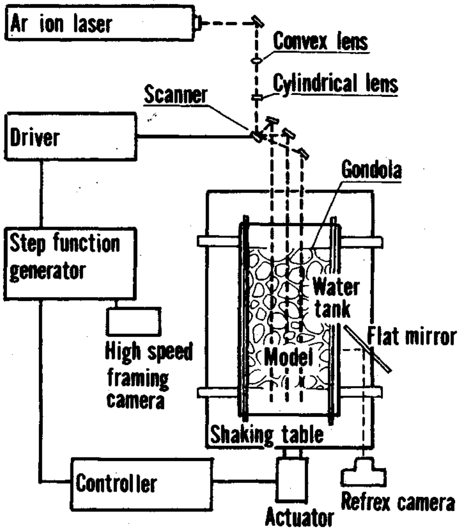

Fig.13 Apparatus for dynamic failure test.

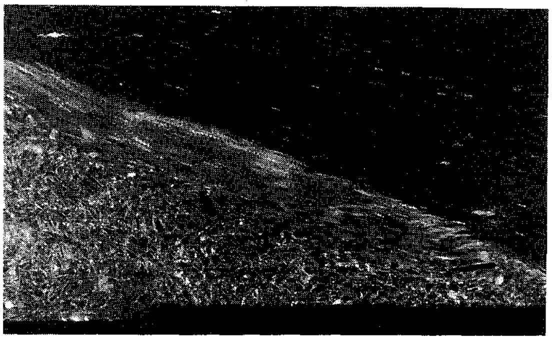

Fig.14,a Excitement frequency = 4 Hz, base acceleration = 51.2 – 54.0 gal.

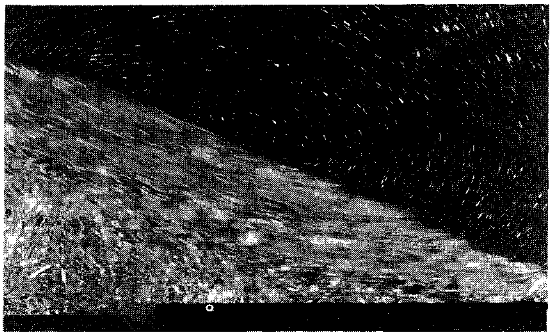

Fig.14,b Excitement frequency= 22 Hz, base acceleration = 153.4 – 162.3 gal.

Fig.14 Slope failure of a model.

Figs. 14(a) and **(b)** show the collapse of the model's surface for different excitement frequency. LLS travels through the middle of the embankment thickness. The surface slipped down as an individual body, while the particles interlocked in the depth of the model experienced little relative motion. Each streak in **Fig.14(a)** represents a particle slide and seems to be a series of dots whose number coincides with the value of the excitement frequency. This indicates that the surface slipped down step by step, repeatedly slipping and sticking. The surface of the model began to slide when the acceleration amplitude exceeded a threshold. **Figs. 15** and **16** show the variations with frequency of threshold acceleration and of threshold velocity, respectively. The threshold acceleration increased with increasing frequency, while variation of threshold velocity was rather small, and was scattered in the

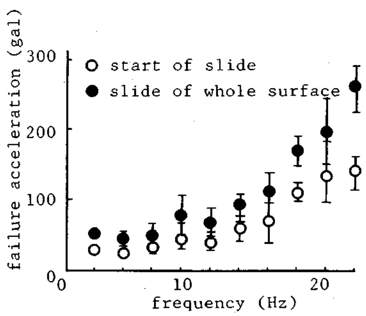

Fig.15 Variation of failure acceleration with frequency.

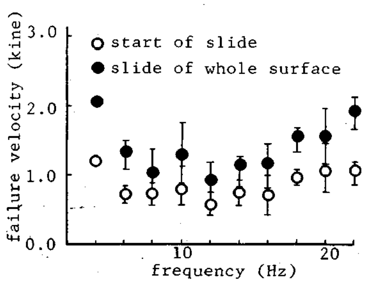

Fig.16 Variation of failure velocity with frequency.

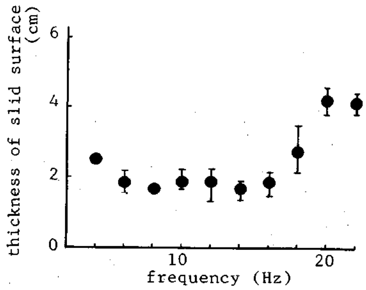

Fig.17 Variation of thickness of slid surface with frequency.

range of 0.5 to 2.0 kine. It is noteworthy that the thickness of the slip surface also increased as the excitement frequency increased (**Fig.17**).

5. CONCLUSIONS

A new visualization technique called "Laser-Aided Tomography" (LAT), was developed for the study of the dynamic behavior of underwater granular structures. Conclusions obtained through the study are summarized as follows:

(1) According to the proposed method, first a model made of glass particles is immersed in a liquid with the same refractive index, and consequently, becomes transparent. An intense laser-light "sheet" (LLS) is then passed through this model, illuminating the contour lines of all the particles in the "cut" cross-section due to the diffused light on the fracture surfaces of the grains. Scanning the model with LLS enables us to observe its whole-field deformation.

(2) Utilization of this method with a smaller particle size will expand its application to analyses of structures made up of finer grains. When particles with a representative size of about 1 mm or smaller are used, it is not easy to have a clear look at each particle on the LLS. A thin strip of glass powder placed between the particle layers is brightly illuminated by the diffused laser light and contributes to a better visualization of the deformation process in the LAT test.

(3) PSC test on glass particles with a representative size of 1 mm showed that the thickness of the shear band under fairly low confining pressure is about 23 mm or nearly 20 times as thick as the representative particle size. The thickness of the shear band will be important in the study of the deformation process observed in the LAT experiments.

(4) Embankment-shaped models made of screened particles (2 mm <grain< 5 mm) were shaken sinusoidally in the liquid. The surface of the model began to slide when the amplitude of base acceleration exceeded a threshold. The threshold acceleration increased with excitement frequency, while variation of threshold velocity was rather small, and was scattered in the range of 0.5 to 2.0 kine. The thickness of the slip surface also increased with the frequency.

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LATによる粒状体構造変化の可視化

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粒状体からなる土木構造物の模型の内部で進行する変形、破壊をリアルタイムに可視化する手法を開発した。この手法はガラス粒子を積んで造った構造模型を同じ屈折率の液体に浸して透明にし、レーザー光のシートを模型の任意断面に透過させるもので、ガラス表面での散乱光で個々の粒子の輪郭や粒子相互の接触状況を観測することができる。この手法による実験例を示し、観測された変形過程、今後の技術的課題について検討を加えた。