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A New Approach for Evaluating Stability and Deformation of Earthstructure in Earthquake

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SYNOPSIS: A new procedure for determining the shear strength of sand for slope stability analysis in earthquake is proposed together with a simplified procedure for predicting deformation in earthquake. The proposed method is based on the advanced total stress method and uses undrained strength of sand with consideration on strength anisotropy. Soil parameters required in the use of proposed method as well as for deformation prediction are indicated and then results of stability and deformation analyses with the proposed method are presented for a revetment constructed on a silty sand in Tokyo Bay together with 1) field and laboratory tests results, 2) results with the method currently authorized in Japan and 3) field behaviour of this revetment in the Chiba-Tohooeki earthquake of 1987.

INTRODUCTION

Proper evaluation of liquefaction potential and slope stability will be pointed out as the major two subjects in geotechnical engineering in earthquake. Many efforts have been devoted for these schemes and practical method for predicting liquefaction potential have been authorized with reasonable accuracy. It seems, however, that the procedure for evaluating slope stability has not reached a practical stage but a classic method such as the seismic method is still used in routine design work.

It should be first pointed out that liquefaction potential is evaluated based on undrained shear behaviour, whereas slope stability in routine design work is analyzed with the drained shear strength, τ_{fd} as can be seen in seismic coefficient method. Since slope failure in earthquake takes place in a very short time, undrained shear strength, τ_{fu} is likely to be mobilized.

It has been reported, on the other hand, that slope failure in earthquake mostly takes place after completion of main shake (Ishihara, 1980; Seed, 1987). For this case, it is suggested that decrease of the shear strength with excess pore water pressure built-up induced by earthquake is to be considered, while horizontal seismic coefficient is zero.

Poulos, et al. (1985) proposed to use τ_{fu} given by the steady-state line for stability analysis. This method can eliminate various uncertainties involved in seismic condition but could only be available to use for such a sand which indicates flow behaviour in undrained shear. But such a material is difficult to be found in Japanese sand deposits even in reclaimed fill in loose state (Hanzawa, 1974).

Another important subject is proper evaluation of deformation of structure in earthquake. One of the practical methods for this purpose is to predict properly the change of rigidity of soil before and after earthquake from which residual deformation will be obtained. The flow chart for evaluating both stability and deformation of earth structure in earthquake will be as shown

in Fig. 1.

In this paper, a new procedure for determining the shear strength for stability analysis in earthquake is presented together with a simplified procedure for predicting deformation. Fundamental concept of the proposed method is first shown and then a case study for a revetment constructed on a loose silty sand in Tokyo Bay is described in detail. Results of stability and deformation analyses with the proposed method are presented and compared with the field behaviour of the revetment in the Chiba-tohooeki earthquake of 1987.

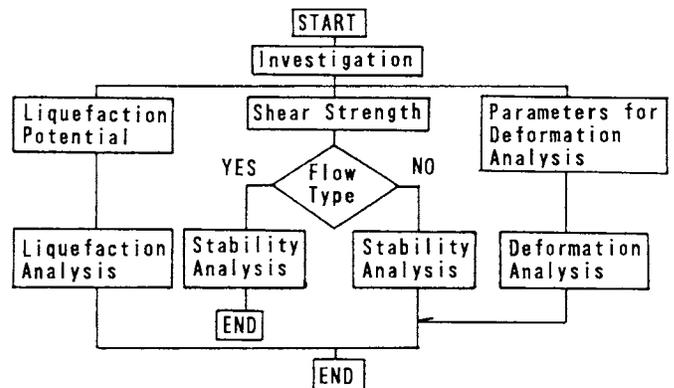


Fig. 1 Flow chart for stability and deformation analyses of structure in earthquake

SHEAR STRENGTH FOR STABILITY ANALYSIS

Effective stress path obtained from direct shear test on a loose fine sand under constant volume condition is indicated in Fig. 2. As clearly be seen, τ_{fu1} given by point A is greater than τ_{fd} given by point B. According to the concept of

the advanced total stress method, τ_{fu} is given as a function of the effective vertical stress before shear, σ'_{vo} as expressed by Eq. (1).

$$\tau_{fu} = \sigma'_{vo} \times \tan\phi_{ap1} \quad (1)$$

where ϕ_{ap1} is the apparent friction angle given by τ_{fu1}/σ'_{vo} ratio.

