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VISUALIZATION OF DYNAMIC BEHAVIOR OF PARTICLE ASSEMBLAGE IN UNDERWATER GRANULAR STRUCTURE MODELS

by

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1. INTRODUCTION

It is very important to study dynamic behavior of granular off-shore and near-shore structures such as islands of gravel and sand, rock embankments, masonry foundation of large piers and so on. It is, however, not easy to predict possible failure patterns mainly because of complicated interaction between water and an irregularly shaped assemblage of fairly large particles. Carefully prepared experiments on models will provide us important information of the failure mechanism. However, the problem is to observe the phenomena going on inside a model.

There are several methods for this purpose available. One of them is taking photographs of lead bullets in a model by the x-ray technique[1). This technique also enables us to observe vague shade of slip surfaces inside a model. However, since this technique yields only two-dimensional information, photographs taken in different angle would be necessary to obtain three-dimensional information. And the x-ray used in a dynamic experiment should be quite intense because exposure time must be extremely short so that a clear snapshot will be obtained.

The other technique sometimes used is to observe motion of markers or photoelastic fringes in an assemblage of glass particles in a liquid with the same refractive index. This technique is well known as the "immersion method", and many researchers such as Allersma, H. G. B.[2)], Ura, T.[3)] used and improved this technique originally developed by Wakabayashi, T.[4)] and Dantu, P.[5)]. However, observation of dynamic behavior of each particle itself interlocking in an assemblage is impossible even by these techniques.

In order to make close observation of behavior of particles inside a model, the authors have developed a new method. In our method, the above-

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mentioned "immersion method" is also used, and a laser light sheet (L.L.S.) is used to visualize motion of particles in a model. The first half of this paper is addressed to a description of this technique, and in the latter half, feasibility of this technique is demonstrated through an experiment.

2. PROPOSED METHOD

In our method, a model of interest is made of particles of crashed optical glass, and is immersed, as has been mentioned above, in liquid with the same refractive index as the glass. It is needless to say that the liquid for this purpose must be (1) colorless and transparent, (2) chemically stable and less volatile. And it is desirable that (3) variation of refractive index with temperature is small and mild when it is difficult to keep temperature constant. It is also required for the liquid to be (4) less viscous to obtain large Reynolds number in a dynamic experiment. When optical glass is used as model material, refractive index will lie between 1.4 and 1.9, and this is suggestive that we can use a mixture of oils or aromatic hydrocarbons as a suitable liquid. Reviewing the aforementioned requirements, the authors used a mixture of turpentine oil and tetralin. Both are generally used as solvents, and their chemical and physical properties are listed in Table 1. Since they are extremely cheap, it is easy to make a fairly large granular structure model in the liquid. Fig. 1 shows relationship between temperature and refractive indexes of these two solvents for monochromatic light having wave length of 514.5nm emitted from an Ar-ion laser. Tetralin is higher in refractive index than turpentine oil. Refractive indexes of both solvents decrease gradually with increasing temperature. Gradients of these lines in this figure are almost the same and about -0.03 /deg at 20°c. Densities of these solvents also depend on temperature as shown in Fig. 2. These figures 1 and 2 are used to calculate refractive index of the mixture. The refractive index of the mixture is obtained by the following equation as:

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

where n ,ρ = refractive index and density of mixture,

n_1,ρ_1 = refractive index and density of turpentine oil,

n_2,ρ_2 = refractive index and density of tetralin and

Table 1 Physical Properties of Turpentine Oil and Tetralin

	Turpentine oil	Tetralin
Boiling point	153~175°c	207.6°c
Specific gravity (0~40°c)	0.815~0.850 (See Fig.2.)	0.960~0.996 (See Fig.2.)
Refractive index (514.5nm)	1.481~1.491 (See Fig.1.)	1.546~1.557 (See Fig.1.)
Coefficient of viscosity	1.257 cps (25°c)	2.02 cps (20°c) 1.30 cps (50°c)
Surface tension	————	36.30 dyn/cm (13.3°c) 33.63 dyn/cm (36.7°c)
Specific heat	0.453 cal/g·deg	0.403 cal/g·deg

