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SEISMIC COEFFICIENT IN SEISMIC STABILITY ANALYSIS OF EMBANKMENT

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SUMMARY

This paper presents a relation between the maximum acceleration and seismic coefficient for the seismic stability analysis of embankment obtained from a series of shaking table tests. The tests consisting of 3 kinds of sinusoidal wave and 3 kinds of irregular wave excitation showed that the crest settlement is greatly influenced by the excitation wave form. Three methods to obtain a seismic coefficient are described.

INTRODUCTION

The seismic stability of an embankment is conventionally analyzed by combining the method of limit equilibrium of slopes and pseudostatic method. In the analysis the determination of seismic coefficient and dynamic shear strength of soils is important. However, the relation between the seismic coefficient and the original irregular seismic motion has not been well established.

A series of shaking table tests of model embankments resting on a saturated sand ground were carried out in order to examine the effect of seismic wave form and to estimate the seismic coefficient to be used for a seismic stability analysis.

EXPERIMENTAL METHOD

Model

Six models whose dimension is shown in Fig.1 were constructed in a rectangular shaking box (2.5m long, 60cm high and 68cm wide). These models were respectively excited by different seismic motions.

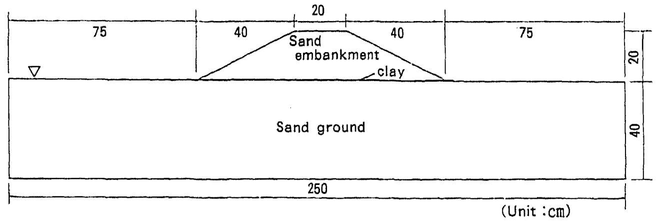

Fig. 1 Model Configulation

The models were made of Toyoura sand. Heat-dried sand was air-pluviated through a sand hopper to make a ground of relative density of 80%. Deaired water was supplied from the bottom of the box. The embank-ment part was made of wet sand (w≒9%) by hand tamping.

Average relative densities of the models ranged from 68 to 79%.

Test Method and Test Conditions

A resonant test and strong shaking tests were conducted for each of the 6 models.

(1) Resonant test

In a resonant test each model was sinusoidally excited under a small acceleration which will not cause a failure or liquefaction by changing the frequency step by step from 5 to 30 Hz.

(2) Strong shaking test

In strong shaking tests each model was excited with different wave form. The excitation wave forms were regular (sinusoidal) and irregular ones.

Table 1 summarizes excitation conditions. Sinusoidal waves with a frequency 2.5, 10 and 5 Hz were used in the case 1, 2 and 3 respectively while a shock type wave shown in Fig.2 was used in the case 4, vibration type waves shown in Fig.2 were used in the cases 5 and 6. The time axis of the wave form for the case 6 is twice of the case 5, though the wave form is the same.

Among the characteristics of the excitation wave form, the acceleration amplitude and the number of cycles Nc are considered substantial factors for the failure of the model. These are easily determined for a regular wave. It was assumed the product of the predominant frequency fo and excitation duration t_d to represent the number of cycles Nc for an irregular wave.

In the strong shaking tests, 5 to 15 steps of different excitation acceleration were applied for each case.

Table 1 Excitation Conditions

Case	Wave Form	Frequency f*)	Duration td	f×td	No. of steps	Max. Acc. Range
1	Regular (N=20)	f=2.5 Hz	8 sec	20	4	117 − 409
2	do (do)	f=10 Hz	2 sec	20	10	172 − 542
3	do (do)	f=5 Hz	4 sec	20	6	90 − 358
4	Irregular (Shock Type)	f_0=5 Hz	5 sec	25	14	94 − 991
5	do (Vibration Type)	f_0=5 Hz	5 sec	25	8	112 − 832
6	do (Vibration Type)	f_0=2.5 Hz	10 sec	25	7	95 − 774

*) f_0= Predominant frequency for irregular wave

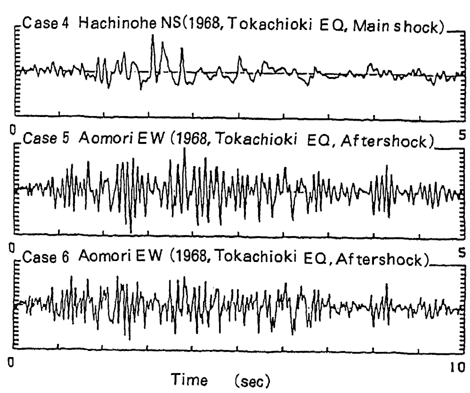

Fig. 2 Excitation Wave Form

Strong Shaking Test Result

(1) Time history

Fig.3 shows examples of time histories of acceleration, pore pressure and crest settlement for the cases where a certain settlement occurred with a relatively large excitation acceleration. The following were observed from such results.