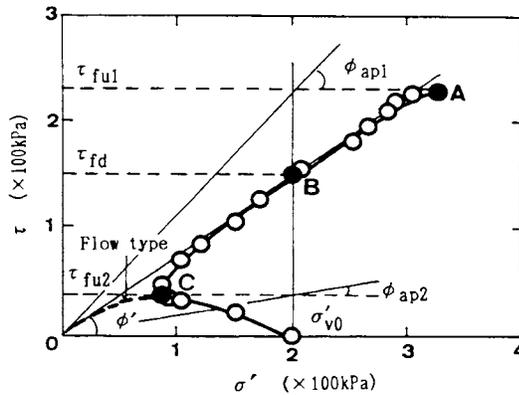


Fig. 2 Typical effective stress path of a loose sand in undrained shear

When τ_{fu} is expressed by Eq. (1), on the other hand, strength anisotropy in ϕ_{ap1} should be considered when used for practice. Then, τ_{fu} for stability analysis designated with the symbol, $\tau_{fu(mob)}$ is given by Eq. (2).

$$\tau_{fu(mob)} = \sigma'_{vo} \times \tan\phi_{ap1} \times \mu_A \quad (2)$$

where μ_A is correction factor for strength anisotropy.

Since strain at which τ_{fu1} is mobilized is significantly large for loose sand, the use of τ_{fu1} would be limited to a structure where large deformation is allowable. For a structure where deformation is strictly limited, it is probably one of the practical methods to use the undrained strength given by point C shown in Fig. 2, where effective stress path turns its direction, as reported by Nakase, et al. (1985).

When the fact that slope failure in earthquake mostly takes place after completion of mainwave, it would also be possible to use the reduced strength corresponding to excess pore water pressure induced by earthquake, designated with the symbol, $\Delta u(e)$ for stability analysis as given by Eq. (3).

$$\tau_{fu(mob)} = (\sigma'_{vo} - \Delta u(e)) \times \tan\phi_{ap} \times \mu_A \quad (3)$$

From the discussions given above, two cases are possible for stability analysis in earthquake as explained below.

- (1) Case I where the shear strength before subjected to earthquake is used with taking of account of horizontal seismic coefficient, k_h , that is, the same as the seismic coefficient method.
- (2) Case II where reduced shear strength corresponding to $\Delta u(e)$ is used without consideration on k_h .

Schematic showing for both cases are as indicated in Fig. 3.

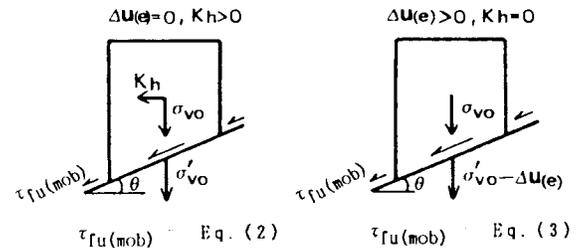


Fig. 3 Schematic showing of stability analysis for Case I (left) and case II (right)

SIMPLIFIED PROCEDURE FOR PREDICTING DEFORMATION

Even if stability analysis indicates a factor of safety, F.S. more than 1.0, it is necessary to check the residual deformation after earthquake for a structure where deformation is strictly limited. Since the stresses acting on structure after earthquake is the same as those before earthquake, it is possible to predict residual deformation when rigidity of soil before and after earthquake is known. Practical sequences are as follows:-

- (1) Excess pore water pressure ratio, $\Delta u(e)/\sigma'_{vo}$ is determined by the response analysis using the proposed earthquake wave.
- (2) Change of rigidity is related to $\Delta u(e)/\sigma'_{vo}$ ratio from laboratory test such as from tri-axial test.
- (3) Static finite element analysis is carried out to obtain deformation before and after earthquake and results in residual deformation.

