Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Visualization and analysis of dynamic behavior of underwater granular structure models

K.Konagai
Institute of Industrial Science, University of Tokyo, Japan
C.Tamura
College of Industrial Technology, Nihon University, Japan

ABSTRACT: A new experimental technique to visualize dynamic behavior of a particle assemblage in a three-dimensional model is developed. A granular structure model in the proposed method is a heap of crushed optical-glass particles in the liquid with the same refractive index, and consequently, is invisible in the liquid. An intense laser-light-sheet (LLS) is then passed through the transparent model, illuminating the contour lines of all the particles on this LLS due to the diffused laser light on the fracture surfaces of grains. Thus, scanning the model with the LLS, it is possible to observe the motion and shape of any particle in it.

1. INTRODUCTION

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

Visualization technique is powerful to obtain the whole-field information, and some techniques for this purpose are available. Those include the "x-ray technique" and "immersion method". The former is the technique to take x-ray photographs of a model made of soil, sand or gravel in which lead bullets are buried as targets[1]. Within the method, not only the bullets but also the change of density in the model material can be visualized through the x-ray. Thus, it is possible to observe vague shade of shear band associated with dilatation. Since this technique itself yields only two-dimensional information, photographs taken in different angle are necessary to obtain three-dimensional image of deformation. Since this process is tedious, computer is often used as an aid to analyze the graphic data (Computed Tomography).

"Immersion method" is another powerful technique. In this method, a model is made of glass particles and is immersed in the liquid with the same refractive index to make the model transparent. Opaque or colored particles are put in the model as marks, and the motions of the marks are observed. This immersion technique is also well-known in the field of photoelasticity and many researchers such as Allersma, H.G.B.[2], Ura T.,[3] used and improved this technique, which was originally and individually developed by Wakabayashi, T.[4], and by Dantu P.[5] in the first half of 1950's.

Though these methods are powerful to observe a whole-field of a model, they yields only information of motions of marks or two-dimensional stress information, usually not enough to define perfectly change in configuration of particle assemblage in a model.

Konagai and Tamura have developed a new experimental method (LAT: Laser-Aided Tomography) to visualize all particles interlocking one another in a three-dimensional model[6,7,8,9]. This paper describes first the detail of the proposed method, and some findings through the LAT experiments on failure process of embankment-shaped models are described in the latter half.

2. PROPOSED METHOD

In the proposed method, particles of crushed optical glass are heaped up to be a model of interest in the liquid with the same refractive index. Consequently, the model is transparent and invisible in the liquid. An intense laser-light-sheet (LLS) is then passed through the model, and illuminates contours of all the particles on this LLS because the chemically active fracture surfaces of grains differ slightly in their optical property from what they used to be before crushing (Fig.1).

Liquid used in the experiment must be (1) colorless and transparent and (2) less volatile. The liquid also needs to be (3) less viscous to obtain large Reynolds number so that the liquid can be used in a dynamic experiment. The authors used a mixture of turpentine and tetralin oils. Since refractive index of the optical glass (BK-7) used in our experiment lies between these two solvents' indices, it is possible to tune the refractive index of the mixture to that of glass.

Tuning of the refractive index is also possible by changing temperature of the liquid because both density and refractive index vary with temperature as shown in Figs. 2 and 3. The average rate of change of refractive index with respect to temperature in the interval from 20°c to 30°c is about -0.00028/deg for the green laser light (wavelength = 514.5 nm). Thus, fine tuning is easy by controlling temperature of the liquid, and heating of the liquid is the easiest way. However, repeating of this process yields volatilization of pinen oil which is the major ingredient of the turpentine oil. Thus, the turpentine oil is needed to be occasionally added to the mixture.

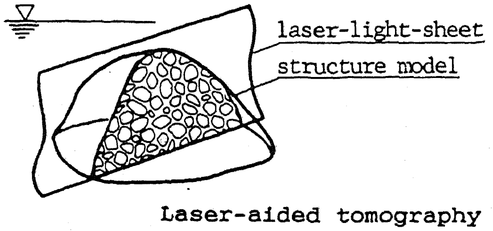

Figure 1. Visualization method.

