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VISUALIZATION OF GRANULAR MATERIAL DEFORMATION THROUGH LASER-AIDED TOMOGRAPHY

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INTRODUCTION

Discrete particles that make up soil are not strongly bonded together like metal crystals, and hence the soil particles are relatively free to move with respect to one another. If we could observe this motion in a cross-section of a granular assemblage under loading conditions, we could more easily study the "laws" which determine its stress-strain behavior and failure mechanism.

A new visualization technique called "Laser-Aided Tomography" (LAT), was developed by Konagai and Tamura(1),(2). According to their 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" 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 grains' fracture surfaces.

It goes without saying that this technique will be a very powerful tool for studying the behavior of civil engineering structures made of coarse materials such as rock and gravel. 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 take a clear picture of the cross-section. Fracture surface micro-cracks are hardly permeated by the liquid. This and the high temperature sensitivity of the liquid's refractive index are the major causes for reduced transparency.

During the course of our study it has become apparent that there are several ways to overcome the problem of reduced transparency with decreased particle size. For example, an increase in energy needed for the crushing of the glass will improve the optical cleanness of the produced grains. Based on gained empirical knowledge we were able to reduce the grain size of the employed glass material to 1 mm in our experiments.

The first half of this paper describes the index properties of the glass material, the setup of the experimental station and some technical measures that need to be met in order to improve the visual information obtained through LAT for the case of finer particles. The latter half addresses the mechanical properties of the glass material through a plane-strain compression test.

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VISUALIZATION OF PARTICLE ASSEMBLAGE DEFORMATION

Fig.1 shows micrographs of the glass grains at a magnification of 10 times. After close examination one can find dense concentric arcs and radial marks on their surfaces. These are rib and hackle marks showing the traces of fracture travel. The grain shape can be classified as very angular.

Fig.2 shows the particle-size accumulation curve for the crushed glass together with those for Silver Leighton Buzzard (SLB)[3] and Toyoura sand[3]. The curve of the glass particles was obtained by using the method specified by the Japanese Society of Soil Mechanics and Foundation Engineering on the basis of a 200 g of material.

Table 1 provides information about some index properties of the above mentioned materials. The glass material shows relatively high values of minimum and maximum void ratios in comparison with the others, and this is closely related to its angular shape.

Fig.3 shows the setup of the experimental apparatus.

The light source is an Ar-ion laser of 4 W-type.

Green light emitted from the laser and reflected by a flat mirror is transformed into a vertical "sheet" by means of some optical elements[1),(2)]. The thinner the laser-light-"sheet" is, the clearer the visualized cross-section is in the model. Thus a convex lens with focal distance of 2 m is included in the arrangement of optical elements. The obtained thin laser-light-"sheet" travels through the transparent model along its long axis.

Figure 1
Micrographs of the glass grains at a magnification of 10 times. After close examination of a single grain, hackle and rib marks can be observed.

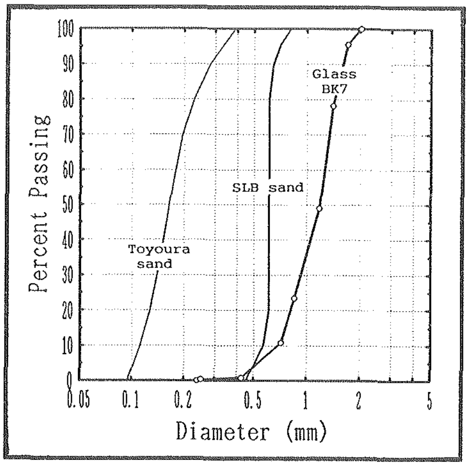

Figure 2
Particle size distribution curves.

Table 1: 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

Glass particles with properties cited in Fig.1 and Table 1 and serving as a model for surface deposit are submerged in a water tank (W390×D140×H150) containing a mixture of tetralin and turpentine oils. The deposit consists of 7 layers. They are heaped one upon another to a total depth of 90 mm after each layer was compacted with the weight of 15 kgf. Between the layers there are 6 thin strips of very fine glass powder, which contribute to better visualization of the failure mechanism.