OUTLINE OF THE CASE STUDY

The structure investigated in this study is caisson typed revetment constructed on loose silty sand in Chiba prefecture in Tokyo Bay as shown in Fig. 4. The proposed site consists of reclaimed sand fill, F.S. with N-blows = 2 to 10, naturally deposited alluvial silty sand, A.S. with N-blows = 6 to 10 and a Pleistocene clay with $\tau_{fu} > 100$ kpa.

In carrying out stability analysis, it is an important point to appropriately evaluate the failure plane, particularly for such a soil condition at the proposed site where failure plane is not likely to be circular arc. When significantly higher undrained strength of Pleistocene clay is considered, it is suggested that the failure will be a straight one passing through A.S. layer as

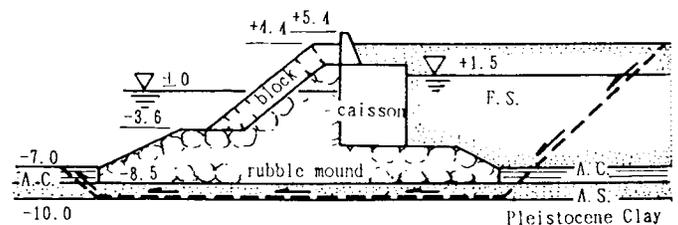


Fig. 4 Cross section, soil conditions and estimated failure plane for the revetment investigated in this study

own in Fig. 4. Stability analysis was carried out for cases I and II as previously explained with the proposed method and the method currently authorized in routine design work in Japan.

FIELD AND LABORATORY TESTS NEWLY CONDUCTED

Tests of dynamic triaxial tests have already conducted on F.S. and A.S. layers for predicting liquefaction potential and for response analysis. It there were only few data on A.S. layer for determining the shear strength and change of rigidity induced by earthquake. Since failure plane was suggested to be a strength one passing through A.S. layer, it is the most important subject to understand proper parameters of A.S. layer. Because of this reason, field and laboratory tests in this investigation were mainly conducted on A.S. layer.

Standard penetration test, SPT, cone penetrometer test and undisturbed sampling with the modified shisho sand sampler (Hanzawa, et al., 1980) were carried out. Gradation components, N-blow, point resistance, q_c and dry density, γ_d of A.S. layer are presented in Fig. 5. It was found that A.S. layer contains lots of fine particles, mostly consisting of silt sized particles from 0.005mm to 0.074mm, ranging from 15% to 45%. A.S. layer was then divided into two layers by fine content. 1) A.S.20 with F.C. \approx 20% and 2) A.S.40 with F.C. \approx 40%, respectively.

In order to determine the strength parameters for stability analysis, three kinds of triaxial tests were conducted on both F.S. and A.S. layer as explained below.

- 1) CKoCVC and CKoCVCe tests where undisturbed sample is first Ko-consolidated at σ'_{vo} and then subjected to compression (C test) and extension (E test) under constant volume condition in order to determine ϕ' and ϕ'_{ap} together with strength anisotropy induced by different shear mode. In the constant volume test, the water level in the burette for volume change measurement was maintained at a constant level during shear by changing confining pressure, which directly gives effective stress. One advantage of this test is its ability to avoid the effect of entrapped air on Δu when sample is not fully saturated (Bishop and Henkel, 1962).
- 2) CICVC₁ test where representative samples from F.S. and A.S. layers were reconstituted in a loose state, consolidated isotropically and finally subjected to compression under constant volume condition. This test was carried

out in order to determine the steady-state line proposed by Poulos, et al.

- 3) CICVC₂ test where undisturbed samples were isotropically consolidated at a stress much greater than σ'_{vo} and then subjected to compression under constant volume condition.

In order to conduct deformation analysis, dynamic and static triaxial tests were carried out as explained below.

