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

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YNOPSIS: A new procedure for determining the shear strength of sand for slope stability analysis n earthquake is proposed together with a simplified procedure for predicting deformation in earthuake. The proposed method is based on the advanced total stress method and uses undrained strength f sand with consideration on strength anisotropy. Soil parameters required in the use of proposed nethod as well as for deformation prediction are indicated and then results of stability and deforation analyses with the proposed method are presented for a revetment constructed on a silty sand n Tokyo Bay together with 1) field and laboratory tests resutls, 2) results with the method current y authorized in Japan and 3) field behaviour of this revetment in the Chiba-Tohooki earthquake of 987.

NTRODUCTION

ropoer evaluation of liquefaction potential and slope stability will be pointed out as the major wo subjects in geotechnical engineering in earthuake. Many efforts have been devoted for these hemes and practical method for predicting liquefaction potential have been authorized with reasonable accuracy. It seems, however, that the rocedure 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 plcae 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 earhquake 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 Japanes 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 earth quake 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-tohooki earthquake of 1987.

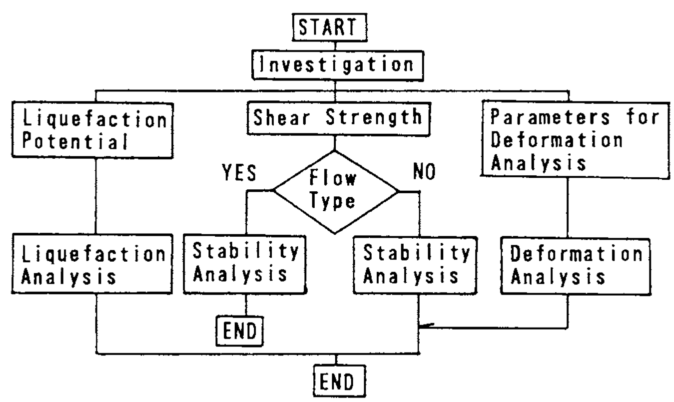

Fig. 1 Flow chart for stability and deformation analyses of structure in earthquake

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).

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

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

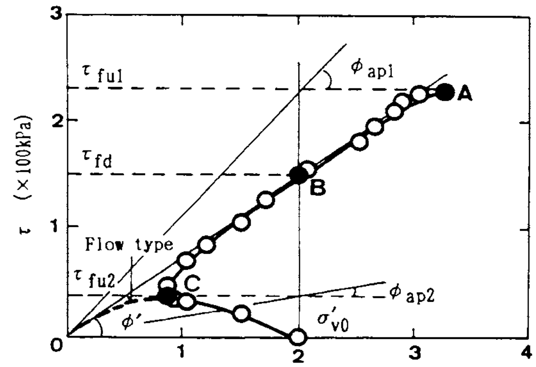

Fig. 2 Typical effective stress path of a loose sand in undrained shear

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).

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

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).

$$\tau_{fu(mob)} = (\sigma'_{vo} - \Delta u_{(e)}) \times \tan\Phi_{ap} \times \mu_A \qquad (3)$$

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.

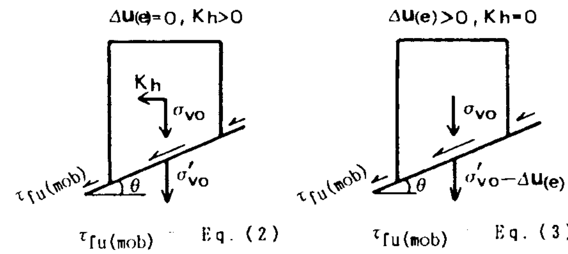

Fig. 3 Schematic showing of stability analysis for Case I (left) and case II (right)

SIMPLIFIED PROCEDURE FOR PREDICTING DEFORMATION

Even if stability analysis indicates a factor o 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 triaxial 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 reclaime sand fill, F.S. with N-blows = 2 to 10, naturall 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 conditio 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 wil be a straight one passing through A.S. layer as