A glass cylinder(diameter=50 mm) was attached to a uniaxial loading machine and used to apply loading pressure to the glass material. This caused deformation and shear failure of the glass specimen.

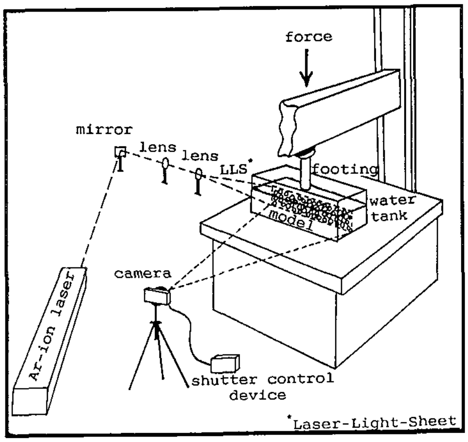

Figure 3
Setup of the experimental apparatus.

An optical electronic device reads a bar code, placed on the frame of the loading machine, and generates trigger pulses which control the shutter timing of the reflex camera. With the help of this device, a picture of the model's central cross-section was taken at every bar code stripe.

Fig.4 shows snapshots of the central cross-section of the model during non-stop loading of the specimen. In this case, the cylinder was driven at a speed of 5 mm/min. Generally, a change in the speed within the range of 5 mm/min to 500 mm/min does not affect the behavior of the particles assemblage.

The observed surface heaving, Fig.4 (b)-(d), represents big volume increases in the granular assemblage. No shear band was observed. The failure pattern is different from that observed in classical experiments using fine sand or clay, in which clear shear bands are formed, and instead is rather similar to that observed by the shearing of gravel.

This phenomenon urges us to study the shearing process of the used glass material more precisely and define the behavior similarities with respect to gravel material.

PLANE-STRAIN COMPRESSION TEST

In order to study the soil mechanics properties and the shearing process of the glass material, 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 will damage the rubber membrane used in the PSC test. Thus, under dry conditions a rectangular specimen of glass particles (W75×D160×H200) 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.

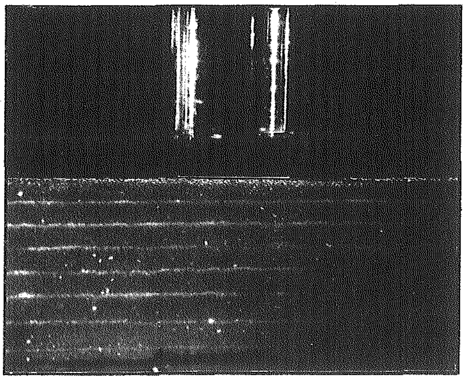

Figure 4,a
Initial condition.