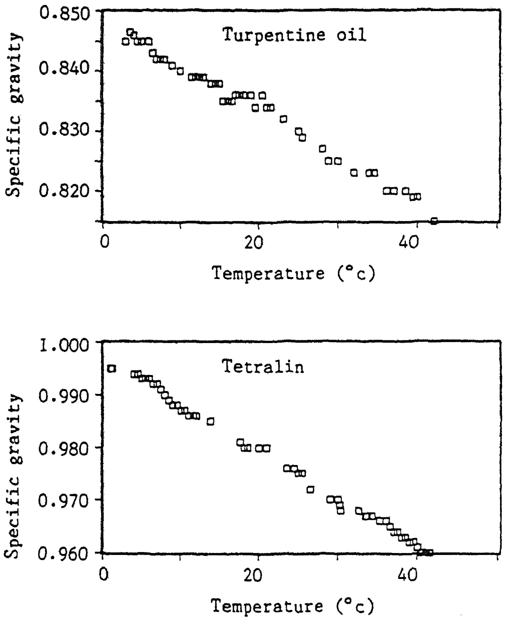

Figure 2. Variation of specific gravity of solvents with temperature.

Refractive index of the glass should lie between those of the two solvents. There are many kinds of glass commercially available. Among them, BK-7 is one of the cheapest one for optical use. Refractive index of the glass roughly annealed is 1.5194 for the monochromatic laser light with wavelength of 514.5 nm. Strip blocks of the glass were broken into particles by a jaw-crusher. Two kinds of mark are seen on the fracture surface; "rib marks" and "hackle marks"10). Dense curved lines running in the transverse 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 a fracture surface of the BK-7. These marks are traces of an intense strain induced at the very time of fracture. Residual strain will be another cause of a slight change of optical property of the surface.

Refractive indices of both the glass and the liquid vary with color as shown in Fig. 5. The curve showing the variation of refractive index of the glass does not fit into the liquid's index. Thus, monochromatic light must be used in the proposed method to avoid color dispersion. Ar-ion laser of 4 W-power type is used in the

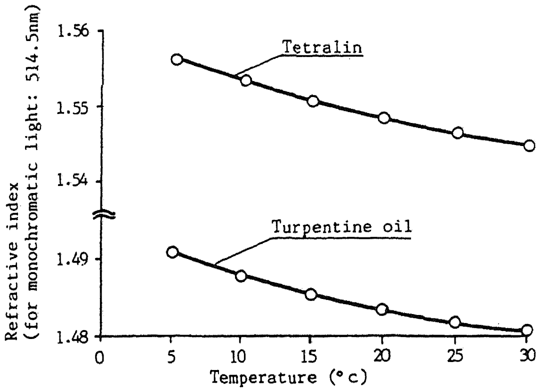

Figure 3. Variation of refractive index of solvents with temperature.

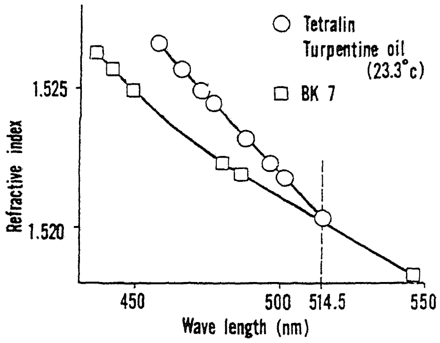

Figure 5. Variation of refractive index with wave length.

experiments. It emits several monochromatic lights by adjusting angle of the built-in prism. The green light of 514.5 nm is used in the experiments because it is the most intense and reaches the power of 1.7W.

High-speed scanning and exact positioning of the LLS (laser-light-sheet) is an essential technique to observe three-dimensional shape and motion of an arbitrarily chosen particle in a model, and high-speed framing camera is a powerful tool to record a sudden change in configuration. The authors devised an instrument to scan a model with the LLS at the same pitch as the high-speed framing. Fig. 6 shows the schematic wiring diagram of this instrument. A disk shutter with a slit revolves in a high-speed-framing camera. The disk has a small mirror on it. A reflecting photo-interrupter is put close to this disk shutter, and consequently, generates pulses of which number coincides with the number of frame advance. Thus, counting the pulses by a digital counter and converting the number into analogue voltage, a step function is obtained with which a galvanic mirror is rotated to scan the model with the LLS. 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 section only by changing the value of V_{ref}.