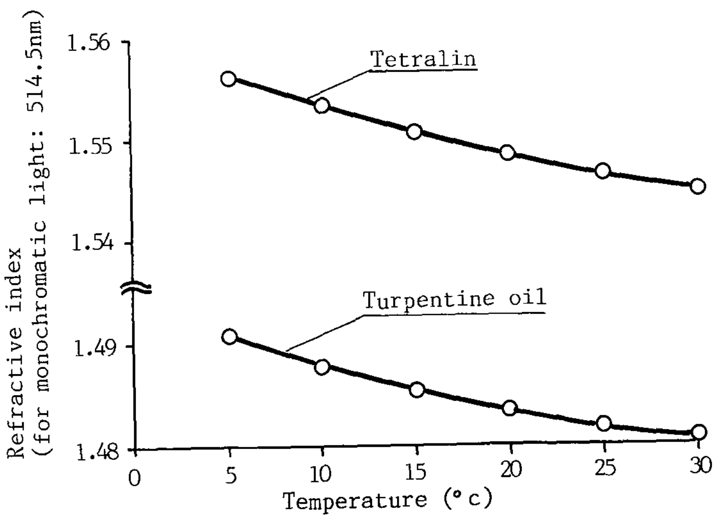


Fig. 1 Variation of Refractive Index of Soluvents with Temperature

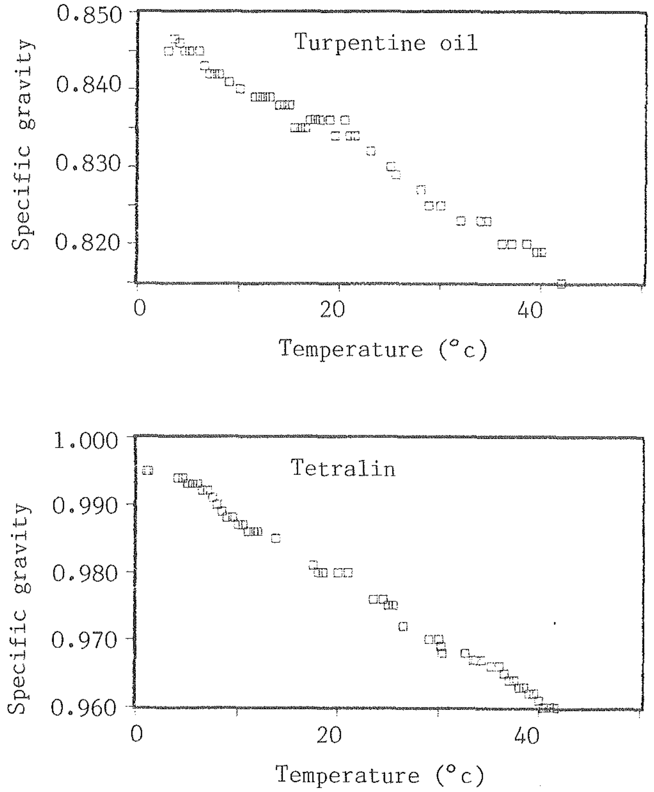


Fig. 2 Variation of Specific Gravity of Solvents with Temperature

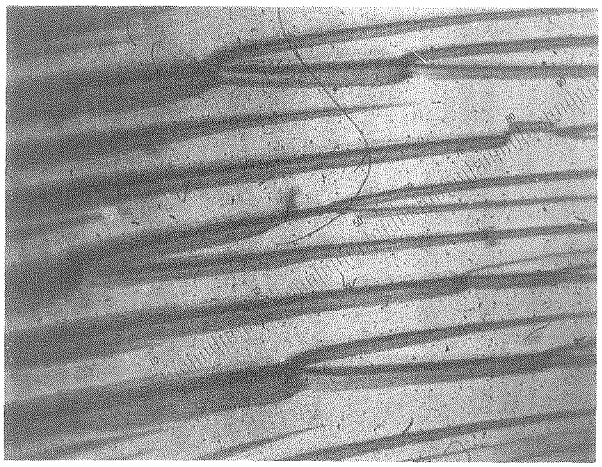


Fig. 3 Hackle Marks on a Surface of BK-7 (× 100)

c = percentage of tetralin content.