- 4) CIDSU test where undisturbed samples were isotropically consolidated at σ'_{vo} , then subjected to cyclic stress until the desired $\Delta u(e)/\sigma'_{vo}$ ratio is obtained, and finally subject to compression. A back pressure of 200kpa was applied. This test was carried out to evaluate the change of rigidity with the change of $\Delta u(e)/\sigma'_{vo}$ ratio.

All the triaxial tests were conducted at a strain rate of 0.05%/min.

TEST RESULTS

One of the typical effective stress paths obtained from CKoCVC and CKoCVCe tests on A.S.40 is shown in Fig. 6. The point where effective stress turn its direction can be seen, which was also observed for all the samples from A.S.40 and F.S. layers. The values of ϕ'_{ap1} , ϕ'_{ap2} and ϕ' obtained from CKoCVC and CKoCVCe tests are summarized for F.S., A.S.20 and A.S.40 in table 1.

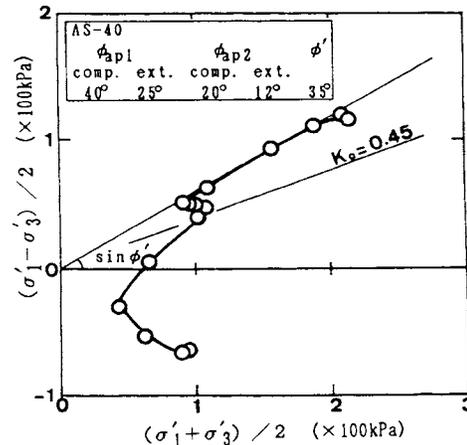


Fig. 6 Effective stress path obtained from CKoCVC and CKoCVCe tests on A.S.40

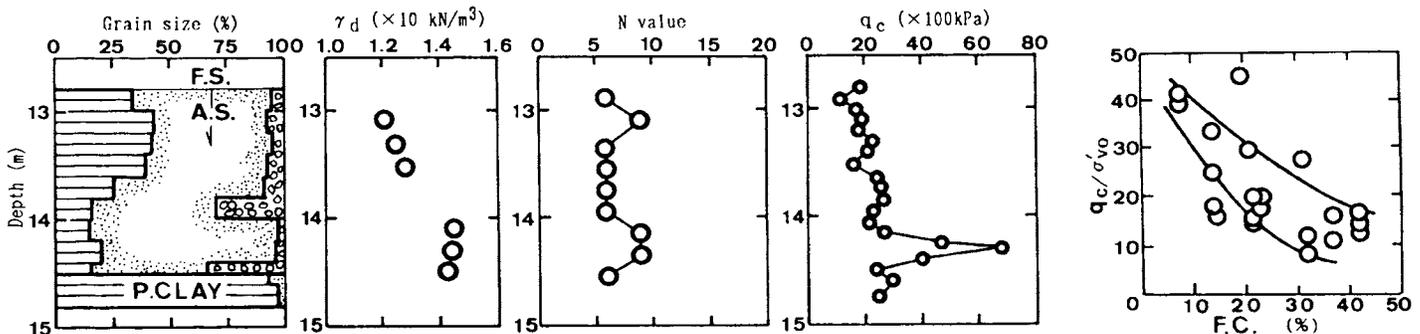


Fig. 5 Gradation components, γ_d , N-blow, q_c and q_c/σ'_{vo} versus F.C. of A.S. layer plotted versus depth

Representative stress- Δu -strain curves measured in CICVC₁ and CICVC₂ tests are presented in Fig. 7. Stress-strain curve from CICVC₁ test did not show complete liquefaction behaviour but indicated limited liquefaction behaviour (Castro, 1969). Though the steady state defined by Poulos was not obtained, the steady state line in this study was determined using the residual shear strength as indicated in Fig. 7. The steady-state line thus determined is summarized in Fig. 8 together with τ_{fu} obtained from CICVC₂ test. AS can be seen, τ_{fu} from CICVC₂ test are located on right side of the steady-state line, which demonstrate that there is no possibility for flow failure at the proposed site.