1. At the early stage of the excitation when the excess pore pressure did not build up much, the response acceleration of the model was almost the same as that of the shaking table.

2. The response acceleration was disturbed when the excess pore pressure built up to a certain value. The degree of disturbance was larger in the side horizontal ground than in the ground below the embankment.

3. The response acceleration after the excess pore pressure built up showed a different behavior depending on the excitation motion. It became large in one case and it became small in another.

4. The response acceleration showed a sharp spike indicating a cyclic mobility which can also be shown as a stress and strain relation.

(2) Shear stress

A shear stress was estimated from the observed acceleration records. Fig.4 shows a calculated shear stress from Fig.3.

(3) Relationship between acceleration and crest settlement

The relation between the excitation acceleration and the cumulative crest settlement at each case and excitation stage is shown in Fig.5. This figure indicates the following.

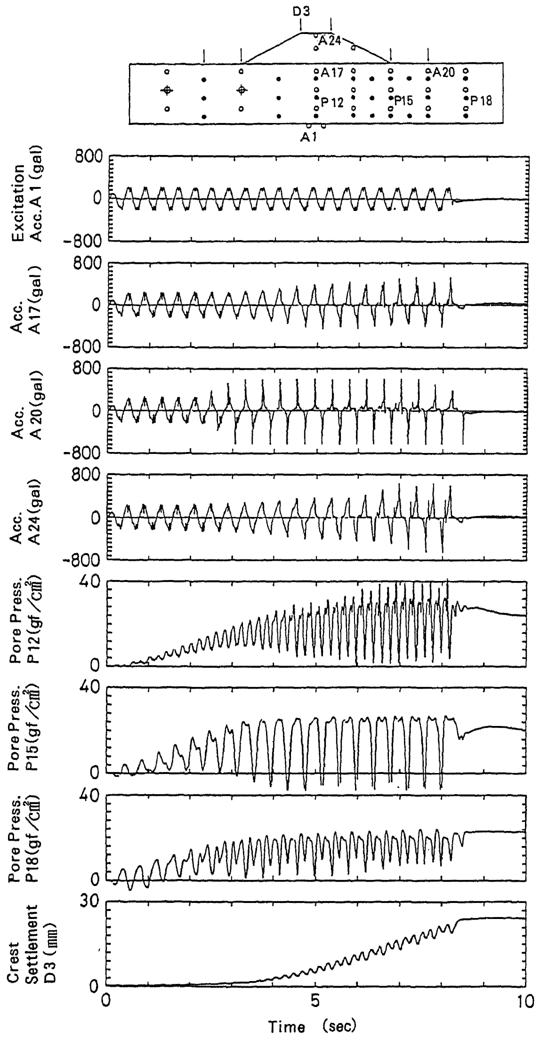

Fig. 3 Time Histories
(Case 1-4, 220 gal Excitation)

1. The excitation by regular waves does not cause much different settlements of the crest due to frequency difference in the range of a settlement of less than 10mm.

When the crest settlement is larger, only a small difference can be seen in the case 1 (f=2.5Hz) and the case 3 (f=5Hz), however, quite a less settlement occurs in the case 2 of higher frequency (f=10Hz) under the same excitation acceleration.

2. In the excitation by irregular waves, a vibration type wave (case 5 and 6) causes larger crest settlement than a shock type wave (case 4). Among vibration type waves, a larger crest settlement occurs in the case 6 with a longer period.

(4) The effect of excitation wave form on crest settlement

The different crest settlements against different excitation wave forms described above were investigated on the basis of the cumulative damage theory.

The dynamic strength of the model ground for the theory was estimated from the measured pore pressure behavior and the calculated shear stress.

Fig.6 shows a relation between recorded cumulative crest settlements and shear stress amplitude under the embankment which was converted to an equivalent number of cycles of 20.

In Fig.6 the data in the cases of regular wave excitation fall on almost the same one curve. This suggests that the difference of crest settlement by the excitation of different frequencies is due to the different response shear stress. However the data of irregular wave excita tion (case 4 to 6) do not exactly fall on a curve of regular wave excitation though they come closer to it than in Fig.5.

Although several reasons for this can be considered, further studies are still needed.