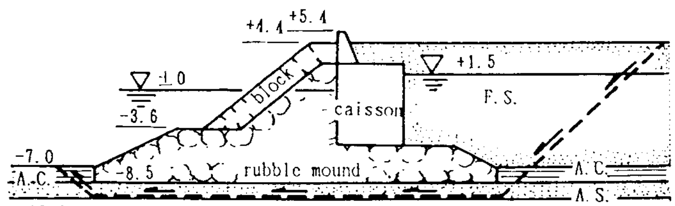

Fig. 4 Cross section, soil conditions and estimated failure plane for the revetment investigated in this study

ıown in Fig. 4. Stability analysis was carried ıt for cases I and II as previously explained ith the proposed method and the method currently ıthorızed in routine design work in Japan.

IELD AND LABORATORY TESTS NEWLY CONDUCTED

ɔts of dynamic triaxial tests have already conıcted on F.S. and A.S. layers for predicting iquefaction potential and for response analysis ıt there were only few data on A.S. layer for etermining the shear strength and change of igidity induced by earthquake. Since failure lane was suggested to be a straingth one passing ırough A.S. layer, it is the most important ıbject to understand proper parameters of A.S. ayer. Because of this reason, field and laboıatory tests in this investigation were mainly ɔnducted on A.S. layer.

tandard penetration test, SPT, cone penetrometer est and undisturbed sampling with the modified ishop sand sampler (Hanzawa, et al., 1980) were arried out. Gradation components, N-blows, point esistance, q_c and dry density, γ_d of A.S. layer re presented in Fig. 5. It was found that A.S. ayer contains lots of fine particles, mostly onsisting of silt sized particles from 0.005mm o 0.074mm, ranging from 15% to 45%. A.S. layer as then devided into two layers by fine content .C., 1) A.S.$_{20}$ with F.C. ≑ 20% and 2) A.S.$_{40}$ ith F.C. ≑ 40%, respectively.

n order to determine the strength parameters or stability analysis, three kinds of triaxial ests were conducted on both F.S. and A.S. layer s explained below.

1) CKoCVC and CKoCVE 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 vlume 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) CICVC$_1$ 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) CICVC$_2$ 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 rigidy 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 CKoCVE 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 CKoCVE tests are summaried for F.S., A.S.$_{20}$ and A.S.$_{40}$ in table 1.

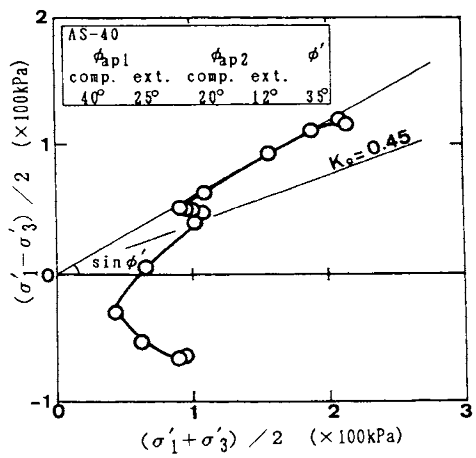

Fig. 6 Effective stress path obtained from CKo CVC and CKoCVE tests on A.S.$_{40}$

