A STUDY ON DYNAMIC FAILURE MECHANISM OF FILL TYPE DAM BASED ON VIBRATION FAILURE TESTS ON SAND MODELS

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SUMMARY

A new analysis model expressing the failure mechanism of a fill dam based on the results of vibration failure tests of dam models to evaluate earthquake-resistant strength is presented taking into consideration slope sliding failure due to earthquake. The concepts of potential sliding zone and potential sliding plane are introduced in the model. Based on this model, it is made possible for earthquake response calculation results to be examined from the viewpoint of dynamic failure.

1. INTRODUCTION

The history of fill dams is long and there is a greater number of these dams having been subjected to strong earthquakes compared with dams of other types. With regard to earthquake resistance, research has been done from various angles, through earthquake observations, vibration tests, numerical response analyses, and model experiment analyses. As the accumulation of earthquake observation records increased, it was learned that with dams of heights 15 m and more, there have been very many cases of damage not being sustained even when the dam bodies shook from accelerations greater than the maximum accelerations corresponding to design seismic coefficients, while there have been cases of damage occurring due to input earthquake motions of relatively low acceleration level.

In order for rational earthquake-resistant design to be carried out, it is important for earthquake-resistant strength to be correctly understood. In evaluating the earthquake-resistant strength of a fill dam, one of the difficulties that may be first cited is the complexity of the mechanical properties of dam construction materials--including foundation materials in cases. Further, it should be added that unlike an ordinary framed structure, it is a massive one and the stress conditions are complex. The strengths of the materials are evaluated by shear strength, and it must be added especially that there is dependence on the stress conditions.

Although it is not an easy matter to clarify the earthquake-resistant strength of such a structural body, at the present time when it is becoming possible for earthquake responses of fill dams to be calculated by numerical

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analyses, this is a basic problem the solution of which is urgently called for. It is with this purpose that the authors for more than a dozen years have carried out vibration failure tests using analysis models of fill dams, and have performed analyses on the results. Recently, as a result of experiments and analyses on two-dimensional models (no water impoundment) built of sand, it was succeeded in making a mathematical model which can explain the sliding failure condition of a slope surface both qualitatively and quantitatively, and this will be reported. It is considered that with this model it now appears a method can be found to evaluate the results of earthquake response analyses of fill dams from the viewpoint of sliding failure.

2. OUTLINE OF MODEL AND EXAMPLE OF CALCULATION OF STRESS DISTRIBUTION

The examples given are two-dimensional models of a dam with a height of 70 cm and upstream and downstream slopes of 1:2, built on a shaking table. The material of the models is Onahama sand of effective diameter D = 0.14 mm, uniformity coefficient U_c = 1.32, and specific gravity 2.71. Since the moisture content of sand influences rigidity, angle of internal friction, and cohesion, a double-cell triaxial testing machine was employed, and triaxial testing was performed under extremely low restraining pressures (0.07 - 0.3 kgf/cm^2). Further, that rigidity increases with increase in restraining pressure was confirmed by measurements of propagation velocities of wave motions. Moisture contents, based on the results of preliminary vibration failure tests, were taken to be 1.19 to 2.4% so that typical failure conditions would be produced, while densities were similarly taken as 1.3 g/cm^3 to 1.47 g/cm^3.

With regard to the models, resonance tests at low acceleration levels, or failure tests by sine wave vibrations with frequencies kept constant were carried out. In connection with the latter tests, the densities of various parts of the model cross sections were measured before testing, immediately before occurrence of failure, and after failure, and cohesion was determined. Details of the tests are omitted here.

Figure 1 is an example of stress conditions calculated based on the physical properties of the material determined as described above. As the input waveform, stationary sinusoidal waveforms of lengths of 10 to 15 waves were used in correspondence with the vibration failure tests. The damping ratio was taken to be 15% estimated from the results of resonance vibration tests. The Poisson's ratio was made a constant value of 0.45 disregarding strain dependency. Response calculations were carried out assuming the foundation of the dam to be a rigid body, and performing direct integration emplying the finite element method. The characteristics of the model materials were considered, and in case tension was produced in principal stress, the rigidity of the element concerned was reduced, the nonlinear properties were calculated by the equivalent linear method, and the solution was made to converge.

