KEY PARAMETERS GOVERNING DYNAMIC GRANULAR SLOPE STABILITY

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Stability of a granular slope during earthquakes is usually evaluated assuming Coulomb's friction on its internal shear plane, and thus, acceleration of seismic motion is an important parameter for the evaluation of its stability. Irreversible deformation of a granular slope however is mainly due to a change in its fabric accompanied by noticeable dilation, through which a certain amount of energy is consumed. It is therefore noted that ground velocity as well as acceleration is another important key providing a stability index. On the basis of findings through experiments by means of a new visualization technique, Laser-Aided Tomography, a simple approach for the evaluation of dynamic slope stability is discussed.

Key words: granular slope, slope stability, dilation

1. INTRODUCTION

Earthquake-induced failures not only in natural but also in artificial slopes have caused considerable amounts of damage throughout history. On the other hand fortunately, no rock-fill dam in Japan has been seriously damaged so far. This seemingly suggests that rock-fill dams have been rationally or conservatively designed. It has been, however, clarified through many observations of their seismic responses that acceleration at the top of an embankment is liable to be several times stronger than its base acceleration, and often exceeds the design seismic coefficient. A slope subjected to a strong shake of this extent must have reached its critical state even though the resulting deformation was just a minor problem as it happened. It is noted in this discussion that pseudo-static analysis used in the design process provides an index of stability but no information on deformation associated with surface slide, which strongly affects the serviceability of a granular structure after earthquakes. It would be therefore of great importance for visual information of large deformation within a granular material to be provided.

Since natural materials including rocks are not easily tested in laboratory conditions, a model experiment is a useful tool offering an important insight into the features of a granular assemblage. This paper describes some findings observed through a course of LAT experiments, which allows the whole-field image of deformation in the interior of a model to be obtained as well as every discrete particle's shape and motion.

2. THRESHOLD ACCELERATION

Shear-banding within a granular material often develops into a general surface failure. It is however not easy to observe the real-time process of shear-banding in the interior of a granular material. Konagai\(^1,2\) et al. have developed a new method, Laser Aided Tomography (LAT: Fig. 1), that allows the whole-field image of deformation in the interior of a granular structure model to be visualized. In this method, 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.

Dynamic failure test of embankment-shaped models (Fig. 2a, 2b) were conducted using LAT. 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 (Fig. 3). This threshold acceleration increases with increasing excitation frequency (Fig. 4), and this tendency becomes clearer as the grain size increases. The curve in Fig. 4 exactly looks like the one showing the variation of a half-sine acceleration pulse that required for a rectangular rigid block to be overturned.\(^3\) When a rectangular block is to be overturned, the center of its gravity must be lifted to a certain extent (Fig. 5a). This process is physically identical to the dilating process of a slope. In other word, a certain amount of
liquid with the same refractive index as glass

Laser light sheet
granular structure model

Fig. 1. Laser-Aided Tomography.

(a) t=5s, acceleration=20gal
(b) t=7s, acceleration=28gal

Fig. 2. Cross-section of embankment model.

Fig. 3. Volumetric change ($V_{\text{dynamic}}/V_{\text{static}}$) of embankment model.

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.

The physical meaning of slope failure is, thus, quite analogous to the one of an overturning block. Using this analogy, Konagai\textsuperscript{2)} has proposed a simple conceptual model, which is schematically illustrated in Fig. 5b. In this model, the threshold acceleration $a$ is given as:

$$ a = g' \left( \theta - \theta_i \right) \sqrt{1 + \frac{L}{g'} \omega^2} \quad (1) $$

where, $\theta_i$ is a static angle of repose, $\theta$ is the inclination of the sliding surface, $L$ is the representative size of surface roughness and $\omega$ is excitation 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:

$$ g' = \frac{\gamma_s - \gamma_w}{\gamma_s + C_m \gamma_w} g \quad (2) $$
where, $\gamma_g$ and $\gamma_w$ 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 $\gamma_w=0$ 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 $\omega$ increases:

$$a \approx \omega \sqrt{gL(\theta_0-\theta)}$$

(3)

Dividing equation (3) by $\omega$ yields:

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

(4)

Both the threshold acceleration $a$ and the velocity $v$, thus, can be the key indices for evaluating slope stability. Among the four parameters used in equation (1), the static angle of repose $\theta_0$ 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 Fig. 4, 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. Fig. 6 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\(^4\). 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 the other factors including grain shape, void ratio and so on, and must be determined from the geotechnical aspect.

3. DEPTH OF FAILURE SURFACE

It is a great concern for dam engineers where in a dam a possible failure surface is likely to be formed, because its depth may affect greatly the serviceability of the dam. In design processes, this estimation is commonly done by means of such conventional stability analyses as the circular slip surface method. A granular assemblage in its critical state, however, exhibits very complicated features under dynamic loading, which may affect the location of a possible failure surface.