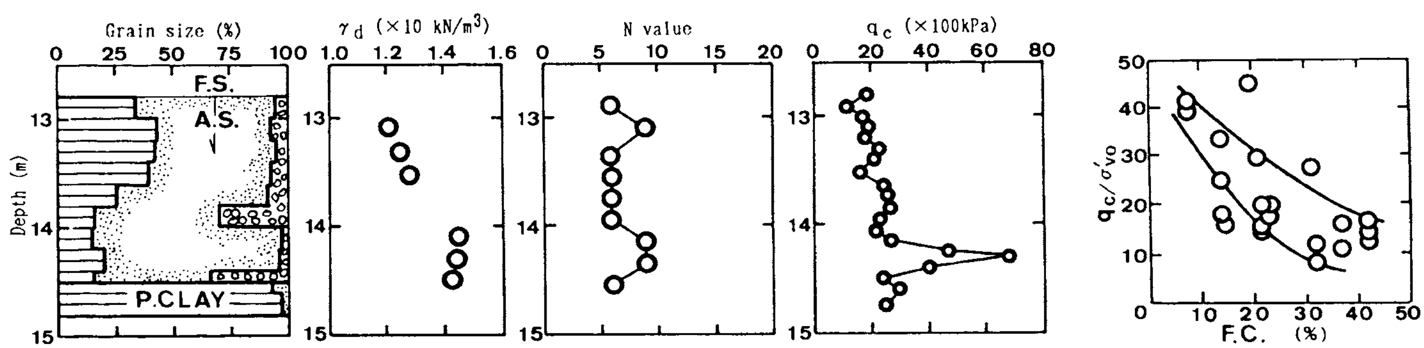

Fig. 5 Gradation components, γ_d, N-blow, q_c and q_c/σ'_{vo} versus F.C. of A.S. layer plotted versus depth

Representative stress-Δu-strain curves measured in $CICVC_1$ and $CICVC_2$ tests are presented in Fig. 7. Stress-strain curve from $CICVC_1$ 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 $CICVC_2$ test. AS can be seen, τ_{fu} from $CICVC_2$ 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.

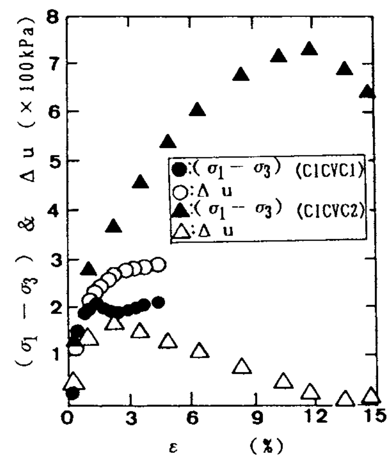

Fig. 7 Stress-Δu-strain curves from $CICVC_1$ and $CICVC_2$ tests

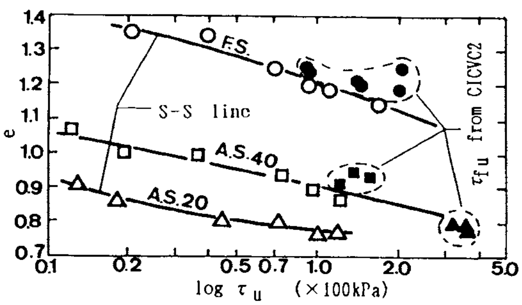

Fig. 8 τ_{fu} obtained from $CICVC_1$ and $CICVC_2$ tests

Table I Values of $\Phi ap1$, $\Phi ap2$ and Φ' obtained from CKoCVC and CKoCVE tests

Layer	$\Phi ap1$ comp.	$\Phi ap1$ ext.	$\Phi ap2$ comp.	$\Phi ap2$ ext.	Φ'
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 straingth line as shown ir Fig. 4, compression strength for F.S., and average strength of compression and extension onec for A.S. were used. In addition, only $\Phi ap1$ was used for F.S. layer because large deformation could be allowable for this layer. Stability analysis was conducted for 2 cases, case I wher $k_h \neq 0$ and $\Delta u_{(e)} = 0$, and case II where $k_h = 0$ and $\Delta u_{(e)} \neq 0$. In carrying out stability analyc for case I, routine method where τ_{fd} is used wa also conducted.