3. METHOD OF STABILITY ANALYSIS

3-1 Analysis Theory

The method of analyzing stability against sliding of the slope of the dam

model may be described in sequence as follows:

i) The shear strength (τ_s) of the dam body material is expressed by the formula below using cohesion (c) and angle of internal friction (ϕ):

$$\tau_s = c + P \tan \phi$$

where, P is normal stress.

ii) Calculations are carried out on the responses of the dam body, and the stress conditions inside the dam body are determined.

iii) The shear stress (τ) and shear strength (τ_s) inside the dam body obtained from stress calculations are compared, and a portion where shear stress exceeds shear strength is taken to be a potential sliding zone.

iv) The directions of potential sliding are established from the stress conditions of the various points obtained by stress calculations, the directions of adjacent points are tangentially connected, and the potential sliding plane is prepared inside the potential sliding zone.

v) A potential sliding plane is formed continuously inside the dam body, and sliding occurs when this plane reaches the surface of the dam.

Needless to say, it is necessary for actual mechanical values to be used in the stress calculations of ii) above, but the main points of the concept of this method are given in iii) to v). In effect, the potential sliding zone and the direction of potential sliding are assumed to exist with the condition that these are formed continuously inside the dam body. These will next be explained.

3-2 Characteristics of Local Stresses in Dam Body

The diagram shown in Fig. 2 is Mohr's circle and is for the purpose of explaining the concepts of potential sliding zone and potential direction of sliding at a single point. A fill dam is a massive structure, and stress conditions and strengths inside the dam body are not uniform, varying greatly according to location. Displacements and deformations of adjacent points influence each other, and restrain each other. Stress conditions vary locally. For example, when partial sliding occurs stresses are redistributed, and although stress conditions vary locally, they are internally balanced, and there is hardly any difference as a whole. In case vibration load is applied, such a trend will be further enhanced. It is practically impossible to determine such stress conditions as they vary with time considering the complex mechanical characteristics of the material. Therefore, it was hypothesized that a stress condition exceeding the strength of the material (termed overstressed condition) exists locally. It is considered that this hypothesis is reasonable for a limited local area.

Figure 3 shows the stress conditions of the entire dam body recalculated

on assuming occurrence of sliding at a part of the dam body for relative displacement to occur, with this converted to reduction in rigidity. In the figure, C_1 indicates the cohesion of the surface layer and C_3 that of the various parts in the interior, As for ϕ, it is angle of internal friction, while the numerals given the isopleths comprise the difference between shear force and shear strength obtained in response calculations expressed in units of 10^{-4} kgf/cm^2, with + values showing potential sliding.

Figure 3(b) is the stress condition when the rigidity of one element of the dam body in Fig. 3(a) has been reduced to one third. It may be seen that local variations in stress occur, but around this area and for the dam body as a whole there is almost no variation in stress. This shows that it is possible for an overstressed condition to exist locally inside the dam. The potential sliding direction was established in correspondence with such a potential sliding zone. This direction actually is determined by redistribution of stresses, but due to the previously-mentioned reason, it was decided here to establish the zone on both sides of the direction in which sliding was most likely to occur as determined by the calculated stress condition shown in Fig. 2.

When it is taken into account that stress distribution inside the dam during vibration generally varies gradually and that sliding of the slope surface occurs in a fairly broad range, it may be considered that it is possible to assume a potential sliding plane tangentially connecting the potential sliding directions of the individual points, and a potential sliding zone.

3-3 Comparisons of Experimental and Analytical Results

Figure 4 shows examples of stability analyses of sand models used for experiments. In case of exciting at 8 Hz and 400 gal, potential sliding zones (hatched portions) are produced at the dam crest and toe. The two zones are expanded along the slope surface as acceleration is increased, until finally they merge at mid-height of the slope. In this case, the width of the potential sliding zone along the slope is not expanded very much, but the possibility of sliding gradually is increased, and this is judged by the fact that the difference between shear stress and shear strength increases. Also, by joining of the two zones, it is made possible to draw a potential sliding plane passing through the joining point and along the slope, and in addition, the potential sliding plane reaches the surface of the slope.

Based on the above results, it is estimated that sliding of the surface occurs when shaking table acceleration is 425 - 450 gal.

