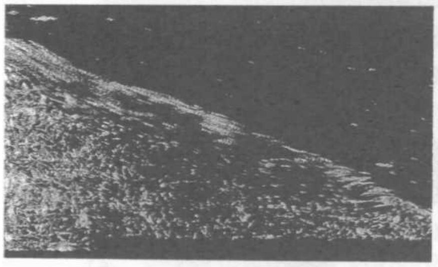
4. DEPTH OF FAILURE SURFACE

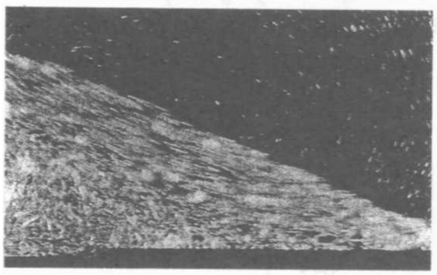
Earthquake-induced acceleration varies with time. As the acceleration comes close to the threshold acceleration a in equation (1) (or equation (6)), available resisting force acting on a potential failure mass drops down to its residual value, and when the acceleration further increase, the motion of the failure mass will be accelerated suddenly. The necessity of predicting slope displacements thus emerges, because the serviceability of a slope after an earthquake is controlled by deformations. Using the analogy between a potential landslide and a block resting on an inclined plane, Newmark has developed a simple method for prediction of the permanent displacement of a slope subjected to an arbitrary ground motion. This model has a number of attractive features because of its simplicity, and effects of various parameters on the slope displacements have been investigated by a number of researchers. The method, however, provides the information on deformations associated with slope failure but no information regarding where in a granular slope a failure surface is likely to be formed. In general, failure surface tends to develop through the weakest part in the interior of soil, being affected by the presence of boundaries. Given a rather homogeneous granular material, however, it is not easy to locate a possible failure surface. Figure 13 shows mid-cross-sections of a granular slope 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 Figure 14 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 (Lade, 1982 and Ibsen, 1994). Figure 15 shows the variations of both mobilized friction angle and dilatancy angle with respect to the shear strain (Lade, 1982). 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 Figure 15) is tentatively approximated by a tri-linear curve in Figure 16, 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. Figure 17 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 excitement is over.



a) Excitement frequency=4Hz,
base acceleration=51.2 - 54.0 gal



(b) Excitement frequency=22Hz,
base acceleration=153.4 - 162.3 gal

Figure 13. Change in the depth of surface slide due to excitement frequency

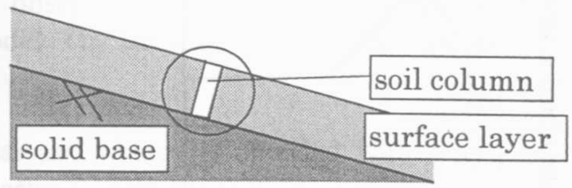


Figure 14. Infinite slope model

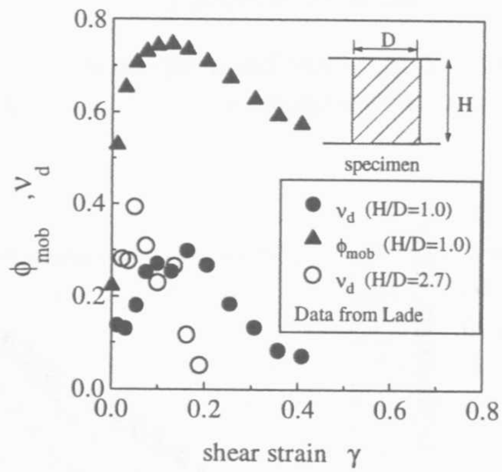


Figure15. Variation of both mobilized froction angle and dilatancy angle with shear strain (Lade 1982)

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 Figure 18. Increasing the excitement 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 Figure 18 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 Figure 16). 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 excitement is over. When the very initial gradient of the curve in Figure 16 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 excitement 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.

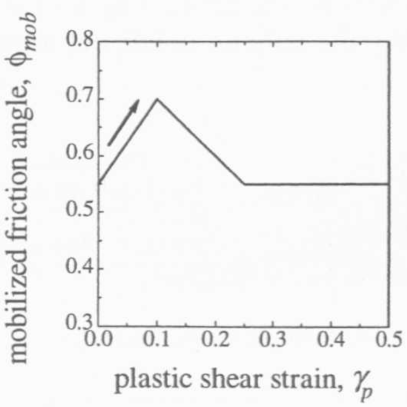


Figure 16. ϕ_{mob}- γ_p relationship used in the analysis

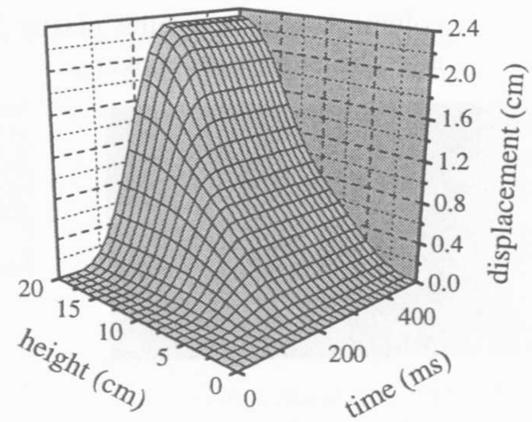


Figure 17. Time history of displacement distribution within column

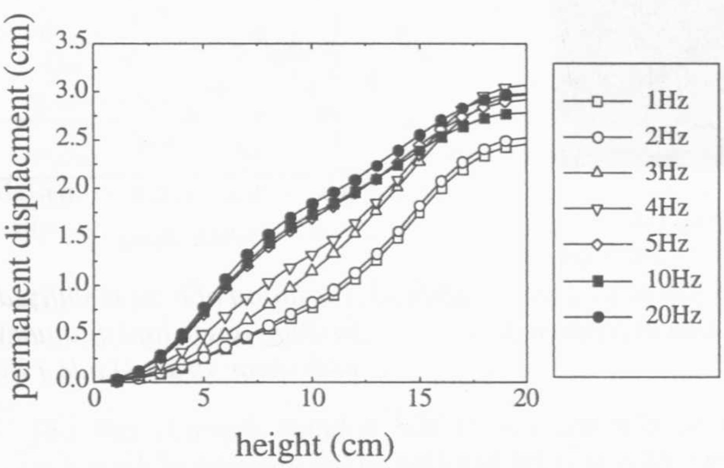


Figure 18. Variation of deformation mode with excitement frequency

5. CONCLUSIONS

The Great Hanshin Earthquake of 1995 has left signs of its intense seismic motion in soils at various places in Kobe, and these signs are found to be correlated somehow with the features of disaster at those places. Its strong shake was responsible for a number of slope failures. Considerable displacements seem to have been build up even within nearly flat soil deposits, which fact was proved by the data regarding dislocated rings of manholes in Kobe. These dislocations left on ring joints indicate large strains that are much bigger than the strain at which a typical dense sandy material exhibits its peak strength. The importance of studying dynamic behaviors of a granular material experiencing this big strain, thus, emerges from the findings through the investigation.

A granular assemblage exhibits unique features when it is dynamically deformed: some of which are extremely difficult to describe 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 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 material. 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 θ_0, slope inclination θ, roughness of the failure surface L, and excitement frequency ω.

2) The curve showing the variation of threshold acceleration with excitement frequency ω 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 granular slope 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) Excitement frequency as well as the intensity of a shake given to a slope is liable to affect the depth of a possible failure surface: which phenomenon 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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