CONSIDERATION OF EQUIVALENT SEISMIC COEFFICIENT

<u>Method</u>

It has been described that the equivalent shear stress estimated from a measured acceleration can be a unified index for a crest settlement. Meanwhile when such a crest settlement is to be related to a seismic stability analysis, it is needed to convert a seismic motion into an equivalent seismic coefficient, to estimate a dynamic strength of a soil and to evaluate a stability analysis result. The equivalent seismic coefficient is estimated by one of the following methods.

a) Semi-theoretical estimation by the cumulative damage theory

The theory is applied for the response acceleration wave form assuming its proportion to dynamic shear stress, which can be approximated by the excitation acceleration wave form assuming the response as a quasi-rigid body and the material characteristics, i.e., a damage curve.

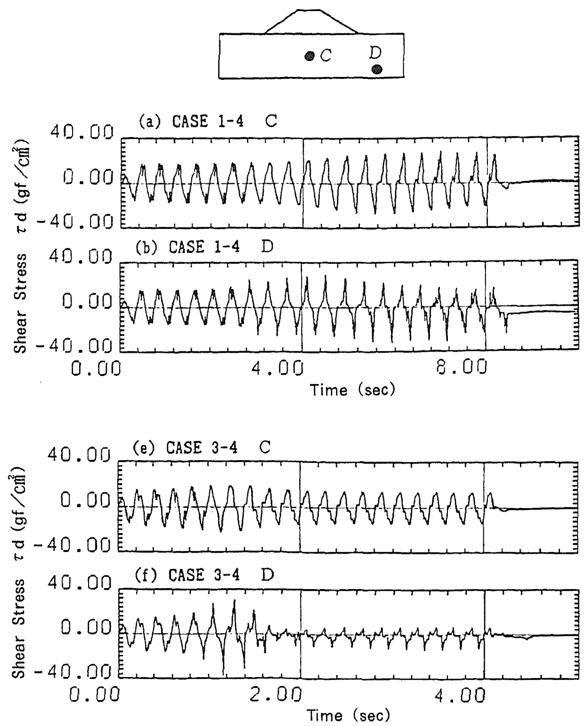

Fig. 4 Dynamic Shear Stress

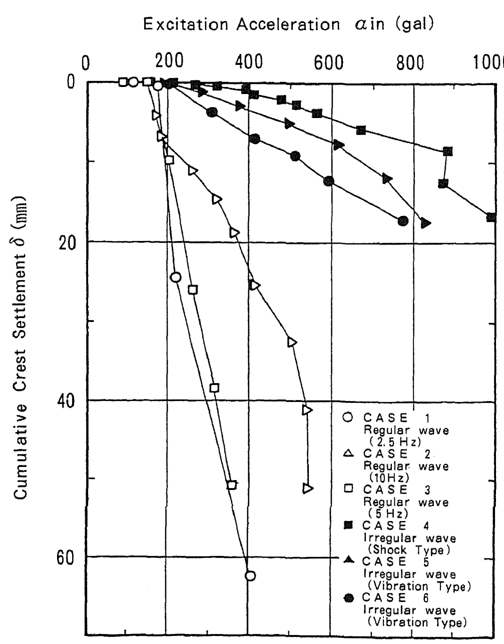

Fig. 5 Excitation Acc. vs. Cumulative Crest Settlement

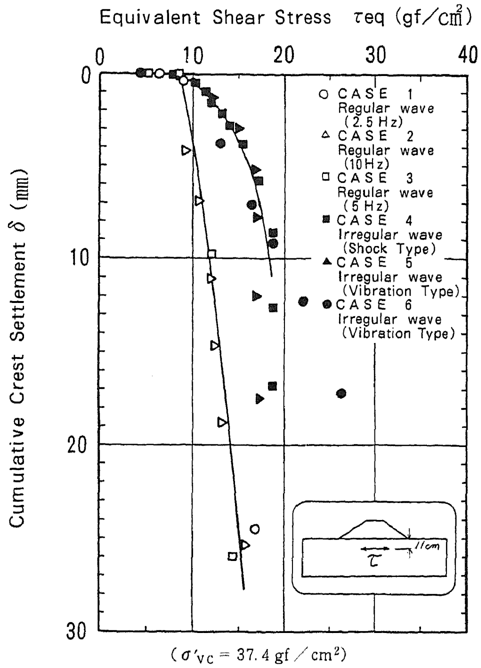

Fig. 6 Equivalent Shear Stress vs. Cumulative Crest Settlement

b) Empirical estimation by use of model shaking table test results

The acceleration of the tests of an irregular wave excitation and a regular one to generate an identical damage (settlement) are compared. Fundamental data for such a purpose are shown in Fig.5. Since the response for a regular wave is not always regular when the excess pore pressure builds up to a certain level and the settlement is influenced by the excitation frequency, the average value of three excitation acceleration for respective values of settlement is assumed to be a representative acceleration a_{eq}.