Refractive index of the glass used in our method should lie between those of above-mentioned solvents, and there are many kinds of glass commercially available. Among them, BK-7 is one of the cheapest one for optical use. Refractive index of this glass for the light with wave length of 514.5nm is 1.5204. It scarcely includes optical inhomogeneity such as striae and entrapped air bubbles. A strip block of the BK-7 is broken into particles in the mixture of turpentine oil and tetralin by blows of hammer so that the liquid will easily permeate fracture cracks. Two kinds of marks are visible on fracture surfaces; "rib marks" and "hackle marks"[6]. Dense curved lines running almost perpendicular to the direction of fracture travel are called "rib marks". They throw a shell-like luster on fracture surfaces. "Hackle marks" appear as radial lines parallel to the direction of fracture travel. Fig. 3 is a microphotograph of the "hackle marks" on a fracture surface of the BK-7. These marks are suggestive of an intense strain induced at the time of fracture. Residual strain and chemical changes observed on fracture surfaces are causes of slight change of optical properties and diffusion of light on the surfaces. Thus, an intense laser light sheet (L.L.S.) passing through a model in the liquid illuminates outlines of invisible particles on this light sheet clearly. And scanning of the laser light sheet enables us to observe three-dimensional behavior of a model.

3. EXPERIMENT

Fig. 4 shows the apparatus for the experiment. The light source is an Ar-ion laser of 4W-power type. Green light(514.5nm) emitted from this laser reaches the power of 1.7W, and is expanded to be a thin vertical sheet by an arrangement of optical elements (symmetric-convex lens (f=2.0m), plano-concave cylindrical lens(f=12.7mm), flat mirror (5cm*5cm)). These lenses are covered with dielectric multilayer antireflection coating, and reflection coefficient for monochromatic light of wavelength of 514.5nm does not exceed 0.4%. A glass box on the left-hand side in Fig. 4 is a water tank with a granular structure model in, and is mounted on a shaking table.

Fig. 5 shows a model of a rock embankment in the water tank. This model underlays an expanded aluminum plate whose porous surface enhances frictional