The results of stability evaluation and two experiments are shown together in Fig. 5. Dotted lines are slip lines while dot-dash and dot-dot-dash lines indicate surface configurations of models after failure tests. The accelerations of the shaking table at collapses obtained in the experiments were 456 and 470 gal, respectively, to roughly coincide with calculations, and it can be seen that the slip lines of the two also coincided well. The results of experiments that depths of the slip lines from the slope surface are increased with increased cohesion of the dam body material, and moreover, acceleration at failure is increased, coincide well with the results of analysis by this stability analysis method.

4. INFLUENCE OF ANGLE OF INTERNAL FRICTION OF MATERIAL ON FAILURE

The influence of cohesion on failure has previously been reported. Here, the before-mentioned stability analysis method was used to investigate what kind of effect the angle of internal friction would have, and what kind of relationship there would be with cohesion.

Figures 6(a), (b), and (c) show the results of response calculations when angles of internal friction were 33, 39 and 45 deg, respectively, in case of no friction. In all of these examples, potential sliding zones were produced at crests and slope toes, with these joined at the middle portions of the slopes. As is clearly shown in the figures, it can be estimated that sliding will occur, not from just the crest portion, but from the surface layer of the entire slope. The stress conditions as seen from the standpoint of stability are similar for all three, but the degrees of acceleration differ, and it can be seen there are prominent increases from 170 to 300 to 425 gal in correspondence with the angles of 33, 39, and 45 deg.

Figure 7 shows what the mutual relationships will be when there is cohesion. The cohesive forces in the examples given here are 0.002 kgf/cm^2 at the surface layer, 0.004 kgf/cm^2 at the intermediate layer, and 0.005 kgf/cm^2 at the bottom portion. Figures 7(a), (b) and (c) show the results of investigating the degrees of stability for angles of internal friction of 33, 39 and 45 deg, respectively. Production of potential sliding zones and joining at middles of slopes are similar, and it is possible to draw potential sliding planes passing through the merger areas. However, when accelerations are compared, it may be seen that the accelerations at which similarly stable conditions are reached are 325, 425 and 520 gal in correspondence with angles of 33, 39 and 45 deg, respectively, for very substantial increases. On comparison with the results given in Fig. 6, it is considered that the influences of the two on failure are more or less independent of each other.

Figure 8 shows the relationships of angle of internal friction, cohesion and acceleration at which sliding is possible. It can be surmised that both have significant effects on sliding failures of slope surfaces.

CLOSING REMARKS

In recent years, with development of dam engineering and progress made in numerical analysis methods, it is becoming increasingly possible to successively determine the behaviors of fill dams during earthquake and compare them with the results of earthquake observations. However, the relationships between earthquake response analyses and failures have not been clearly understood, and analyses to clarify the relationships have been performed based on various mechanical assumptions, but it is felt satisfactory results had not been obtained.

The authors built models of fill dams, subjected them to vibration failures to investigate their behaviors in detail, and in addition, carried out analyses based on the results of mechanical tests of the materials and dynamic characteristics tests of the models. As a result, it was succeeded in finding a method of dynamically evaluating the failure mechanisms and failure

strengths of the models. The basis of this method is that since a fill dam is a massive structure, even if shear stress in excess of shear strength of the material were to be produced at a part of the interior of the dam, because of the restraint from the surrounding parts, a balanced state occurs internally so that sliding failure does not progress, and unless conditions for occurrence of general sliding are not met in the part concerned, sliding will not occur.

Although there are still aspects requiring examination regarding methods of expressing and calculating the mechanical properties of materials, it is considered that a way leading to calculation of earthquake response and evaluation of sliding failure of fill dams has been found through this method.

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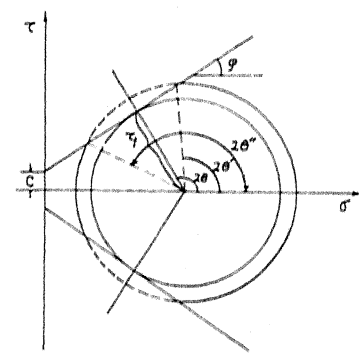

Fig. 2 Stress circle and potential sliding plane.