Fig. 7 shows mid-cross-sections of embankment models visualized in the course of LAT experiments. A linearly increasing sinusoidal shake (4 gal/s) was applied to the models' bases. It is noted here that the slip surface becomes thicker as the excitement frequency increases.

An actual slip surface is neither an ideal circular arc nor one-dimensional uniform layer with an infinite extent. However, to discuss the observed phenomenon in a simpler manner, an infinite surface layer illustrated in Fig. 8 is discussed herein. In order to discuss its plastic deformation, variation of internal friction angle with respect to shear strain should be provided. It is however, not easy to obtain...
a reliable variation through conventional geotechnical tests because strain localization develops within a specimen. To avoid strain localization to some possible extent, no small number of triaxial tests have been performed on a specimen with a height equal to its diameter \((H/D=3.5)\) and smooth interfaces at both ends.\(^5,6\) Fig. 9 shows the variations of both mobilized friction angle and dilatancy angle with respect to the shear strain.\(^5\) Solid circles and triangles show the variations observed in the triaxial tests with \(H/D=1\). It is clear from this figure that the induced shear strain is underestimated in the conventional triaxial test. The difference seems to appear even before the peak value of stress ratio is reached.

The variation of mobilized friction angle obtained through triaxial tests with \(H/D=1\) (solid triangles in Fig. 9) is tentatively approximated by a tri-linear curve in Fig. 10, and used to describe plastic deformation of a column element cut out of the infinite surface layer. The column is sliced into several sub-elements, and each sub-element is assumed to be deformed in a quadratic shape. A half sine pulse was then given to its base. Fig. 11 shows the variation of plastic deformation of the column with time. No sooner than the base acceleration reaches the threshold level, that is, about 60 ms after the base acceleration starts to increase, the entire length of the column begins to exhibit plastic flow. Finally the column is left deformed after the excitation is over.

The residual deformation of the column depends not only on the intensity of the half-sine pulse but also on the duration of the pulse as shown in Fig. 12. Increasing the excitation frequency (=0.5/duration time) and/or the intensity of the pulse as well, the steepest bent left on the deformed column comes closer to its bottom. Since the sharpest bent left on the column can be viewed as the location of failure surface, this tendency depicted in Fig. 12 is consistent with the locations of failure surface observed in the LAT experiments. This unique feature of a granular column can be seen when the curve showing the variation of internal friction angle with shear strain has a gradient upward to the right before the peak value is reached (arrow sign in Fig. 10). Within this range of shear strain, there appears a progressive wave of plastic deformation that propagates very slowly up through the column and fades away immediately after the excitation is over. When the very initial gradient of the curve in Fig. 10 is downward to the right, which is rather unrealistic, shear-banding always takes place at the bottom of the column. The numerical simulations given herein is suggestive of the important effect of the excitation frequency. Needless to say, an
actual seismic motion is not an ideal sinusoidal motion. Therefore, it may be worth-thinking of a frequency-equivalent parameter which can be defined by dividing the maximum peak-ground acceleration by the maximum ground velocity.

4. CONCLUSIONS

A granular assemblage exhibits unique features when it is dynamically deformed: some of which are extremely difficult to be described in terms of the conventional continuum mechanics. A series of LAT experiments, which allow entire images of deformation of granular structure models to be visualized, have conducted to observe the failure process ongoing in the interior of a granular slope model. The findings and conclusions obtained through the study are summarized as follows:

(1) Shear-banding of a granular assemblage is attended with a noticeable dilation that affect greatly the failure process of a granular slope. Taking into account the considerable dilation observed in the LAT experiments, a conceptual model of surface failure was presented. The model is quite analogous with that for an overturning block of which center of gravity must be once lifted to be overturned. The threshold acceleration is given as a function of four key parameters; static angle of repose $\theta$, slope inclination $\beta$, roughness of the failure surface $L$, and excitement frequency $\omega$.

(2) The curve showing the variation of threshold acceleration with excitement frequency $\omega$ is upward to the right. The gradient of the curve, namely the threshold velocity, converges on a constant value as the frequency increases. This indicates that a certain amount of kinetic energy is needed for a surface granular layer to reach its critical state through its dilating process. Both the threshold acceleration $a$ and the velocity $v$, thus, can be the key indices for evaluating slope stability.

(3) Excitation frequency as well as the intensity of a shake given to a slope is likely to affect the depth of a possible failure surface: which has been observed through the LAT experiments. A slip surface of a granular slope model becomes thicker as the excitement frequency increases. The observed tendency is consistent with that confirmed through the numerical simulations.

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