3. VISUALIZATION OF CHANGES IN GRANULAR FABRIC

To grasp the overall behavior of a granular material, it is necessary to study the dynamic changes in its interior fabric. Konagai et al. (1992) have developed a new experimental method, Laser-Aided Tomography (LAT), which enables the visualization of all coarse particles interlocking with one another in a three-dimensional model. Subsequently, Konagai and Rangelow (1994b, 1995) used LAT for smaller particle sizes, expanding its application to analyses of structures made up of finer grains such as sand.

In Laser-Aided Tomography, a granular structure model made up of particles of crushed optical glass immersed in a liquid with the same refractive index becomes invisible. An intense laser-light sheet (LLS) is then passed through the model illuminating the contours of all the particles on a cross-section optically cut by the LLS. Thus, scanning the model with LLS enables us to observe its entire image of deformation (Figure 7).

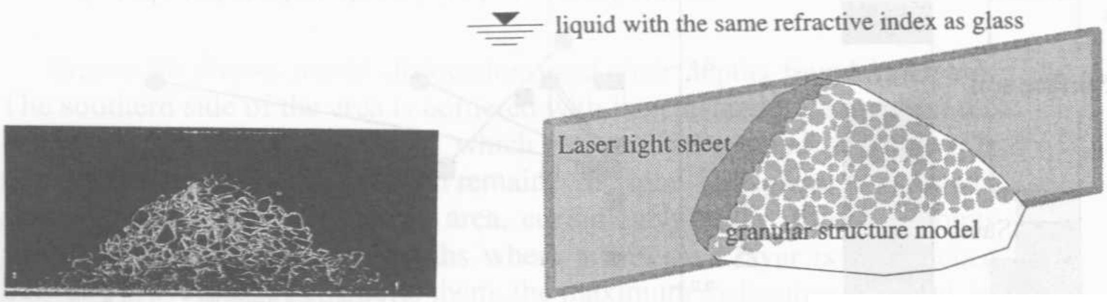
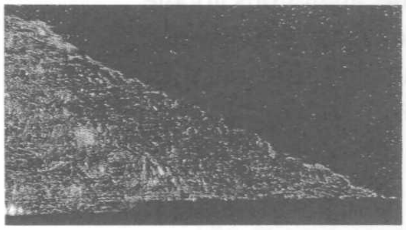
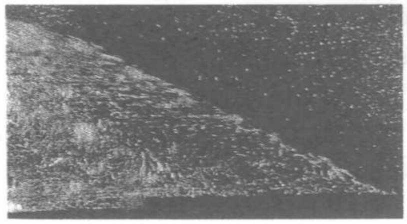


Figure 7. Laser-Aided Tomography

A course of LAT experiments began with a dynamic failure test of embankment-shaped models (Figure 8a, 8b). A sinusoidal shake was given to the model's base, and its amplitude was increased linearly as the time went on (4 gal/s). The embankment surface began to slide when the base acceleration exceeded a threshold, and this failure was accompanied by a considerable dilation (Figure 9). This threshold acceleration increased with increasing excitement frequency (Figure 10), and this tendency became clearer as the grain size increased. The curves in Figure 10 exactly look like the one showing the variation of a half-sine acceleration pulse that required for a rectangular rigid block to be overturned (Housner, 1963). When a rectangular block is overturned, the center of its gravity must be lifted to a certain extent (Figure 11a). This process is physically identical to the dilating process of a slope. In other word, a certain amount of kinetic energy, or velocity, is needed for a slope failure to be initiated. Taking derivative of constant ground velocity with respect to time yields acceleration increasing linearly with frequency, and this is consistent with the observed variation of the threshold acceleration.