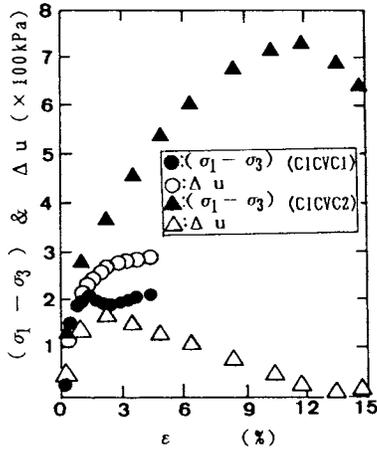


Fig. 7 Stress- Δu -strain curves from CICVC₁ and CICVC₂ tests

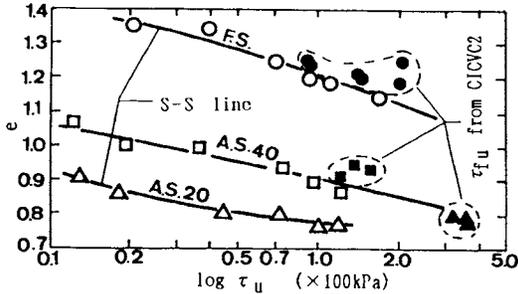


Fig. 8 τ_{fu} obtained from CICVC₁ and CICVC₂ tests

Table I Values of Φ_{ap1} , Φ_{ap2} and Φ' obtained from CKoCVC and CKoCVC tests

Layer	Φ_{ap1}		Φ_{ap2}		Φ'
	comp.	ext.	comp.	ext.	
F.S.	36	25	18	10	35
A.S.20	50	28	25	15	35
A.S.40	40	25	20	12	35

RESULTS OF STABILITY ANALYSIS

Since failure plane for the proposed revetment is evaluated to be a straight line as shown in Fig. 4, compression strength for F.S., and average strength of compression and extension ones for A.S. were used. In addition, only Φ_{ap1} was used for F.S. layer because large deformation could be allowable for this layer. Stability analysis was conducted for 2 cases, case I where $kh \neq 0$ and $\Delta u(e) = 0$, and case II where $kh = 0$ and $\Delta u(e) \neq 0$. In carrying out stability analysis for case I, routine method where τ_{fd} is used was also conducted.

Results of stability analysis for case I are presented in Fig. 10 where F.S. values are plotted versus kh . The values of F.S. obtained with the use of Φ_{ap1} indicated 1.15 to 1.50 times of F.S. from the method used in routine design work

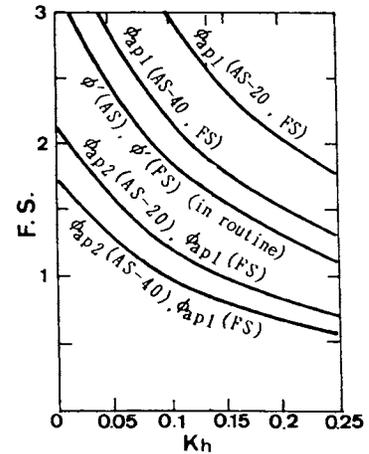


Fig. 10 Results of stability analysis for case I

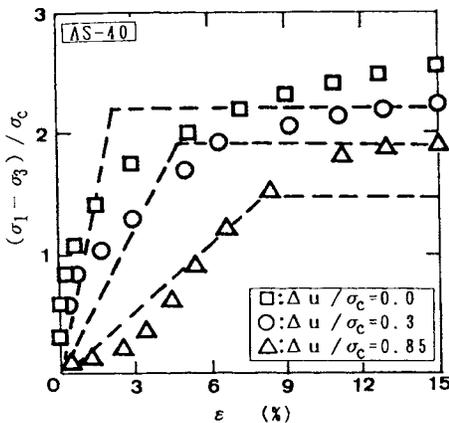
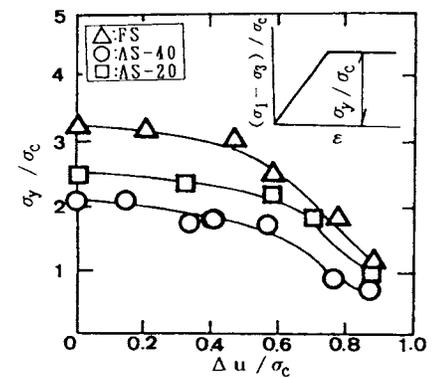
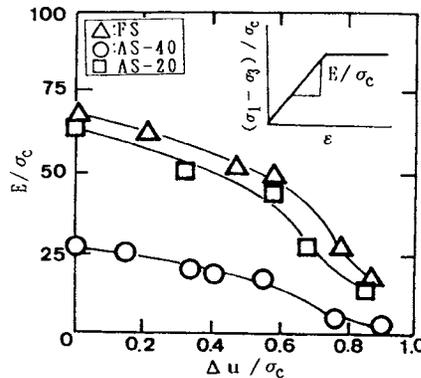