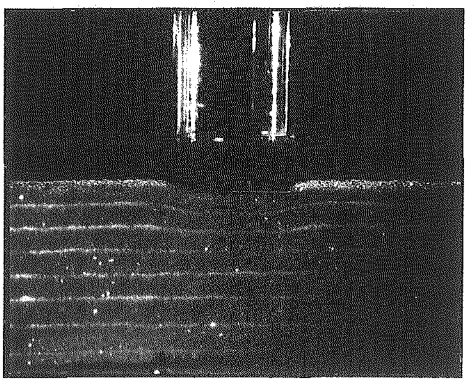

Figure 4,b
Settlement, s = 5 mm

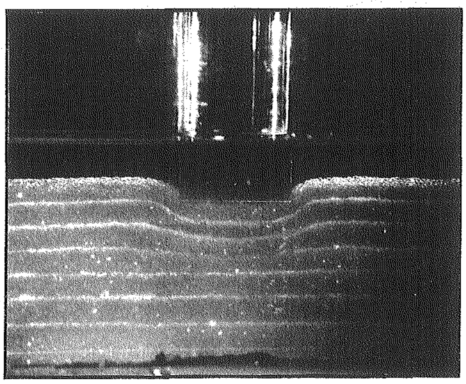

Figure 4,c
Settlement, s = 10 mm

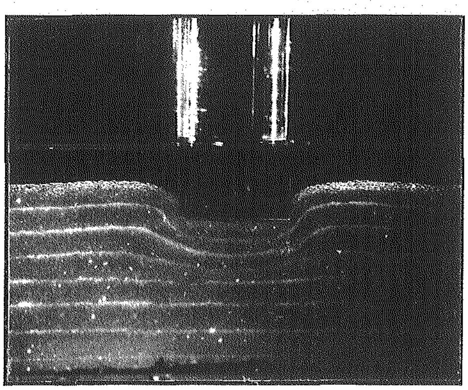

Figure 4,d
Settlement, s = 15 mm

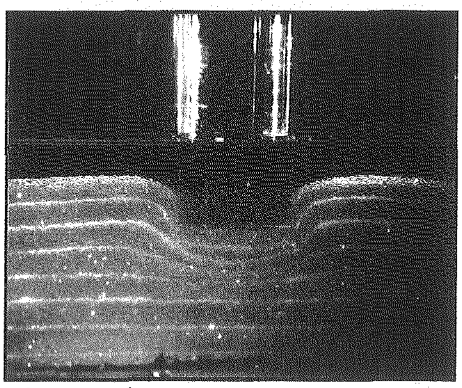

Figure 4,e
Settlement, s = 20 mm

Figure 4
Visualization of the glass material shearing in a bearing capacity test.

Axial strain of the specimen was measured on the lateral surfaces by means of two "Local Deformation Transducers"[(3),(4)]. Eight proximeters were put close to the lateral surface to measure the average lateral strain[(3),(4)].

Fig.5 shows the variations of shearing stress, principal stress ratio, and volumetric strain with axial strain for the glass material, together with those of Toyoura sand and SLB sand, obtained by Park et al. (1991).

Data obtained from another series of PSC tests for Toyoura sand[(5)] showed that the behavior, in terms of the $\sigma_1/\sigma_3 \sim \varepsilon_a$ relationship, under a confining pressure of σ_c=0.05 kgf/cm² is very similar to that under σ_c=0.15 kgf/cm². Therefore, the results acquired through this study mean high values for the shear strength (τ=0.53 kgf/cm²) and friction angle ($\phi \approx 65°$) of the glass material.