(a) t=5s, acceleration=20gal



(b) t=7s, acceleration=28gal

Figure 8. Cross-section of embankment model

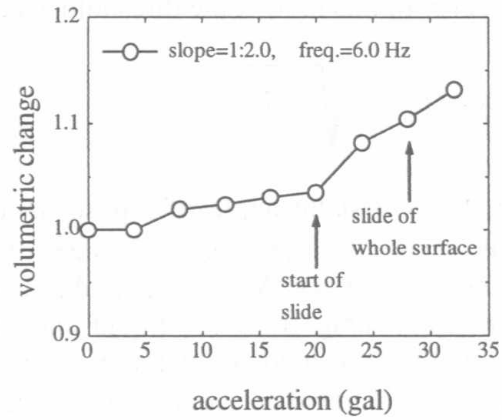
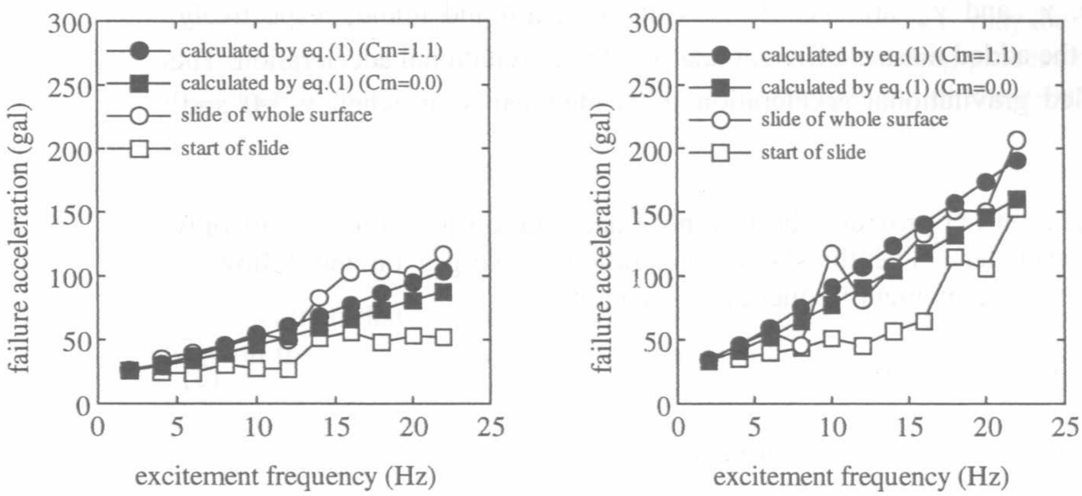
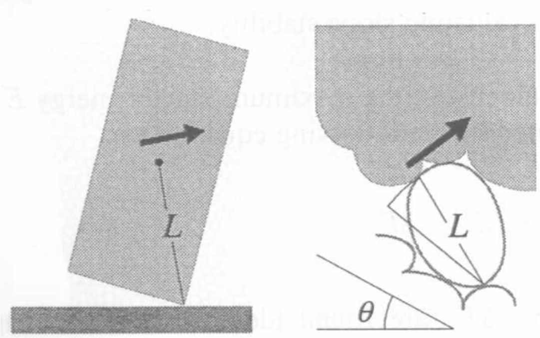


Figure 9. Volumetric change $V_{dynamic}/V_{static}$ of embankment model



(a) slope=1:2, 2mm<grain<5mm (b) slope=1:2, 5mm<grain<12mm

Figure 10. Variation of failure acceleration with excitement frequency



(a) Overturning block **(b)** dilating process

Figure 11. Conceptual model of surface slide

The physical meaning of slope failure is, thus, quite analogous to the one of an overturning block. Using this analogy, Konagai (1994a) has proposed a simple conceptual model, which is schematically illustrated in Figure 11b. In this model, the threshold acceleration a is given as:

$$a = g(\theta_0 - \theta)\sqrt{1 + \frac{L}{g}\omega^2} \tag{1}$$

where, θ_0 is a static angle of repose, θ is the inclination of the sliding surface, L is the representative size of surface roughness and ω is excitement frequency. When a granular assemblage is put within a liquid, buoyancy and drag from the liquid should be taken into account. Their effect on the threshold acceleration is easily incorporated just by using modified gravitational acceleration g' which is defined as:

$$g' = \frac{\gamma_g - \gamma_w}{\gamma_g + C_m \gamma_w} g \tag{2}$$

where, γ_g and γ_w are specific gravities of grain and liquid, respectively, C_m is the added mass coefficient and g is the gravitational acceleration. The modified gravitational acceleration g' is identical to g when γ_w=0 and C_m=0.