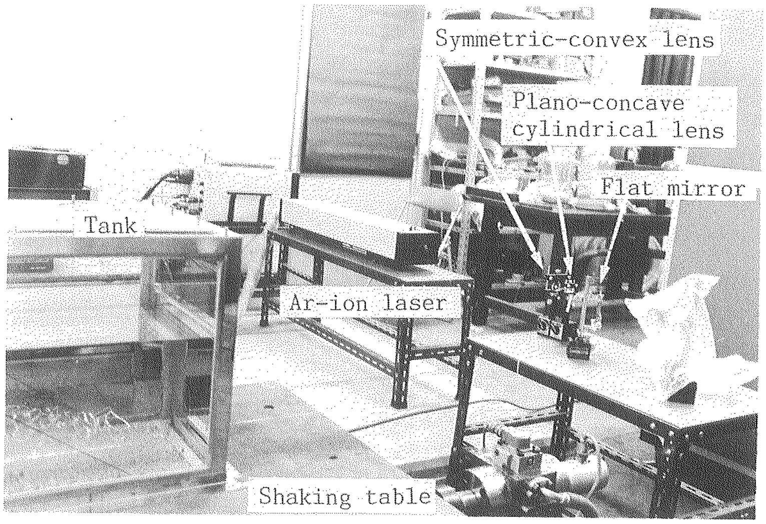


Fig. 4 Apparatus for Experiment

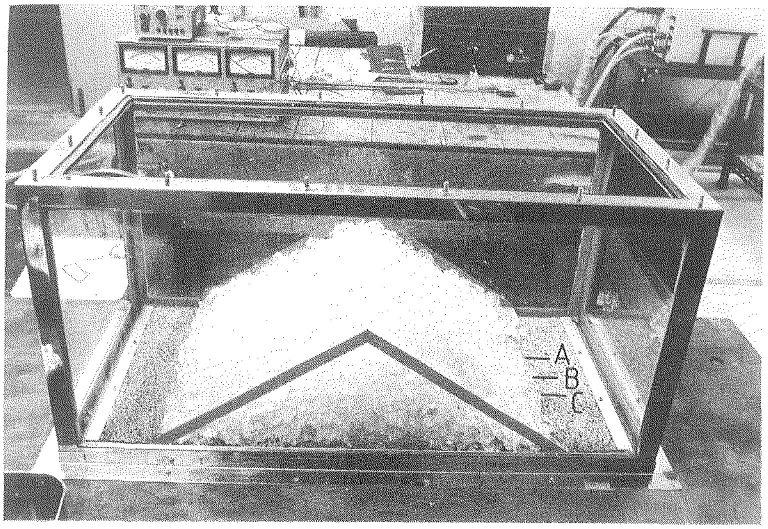
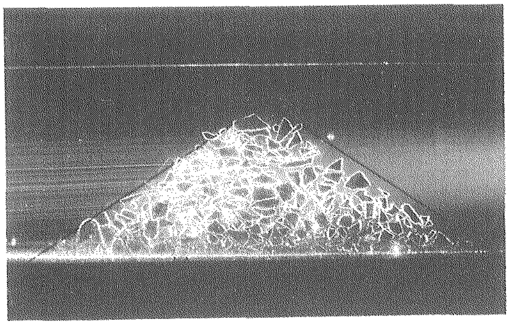
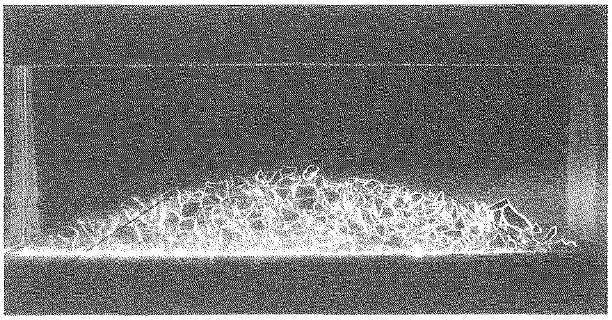