Fig. 7(a) shows a model of rock mound made of fairly coarse particles. A porous aluminum plate, whose rough surface enhances frictional resistance, underlies the model. The

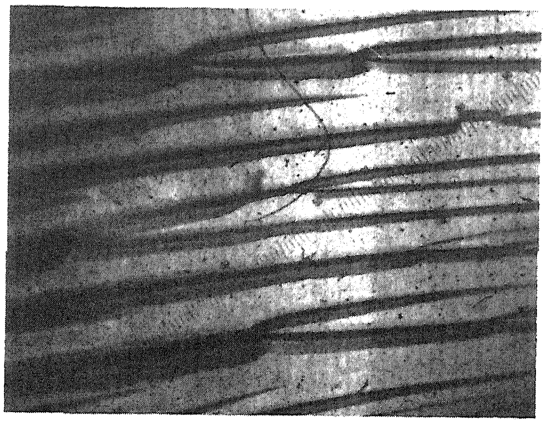

Figure 4. Hackle Marks on a surface of BK-7 (Magnification:100).

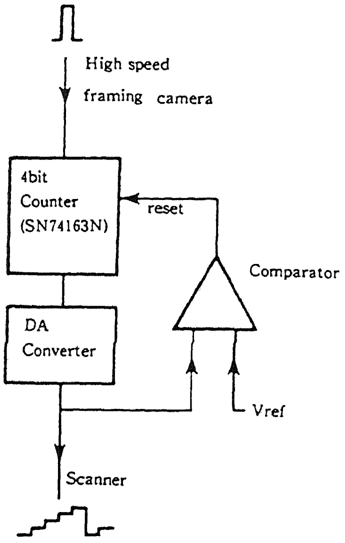

Figure 6. Step function generator.

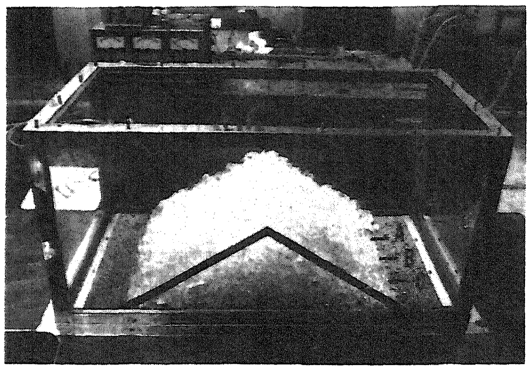

Figure 7,a. Embankment model.

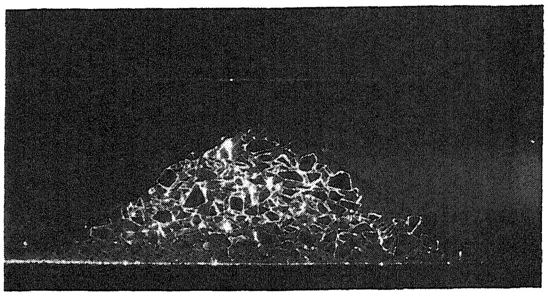

Figure 7,c. Cross-section B.

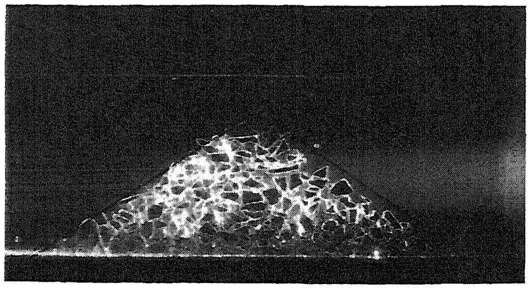

Figure 7,b. Cross-section A.

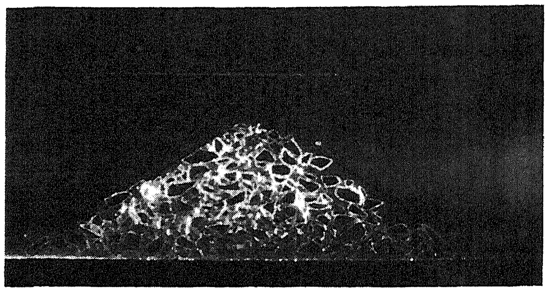

Figure 7,d. Cross-section C.

Figure 7. Cross-section of embankment.