Fig. 9 Normalized stress-strain curves, deformation modulus, E/σ'_c and yielding stress, σ'_y/σ'_c versus $\Delta u(e)/\sigma'_c$ obtained from CIDSU test



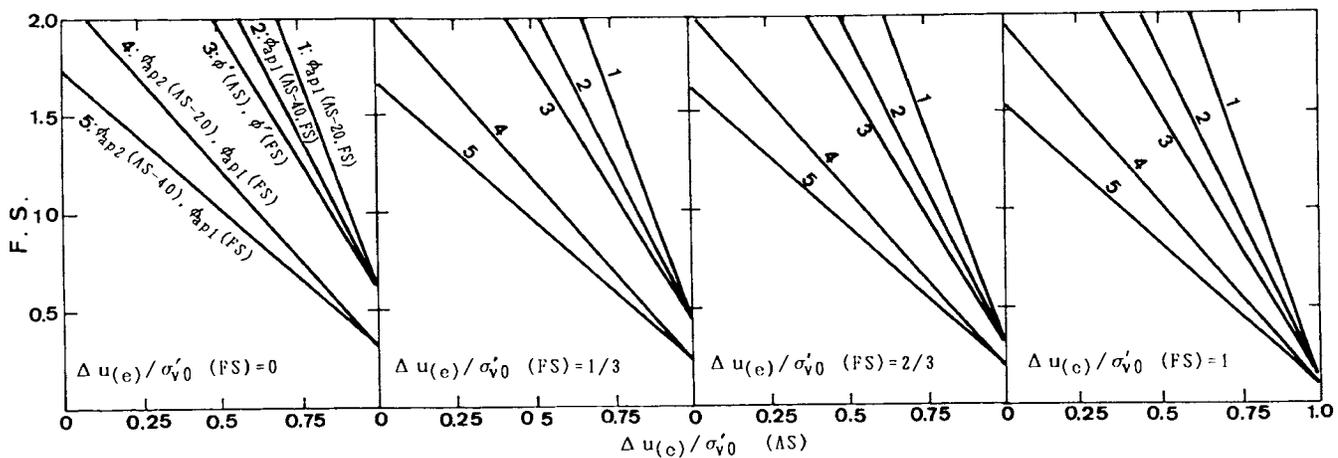


Fig. 11 Results of stability analysis for case II

Results of stability analysis for case II are summarized in Fig. 11 where F.S. values are plotted versus $\Delta u(e)/\sigma'_{v0}$ ratio of A.S. layer with change of $\Delta u(e)/\sigma'_{v0}$ ratio of F.S. layer. It should be noted that even $\Delta u(e)/\sigma'_{v0}$ ratio of F.S. layer reaches 1.0, where F.S. layer is in completely liquefied condition, F.S. value is more than 1.0 when $\Delta u(e)/\sigma'_{v0}$ ratio is less than 0.75 with the use of Φ_{ap1} .