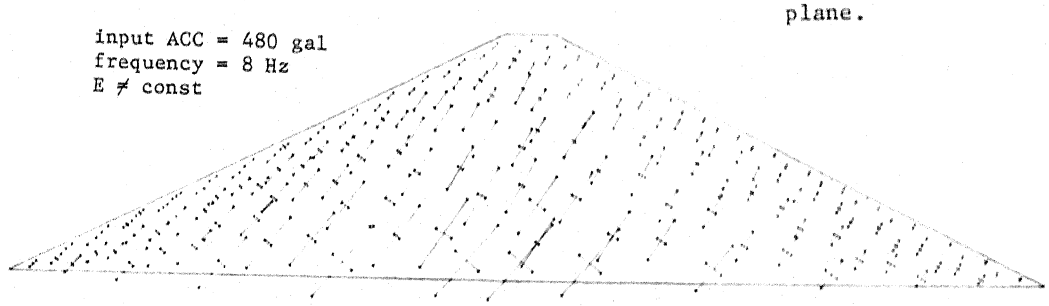

Fig. 2 Principal stress distribution to sinusoidal input wave

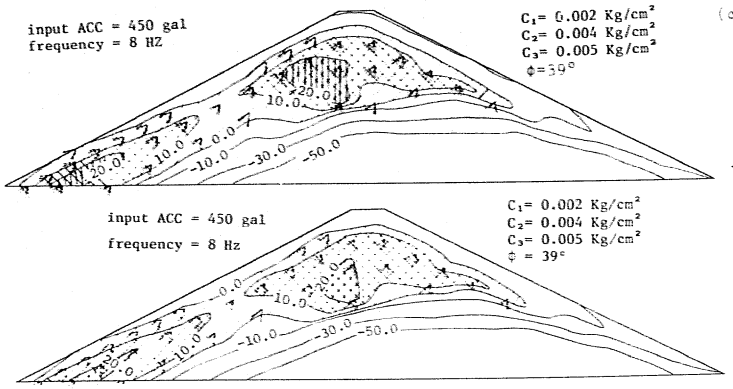

Fig. 3 Influence of partial yielding inside dam on potential sliding zones and directions.

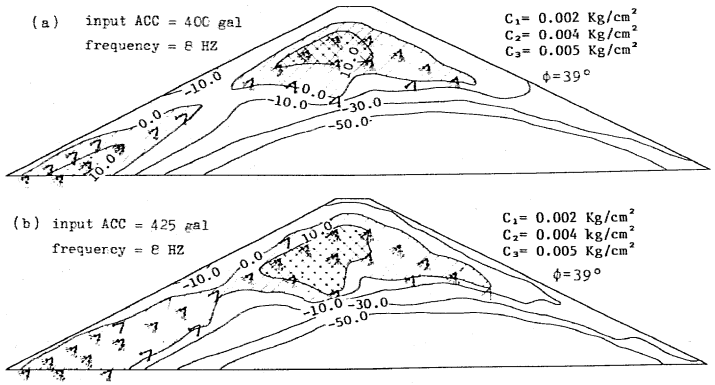

Fig. 4

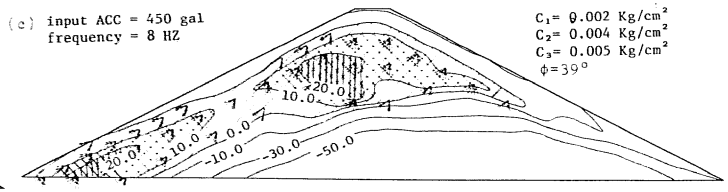

Fig. 4 Results of calculations of potential sliding zones and directions (case of moisture content 1.56%,excitation frequency 8 Hz)

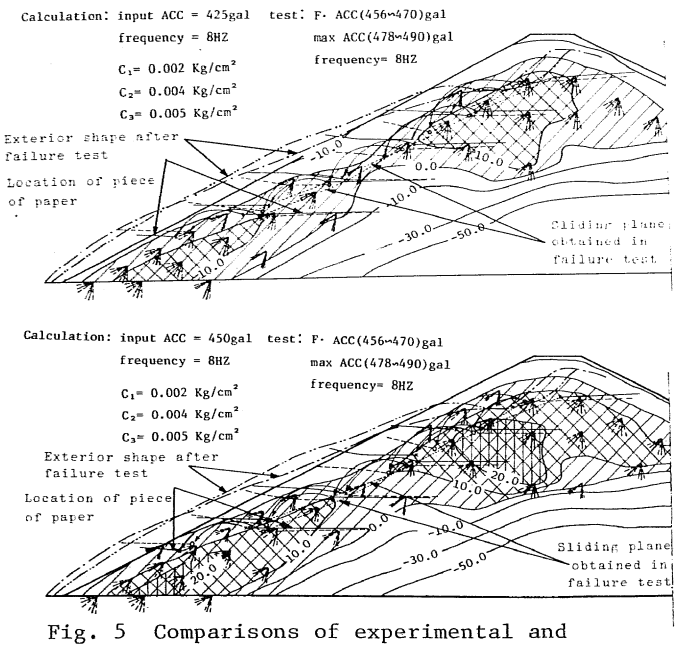

Fig. 5 Comparisons of experimental and calculated results.