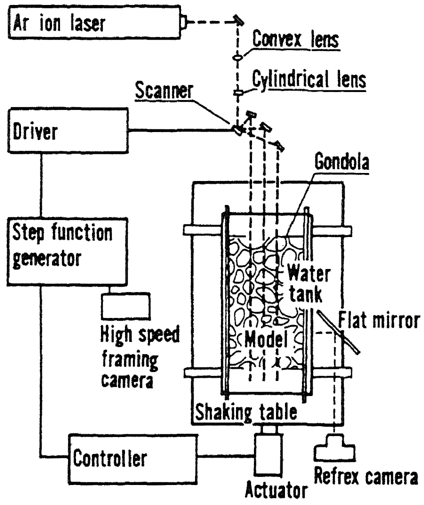

Figure 8. Apparatus for dynamic failure test.

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 in Fig. 7(a) were photographed (Fig.7(b),(c) and (d)). Particles on the LLS are clearly seen in these prints. There are some particles of which contours are not touching the others. It goes without saying that the points where they are touching the other particles are out of the plane of LLS.

3. DYNAMIC FAILURE IN EMBANKMENT-SHAPED MODEL

Dynamic failure tests of embankment-shaped models were conducted using the proposed technique. Fig.8 shows the apparatus for the experiment. Not the liquid but the model must be shaken in the liquid when earthquake response of these structures is discussed. Thus a model was put on a basket in a water tank. This basket hangs from a steel frame which moves with the shaking table, while the water tank spanning the shaking table does not move at all within the steel frame, and consequently, only the basket is shaken in the liquid. The front and rear of the basket are glazed, while both lateral sides of the basket are

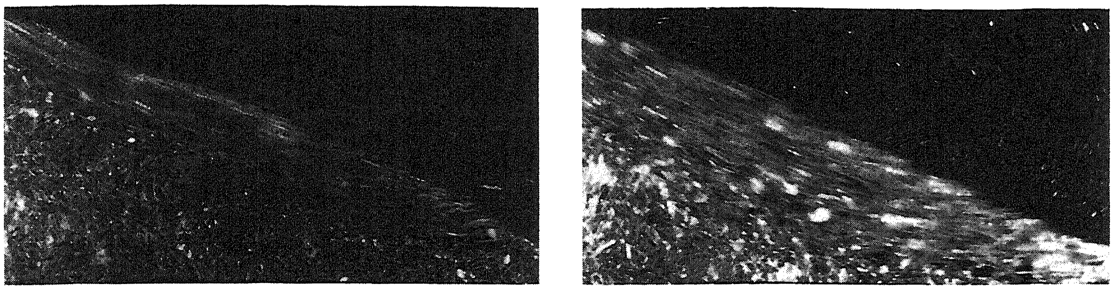

Figure 9,a. Exciting frequency = 4 Hz, base acceleration = 51.2 - 54.0 gal.

Figure 9,b. Exciting frequency= 22 Hz, base acceleration = 53.4 - 62.3 gal.

Figure 9. Slope failure of a model.

open, and the liquid is consequently not stirred much by the motion of the basket. It is not easy to take a clear picture of the model because the model sways during shaking. In order to overcome the problem, a flat mirror was mounted on the shaking table. This mirror slants the cross-section of the model at an angle of 45°. And a reflex camera with a function of successive film advance was put on the floor separating from the shaking table with its optical axis directing to the mirror as shown in the figure. Since the mirror sways with the basket, the mirror reflects the still image of particles on the basket, while the failure and dynamic change in configuration during the shutter time are photographed as streaks. The shutter time of the camera was set at 1 s.

Screened particles (2 mm << 5 mm) serving as a model were heaped up to the 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 linearly increased with time by a personal computer with a D/A converter. This computer also generates pulses to control the timing of shutter of the reflex camera.

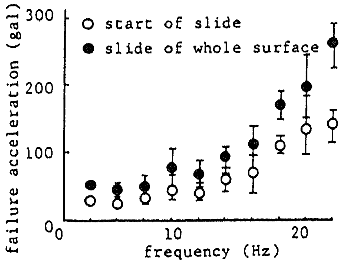

Figure 10. Variation of failure acceleration with frequency.

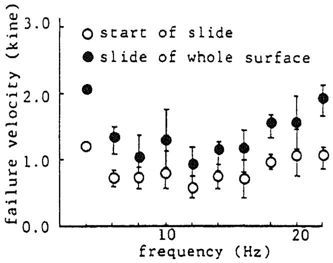

Figure 11. Variation of failure velocity with frequency.