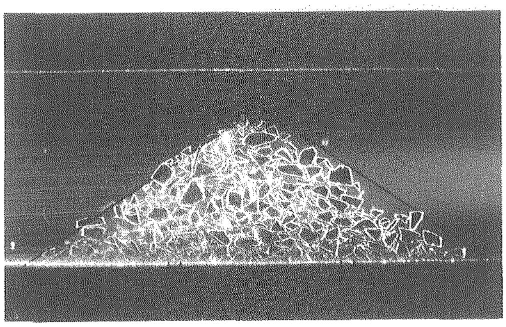
Fig. 5 Model of Rock Embankment

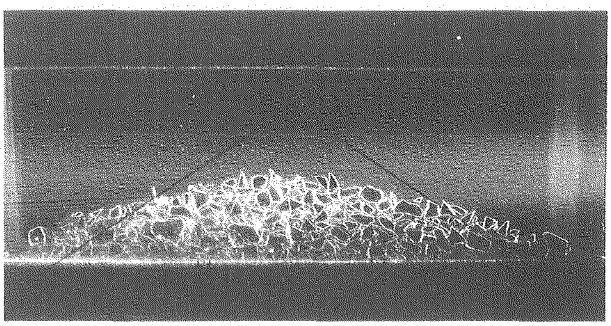




before excitation after excitation

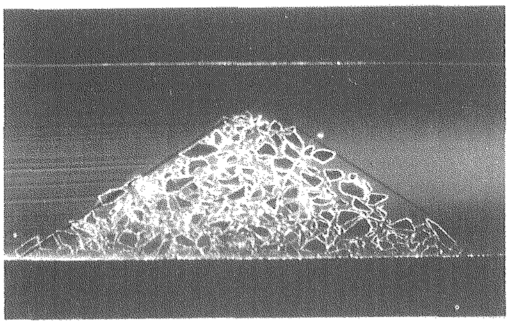
cross section A

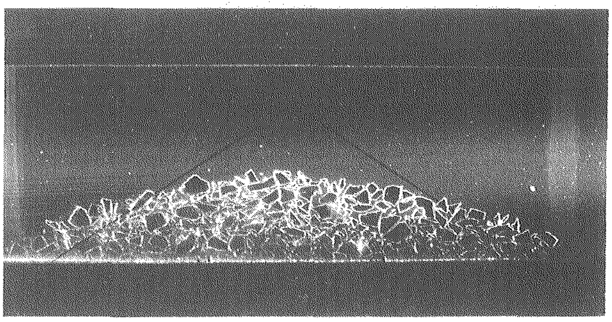




before excitation after excitation

cross section B

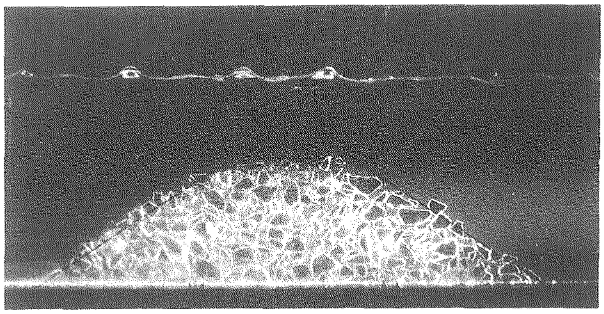




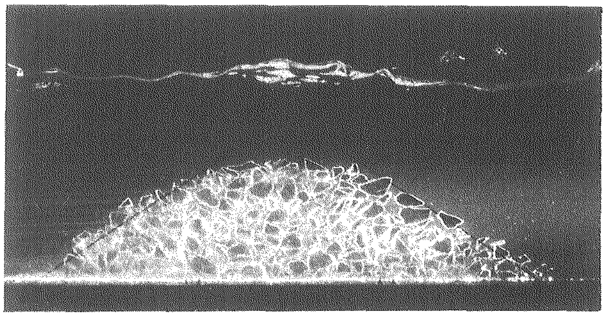
before excitation after excitation

cross section C

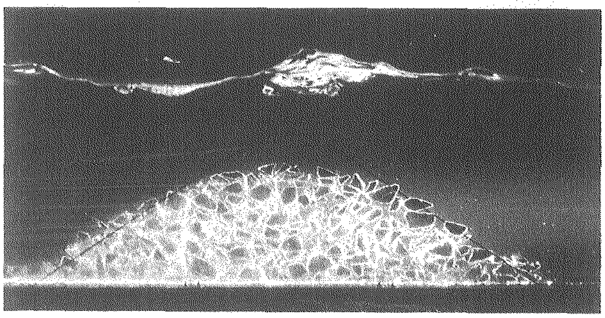
Fig. 6 Cross Sections of Embankment



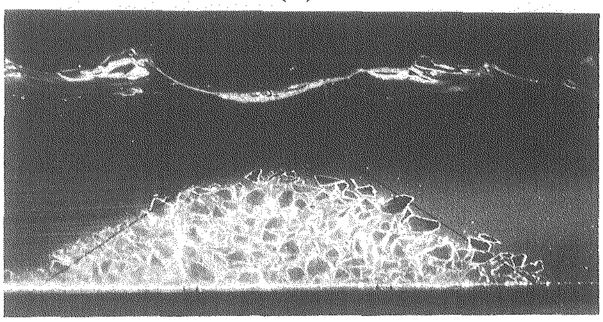
(1)



(2)



(3)



(4)

Fig. 7 Change in Configuration of Particle Assemblage during Excitation (cross section B) resistance. The height and slope of this model are 20cm and 1:1.5, respectively. The liquid surface is 5cm above the top of the model. Before the experiment, three cross sections (A, B, C, in Fig. 5) were photographed, and are shown in Fig. 6. Interlocking condition at any section is clearly visible. There are some particles whose outlines are not in contact with the others, and it is obvious that contact points on these particles are not on the laser light sheet.

This model was shaken in horizontal and transverse direction of the embankment. Excitation frequency is 5Hz, and the base acceleration was amplified from 0 to 300gal in 3min. Dynamic behavior of the central cross section after the base acceleration exceeded 150gal was photographed by a high speed framing camera (Photo-sonic 16mm 1W) and by a reflex camera with a motor driver for successive film advance (maximum speed =4 frames/s). Fig. 7 shows successive snapshots taken by the reflex camera. Time interval between these prints is 3s. Particles near the slope surface change gradually their locations and directions to squeeze fairly large particles out of the model. And fall of a large particle is followed by a sudden change of interlocking condition inside the model. Similar phenomenon can be seen in dynamic failure tests on models of rock-fill dams.

Three different cross sections after excitation are also shown in Fig. 6. comparatively large voids in the widely spread model are filled with small particles yielding a decrease of total volume of the embankment.

4. CONCLUDING REMARKS

In order to study earthquake resistance of granular structures in the water, the authors have developed a new experimental technique to visualize dynamic behavior of interlocking particles in a model structure. This model is an assemblage of crashed glass particles and is immersed in liquid with the same refractive index as the glass. Thus the model could be invisible in the liquid. However, An intense laser light sheet illuminates clearly outlines of these invisible particles on this light sheet because of diffusion of light on fracture surfaces of glass. Using this technique, it becomes easy to observe the motion of each particle inside a model structure. Moreover, scanning of the laser light sheet enables us to observe the whole motion of a granular model.

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