Equation (1) provides the threshold acceleration as a function of only four parameters. The threshold acceleration converges on the following value as the excitement frequency ω increases:

$$a \cong \omega\sqrt{gL}(\theta_o - \theta) \tag{3}$$

Dividing equation (3) by ω yields:

$$v = \frac{a}{\omega} = \sqrt{gL}(\theta_0 - \theta) \tag{4}$$

Both the threshold acceleration a and the velocity v, thus, can be the key indices for evaluating slope stability.

Given the velocity v, the maximum kinetic energy E of the surface mass M is approximated by the following equation as:

$$E \cong \frac{1}{2}Mv^2 = \Delta E_p + \Delta E_f \tag{5}$$

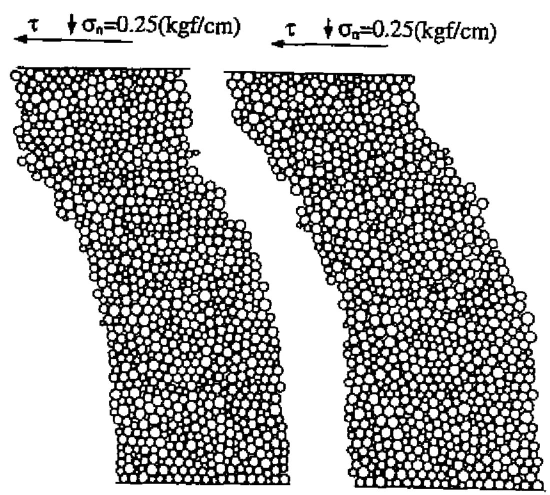
where, ΔE_p and ΔE_f are found identical to the change in the potential energy and the energy consumed through friction, respectively, during the process for the mass M to reach its critical point of stability (Konagai and

Sato, 1994c). Therefore, equation (1) is rewritten, in terms of the energy E required to bring the surface mass to its critical point, as:

$$a = g'(\theta_0 - \theta)\sqrt{1 + \frac{E}{2M}\omega^2} \tag{6}$$

The energy in equation (5) includes only two terms related to dilation and friction. However, the adaptability of this equation will be enhanced by adding up the other necessary terms that describes energies for particle crushing and for letting a water-saturated granular assemblage dilate against the negative pore pressure caused by suction, for instance.

Among the four parameters used in equation (1), the static angle of repose θ_0 is possibly determined by piling up a granular material on an adjustable slope, and then, by tilting it little by little. The surface roughness L is actually a very important parameter directly related to the change in potential energy during the dilating process of a slope. Assuming tentatively that roughness L can be represented by the typical grain size, equation (1) yields solid circles in Figure 10, which eventually agree fairly well with the observed values (open circles). The roughness L, however, may be more closely related to the extent of dilation during shear-banding process rather than a grain size. Figure 12 shows numerical simulations of shear-banding process of two granular columns· one on the left is made up of circular elements, and that on the right is a pile of octagonal elements (Matsushima et al., 1996). Both have about the same void ratios. Left and right sides of each granular column are assumed to be touched together. It is noted in this figure that the extent of dilation is larger in the assemblage of octagonal elements than that of circular elements. The roughness L, thus, depends not only on the representative grain size but also on the other factors including grain shape, void ratio and so on, and must be determined from the geotechnical aspect.



(a)circular elements (b)regular octagonal elements

Figure 12. Shear-banding within granular assemblage