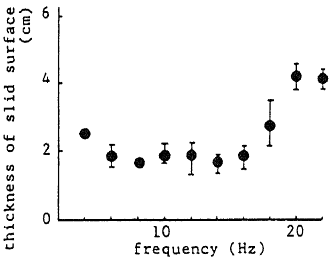

Figure 12. Variation of thickness of slid surface with frequency.

Figs. 9(a) and (b) show the collapse of surfaces of the model for different exciting frequencies. The LLS travels in the middle of the embankment thickness. The surface slipped down in a cluster, while particles interlocked in the depth of the model scarcely experienced any relative motion. Each streak in Fig. 9(a) showing the slide seems to be a series of dots whose number coincides with the exciting frequency. This shows that the surface slipped down step by step repeating slipping and sticking periodically. The surface of a model begins to slide when the amplitude of acceleration exceeds a threshold. Figs. 10 and 11 show the variations of threshold acceleration and velocity with frequency, respectively. The threshold acceleration increases with increasing frequency, while variation of threshold velocity is rather small, and scatters in the range of 0.5 to 2.0 kine. It is noteworthy that the thickness of the slid surface also increases as the exciting frequency increases (Fig. 12).

4. CONCLUSIONS

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

(1) In 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. And scanning of the LLS enables us to observe the whole motion of the model.

(2) Embankment-shaped models made of screened particles (2 mm < < 5 mm) were shaken sinusoidally in the liquid. The surface of a model began to slide when the amplitude of base acceleration exceeded a threshold. The threshold acceleration increases with exciting frequency, while variation of threshold velocity is rather small, and scatters in the range of 0.5 to 2.0 kine.. The thickness of the slid surface also increases with the increase of frequency.

ACKNOWLEDGMENT

The authors acknowledge gratefully the financial support of the Ministry of Education, Science and Culture, Grant-in Aid for Scientific Research, No. 02805052. The authors are indebted to Mr. Kazuo Hirata, Tohoku Electric Power Co. Ltd., formerly a graduate student, Mr. Peter Rangelow and Mr. Takashi Matsushima, graduate students, Institute of Industrial Science, University of Tokyo, for their help throughout the experiments.

REFERENCES

1) Roscoe, K.H., Bassett, R.H. and Cole, E.R.L.: The Determination of Strains in Solids by an X-ray Method, *Civil Engineering and Public Works Reviews*, Vol. 58, pp.873-875 and pp. 1009-1012, 1963.
2) Allersma, H.G.B.: Photoelastic Stress Analysis and Strain in Simple Shear, *IUTAM Conference*, Rotterdam, pp.345-353, 1982.
3) Ura, T. and Sakamaki, T.: Measurement of Three Dimensional Flow of Granular Media (1), *SEISAN-KENKYU (Monthly Journal of Institute of Industrial Science, Univ. of Tokyo)*,Vol.35, No.2, pp.65-67, 1983.
4) Wakabayashi, T.: Photoelastic Method for Determination of Stress in Powdered Mass, *Jour., Physical Society of Japan*, Vol.5, No.5, 1950.
5) Dantu, P.: Contribution a l'etude Mechanique et Geometrique des Milieux Pulverulents, *Proc., Int. Conference on SMFE*, London, Vol.1, pp.144-148, 1957.
6) Konagai, K. and Tamura, C.: Visualization of Dynamic Behavior of Particle Assemblage in Underwater Granular Structure Models, *Bull., Earthquake Resistant Structure Research Center, Univ. of Tokyo*, No.22, pp.3-12, 1989.
7) Konagai, K. and Tamura, C.: Visualization and Analysis of Dynamic Behavior of Granular Structure Models, *Proc., 8th Japan Earthquake Engineering Symposium*, Vol.2, pp.1221-1226, 1990.
8) Konagai, K. and Tamura, C.: Visualization of Dynamic Change in Configuration of Underwater Particle Assemblage, *Proc., European Conference on Structural Dynamics, EURODYN'90*, Bochum, FR Germany, Vol.2, pp.837-841, 1991.
9) Rangelow, P., Konagai, K., Matsushima, K. and Park, C.S.: Visualization of Granular Material Deformation through Laser-Aided Tomography, *Bull., Earthquake Resistant Structure Research Center, Univ. of Tokyo*, No.25, 1992
10) Mckenna, J. F.: A Method for Solving Glass Breakage Problems in Electron Tube Manufacture, *Bull., American Ceramic Society*, Vol.40, No.2, pp.61-65, 1961.