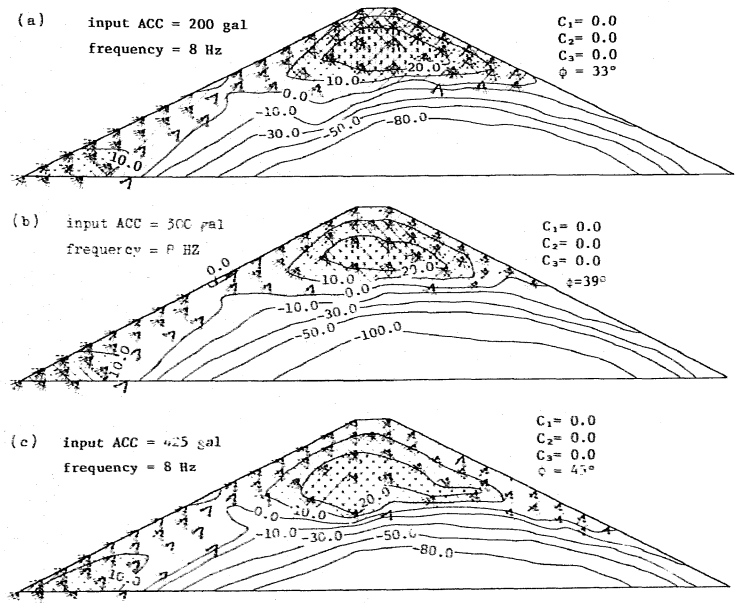

Fig. 6 Results of calculations when varying angle of internal friction (case of cohesion c = 0).

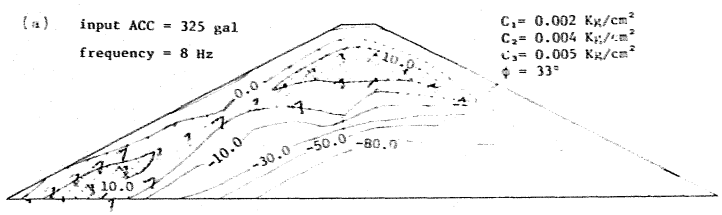

Fig. 7

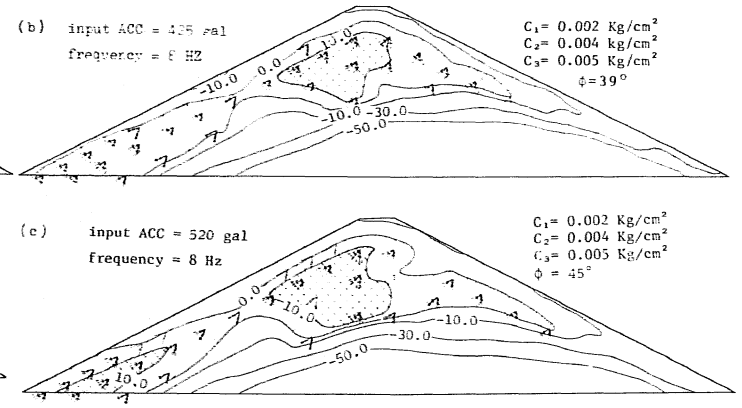

Fig. 7 Results of calculations when varying angle of internal friction (case of cohesion c ≠ 0).

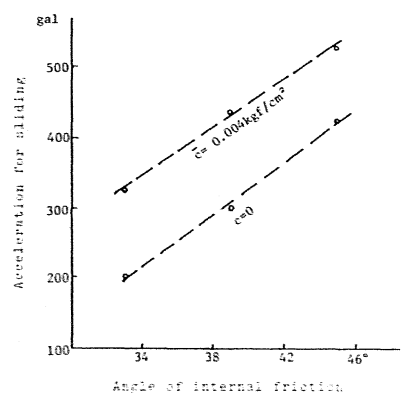

Fig. 8 Relationships of acceleration for sliding with angle of internal friction,cohesion.