c) Estimation by the combination of model shaking table tests and stability analysis results

Model shaking table tests generated crest settlement. Stability analysis results using a strain dependent strength of a soil and a seismic coefficient should have some correlation with a strain along an assumed slip surface. Although the settlement and the strain are to be interdependent, a quantitative relation has not yet been obtained at present. Therefore an equivalent seismic coefficient k_{eq} was calculated as such a value to give a unity of safety factor when a dynamic strength of a soil against a failure shear strain of 5% and number of cycles of 20. The value of k_{eq} was obtained as 0.19.

Calculation Result and Its Consideration

Fig.7 shows the relation between equivalence factor Cr obtained from above methods and the cumulative settlements. The values of Cr are calculated as a_{eq}/a_{max} or k_{eq}/k_{max}. The following are observed from this figure.

1. A shock type wave (case 4) gives a smaller Cr than vibration type waves (case 5 and 6) by any of the above methods.

2. In the method c), the values of Cr for regular wave excitation are close to 1.0 and those for irregular waves are fairly smaller than 1.0. Among the irregular wave excitation, the value Cr for a shock type wave is small, which corresponds to the past knowledge about soil specimen.

3. The value Cr becomes smaller as the reference settlement becomes larger both in the methods b) and c).

4. The comparison of the results by the methods a) and c) shows that Cr is nearly 1.0 in both cases for regular wave excitation, the order of magnitude also agrees for irregular wave excitation and the absolute value corresponds with each other against a crest settlement of 1 to 2 mm.

5. The difference of the results by the methods b) and c) lies in that a constant k_{eq} is used in the method c) while variable k_{eq} is used in the method b). Reflecting such a small difference of k_{eq}, Cr by the method b) is slightly smaller than that by the method c).

Above consideration indicates that among three methods to obtain an equivalence factor Cr, the result obtained from an excitation acceleration using the cumulative damage theory corresponds with experimental results when the reference settlement is small.

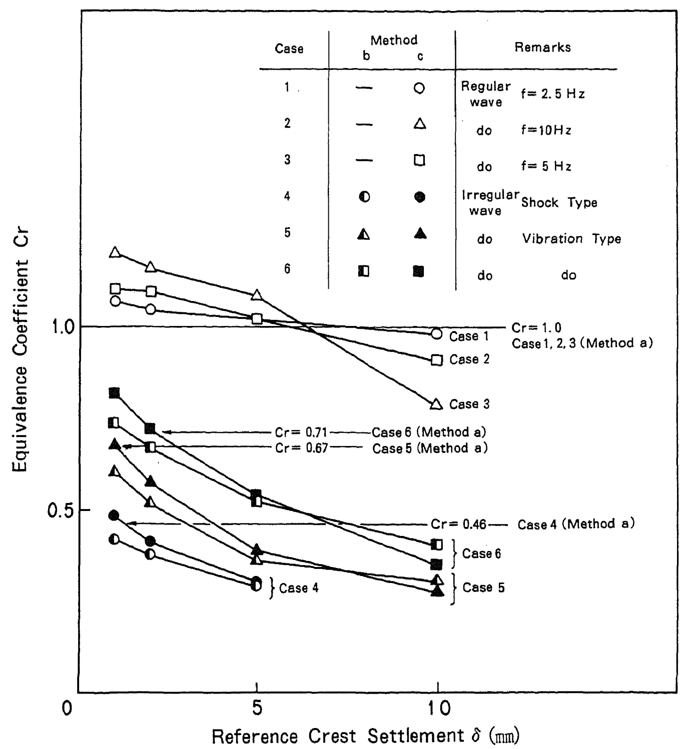

Fig.7 Failure Criteria vs. Equivalence Coefficient (Method a,b,c)

CONCLUSION

Following were presented concerning a series of shaking table tests of a model of embankment on sand ground.

1. The excitation wave form, that is, the frequency in regular wave excitation and the difference of the shock type and vibration type in irregular wave excitation influences much the crest settlement of the model.

2. The effect of the excitation wave form is due to the difference of the response shear stress of the model. This can be explained to some extent by the cumulative damage theory.

3. Three methods to obtain a seismic coefficient were described.