Results of stability analysis for case I are presented in Fig. 10 where F.S. values are plotted versus k_h. The values of F.S. obtained with the use of $\Phi ap1$ indicated 1.15 to 1.50 times of F.S. from the method used in routine design wor

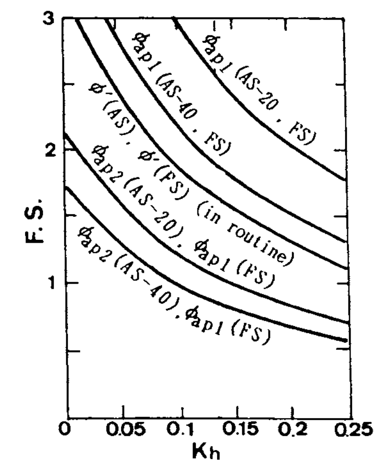

Fig. 10 Results of stability analysis for case

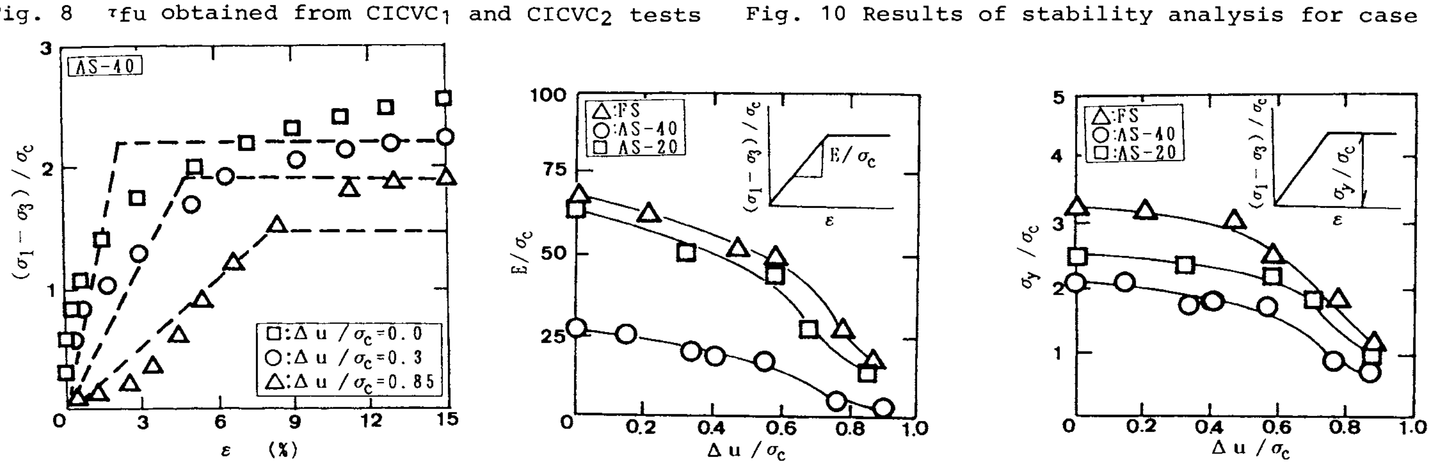

Fig. 9 Normalized stress-strain curves, deformation modulos, E/σ'_c and yielding stress, σ'_y/σ'_c versus $\Delta u(e)/\sigma'c$ obtained from CIDSU test