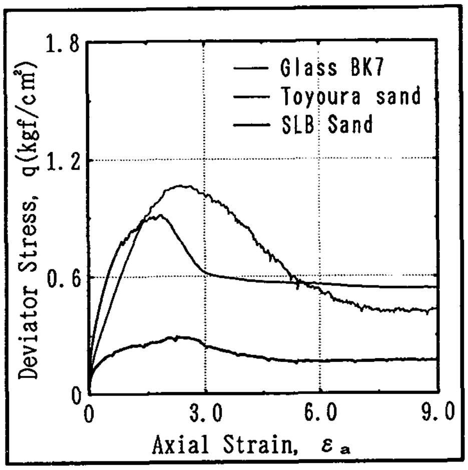

Figure 5,a

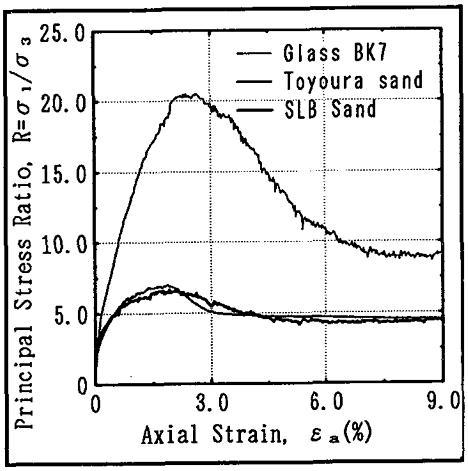

Figure 5,b

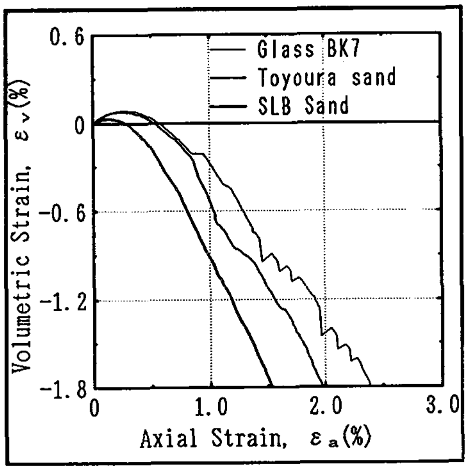

Figure 5,c

Figure 5
Behaviour of the:

glass material : PSC, σ_c=0.05 kgf/cm², e=0.840,

SLB sand[(3),(4)] : PSC, σ_c=0.05 kgf/cm², e=0.549,

Toyoura sand[(3),(4)] : PSC, σ_c=0.15 kgf/cm², e=0.661.

At the end of the PSC test, at a strain level of ε_a=12%, a clear shear band, shown in Fig. 6, was observed. The shear band had a width of about 23 mm or approximately 21 times as thick as the particle's size.

This width is fairly large when compared, on one hand with the geometry and size of the LAT model, and on the other hand with the diameter of the glass cylinder.

Generally, if the LAT model is small, the formation and development of shear bands will be obstructed by its rigid boundaries. This fact implies the importance of the shear band thickness as a "design" criteria for the geometry and size of both the LAT model (glass specimen) and footing (glass cylinder).

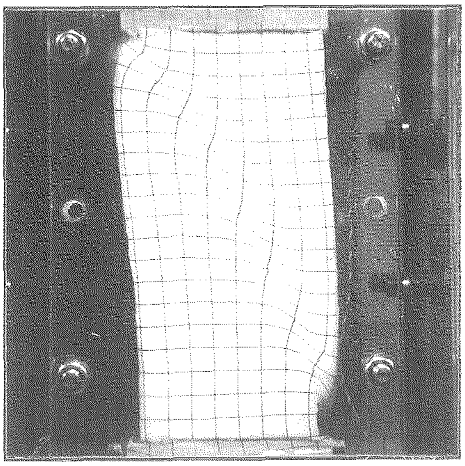

Figure 6
Failure pattern of the glass particles in PSC test, at ε_a = 12%, σ_c = 0.05 kgf/cm², e=0.840.

CONCLUSIONS

In order to expand the application of Laser-Aided Tomography for granular structure models, glass particles with the representative size of 1 mm were used as a model for surface deposit. Conclusions obtained in the course of this work are summarized as follows:

(1) 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. This is a way to overcome the problem of deteriorating visual information quality with decreasing grain size.

(2) Within the LAT experiments, the use of the glass cylinder (diameter = 50 mm) as footing in bearing capacity tests caused surface heaving of the particle deposit. A fairly big dilatation occurred, but no shear band was observed.

(3) A PSC test enabled us to find the relatively high value of the shear strength and friction angle of the glass material and showed that the thickness of the shear band under fairly low confining pressure is about 23 mm or nearly 21 times as thick as the representative particle size.

(4) In order to make the LAT model experiment closely resemble in situ conditions, we suggest that the model apparatus be redesigned at a new scale. The shear band thickness could serve as a "design" criteria for the geometry and size of both the LAT model (glass specimen) and footing (glass cylinder).

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APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

D_{50} = Diameter at which 50 % of the soil is finer
e = Void ratio of soil
e_{max} = Void ratio of soil in loosest condition
e_{min} = Void ratio of soil in densest condition
G_s = Specific gravity of solids
q = Deviator stress
s = Settlement
U_c = Uniformity coefficient
ε_a = Axial strain
ε_v = Volumetric strain
σ_c = Confining pressure
τ = Shear stress
ϕ = Friction angle