RESULTS OF DEFORMATION ANALYSIS

A seismometer has been installed at the proposed site and seismic wave of the Chiba-tohooki earthquake of 1987 was successfully measured at the ground surface and at a depth of (-)35m where a dense Pleistocene sand is distributed. A response analysis was carried out using this measured wave at (-)35m and soil parameters obtained from cyclic triaxial test. Maximum acceleration, α_{max} and $\Delta u(e)/\sigma'_{v0}$ ratio obtained from the response analysis are shown in Fig. 12. The value of α_{max} at the ground surface from the analysis showed good agreement with the measured α_{max} value. Maximum $\Delta u(e)/\sigma'_{v0}$ ratio of F.S. layer reached 0.75 at a depth of 8m, which could well explain that a small scaled liquefaction took place at the site in this earthquake. On the other hand, $\Delta u(e)/\sigma'_{v0}$ ratio of A.S. layer is about 0.2, which gives F.S. value more than 1.0 even with the use of Φ_{ap2} as can be seen from Fig. 11.

Deformation analysis was conducted using $\Delta u(e)/\sigma'_{v0}$ ratio of 0.65 for F.S. layer and 0.25 for A.S. layer, respectively. Then deformation modulus of each layer can be determined from Fig. 9. Result of deformation analysis is presented in Fig. 13. Maximum horizontal deformation and settlement of the parapet placed on the caisson and at the back site were 1.7cm and 5.1cm, respectively as shown in Fig. 13. Observed horizontal deformation of the parapet in the Chiba-tohooki earthquake was 1cm to 2cm, which shows relatively good agreement with the result of deformation analysis.

CONCLUSION

A new procedure for determining the shear strength of sand for slope stability analysis

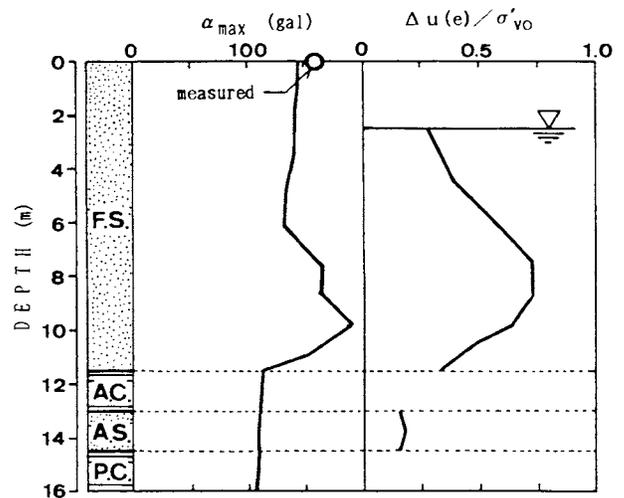


Fig. 12 Maximum α and $\Delta u(e)/\sigma'_{v0}$ ratio obtained from the response analysis using the Chiba-tohooki earthquake wave measured at the proposed site

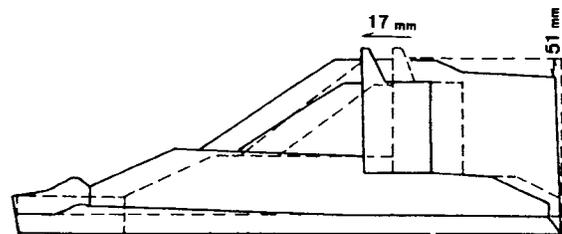


Fig. 13 Result of deformation analysis

in earthquake was proposed together with a simplified procedure for evaluating deformation, and a case study for a revetment was presented. The proposed method is based on the advanced

total stress method and uses the undrained shear strength with consideration on strength anisotropy. Though the study has just been started, the following concluding remarks can be made.

- (1) The use of the undrained shear strength instead of the drained shear strength should better evaluate the actual behaviour of earthstructure in earthquake.
- (2) The proposed method for determining the shear strength can eliminate the difficulty or uncertainty in predicting excess pore water pressure at failure.
- (3) Results of stability analysis with the proposed method for a revetment founded on a loose silty sand did not show any contradiction to the field behaviour of this structure in the Chiba-tohooki earthquake of 1987.
- (4) Results of deformation analysis showed good agreement with the observed deformation in this earthquake.

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