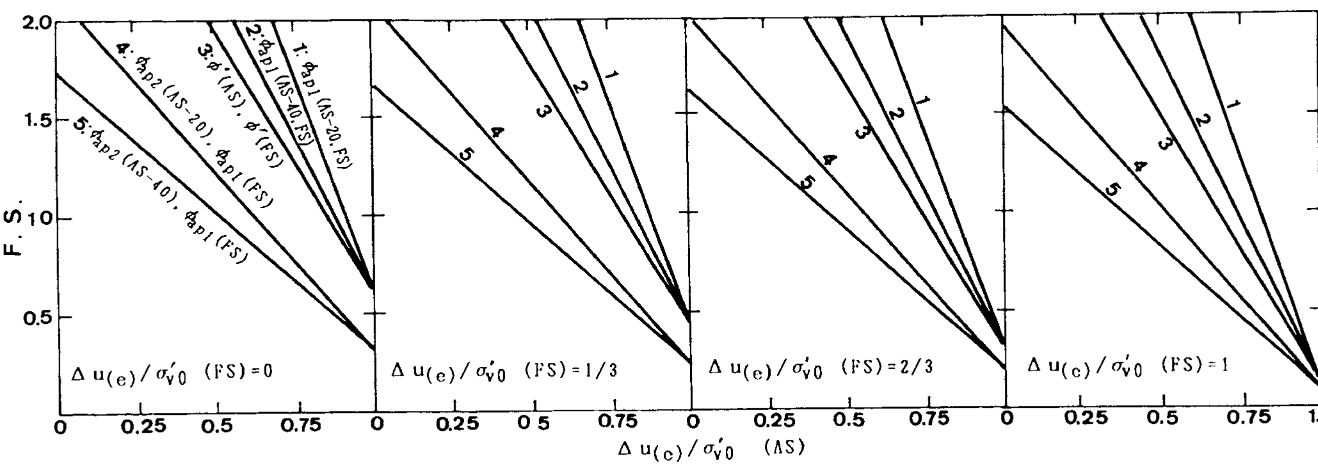

Fig. 11 Results of stability analysis for case II

Results of stability analysis for case II are summarized in Fig. 11 where F.S. values are plotted versus $\Delta u(e)/\sigma'_{vo}$ ratio of A.S. layer with change of $\Delta u_{(e)}/\sigma'_{vo}$ ratio of F.S. layer. It should be noted that even $\Delta u_{(e)}/\sigma'_{vo}$ 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 $\Delta u(e)/\sigma'_{vo}$ 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 $\Delta u_{(e)}/\sigma'_{vo}$ 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 $\Delta u(e)/\sigma'_{vo}$ ratio of F.S. layer reached 0.75 at a depth of 8m, which could well explain that a small scalled liquefaction took place at the site in this earthquake. On the other hand, $\Delta u(e)/\sigma'_{vo}$ 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 $\Delta u_{(e)}/\sigma'_{vo}$ 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-tooki earthquake was 1cm to 2cm, which shows retatively good agreement with the result of deformation analysis.

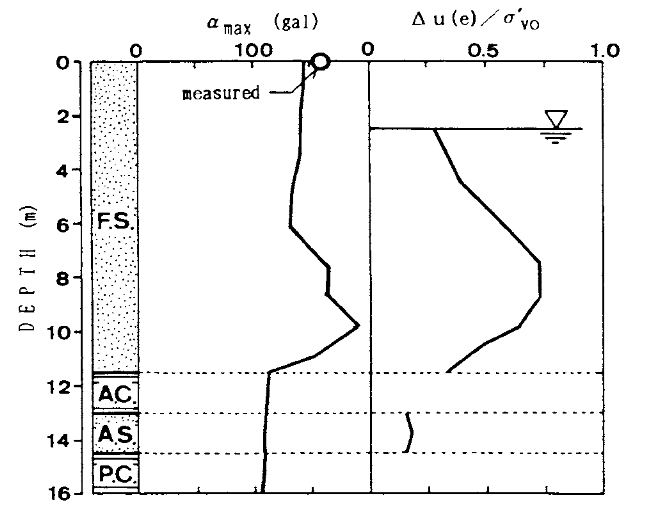

Fig. 12 Maximum α and $\Delta u_{(e)}/\sigma'_{vo}$ ratio obtained from the response analysis using the Chiba-tohooki earthquake wave measured at the proposed site

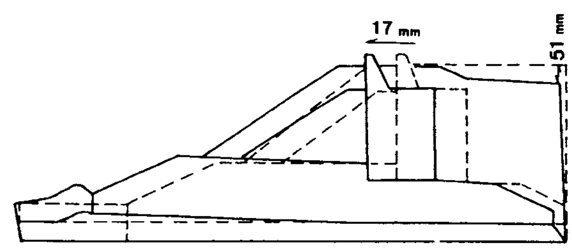

Fig. 13 Result of deformation analysis

CONCLUSION

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

At the final, the authors would like to express their gratitude to Professor K. Ishihara of the University of Tokyo for his constructive advices in doing this study.

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