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SEISMIC RELIABILITY ANALYSIS OF EMBANKMENT SUBJECTED TO EARTHQUAKE

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SUMMARY

The present study deals with a seismic reliability of embankments when a major earthquake occurs. Earthquake with pore water pressure build up in soil usually causes large damage to the embankment. The damage scale is especially related to the pore water pressure build up potential. The present analysis considers general characteristics of pore water pressure build up and dissipation in soil deposit during the earthquake motion. The response of embankments subjected to earthquake motions is also considered in this analysis. The influence of uncertainties of soil strengths and seismic loads on a failure probability, and the comparision between the failure probability and the damage scale of embankments are discussed.

INTRODUCTION

The past severe earthquakes brought about extensive damage to various soil structures such as embankments. It was disclosed, however, that most of those damages were essentially caused by the effects of liquefaction of loose saturated sands distributed along rivers.

Seismic reliabilities of embankments have been discussed by many researchers (e. g. Ref. 1). A few recent studies have treated the problem about the pore water pressure build up in soil in evaluating response of embankments subjected to earthquake motions. Soil strength and seismic load are, in general, ramdom variables. Since, the number of sampling is too small to determine the probability density functions, it is inevitable that even parameters such as mean values and variances of these functions are treated as random variables with uncertainties. In this study, a method of reliability analysis in considering the pore water pressure build up and dynamic response of embankments is proposed. In other words, an analytical technique is developed to evaluate the reduction of soil strength of embankment foundation due to the pore water pressure build up. The influence of randomness and uncertainty of soil strength and seismic load on damage of embankments is investigated. In simplicity, the probability density functions of soil strength and seismic load are assumed to be Gaussian distribution functions. Uncertainty and mean value of failure probability of the embankment are also discussed.

SIMPLIFIED ANALYTICAL PROCEDURE

Seismic reliability of analysis of embankments is presented by simplified analytical procedure shown in Fig. 1. The data used in this study are represented as Table 1. The evaluation of the seismic reliability of embankments consists of the following computational steps;

1) The profile of embankments and ground conditions below embankments are estimated from field data. The soil strengths of embankments are, however, treated as random variables. The number of sampling is not enough to determine the probability density functions. Thus those probability density functions are assumed to be Gaussian distribution functions, and it is inevitable that the parameters such as mean values and variances of the functions are treated as random variables with uncertainties. Random variables in this study are cohesion C, internal frictional angle ϕ and horizontal seismic coefficient k_h.

2) Acceleration coefficient α_A is evaluated by using energy response which reflects the response of the embankment subjected to earthquake motions. α_A, shown in Fig.2, is an equivalent acceleration in static condition to the maximum response acceleration. α_A with damping ratios is obtained by averaging fifteen earthquake responses. The value of $\alpha_A A_S$ is regarded as the average response acceleration within the embankment, in which A_S is the maximum horizontal acceleration at the surface ground. Natural period T of the embankment is given by the following empirical equation introduced by Seed et al.

$$T = \frac{2\pi H}{2.4\,V} \tag{1}$$

in which H(m) is height of the embankment and V (m/sec) is mean value of velocity of S wave in the embankment. If V is obtained from field data, T can be calculated using Eq. (1). Damping ratio h of the embankment presented here is assumed to be 0.2. Vertical seismic coefficient k_v is determined by the relation of k_v=0.6k_h in Ref. 2.

3) A value of the excessive pore water pressure is caluculated using equations of seepage in saturated-unsaturated porous media used in Ref. 3 and of the pore water pressure build up proposed by Martin, Finn and Seed. The obtained maximum value of excessive pore water pressure is used in quasi-static condition.

4) The failure as defined by $R-S\leqslant 0$, in which R is resistance of soil and S is load, will occur at a circular arc slip surface. Resistance R and load S are given by the numerator and denominator of Eq.(2), respectively. Minimum value of safety factor of the embankment at the circular arc slip surface is determined using a stability analysis. The model of the embankment is shown in Fig. 3. The equation of safety factor F_S used in the stability analysis is given by

$$F_S = \frac{\sum_{i=1}^{n}[C_i l_i + \{W_i(1-k_{v_i})\cos\alpha_i - k_{h_i}\sin\alpha_i\}(1-u_i)\tan\phi_i]}{\sum_{i=1}^{n}[W_i\{(1-k_{v_i})\sin\alpha_i + k_{h_i}\cos\alpha_i\}]} \tag{2}$$

in which n is number of slice, C_i is cohesion of soil in the i'th slice, l_i is length of circular arc slip surface, W_i is weight of soil, α_i is angle of the tangent of center at bottom of the i'th slice to horizontal axis, u_i is pore water pressure ratio ($=u_d/\sigma_V'$), where u_d/σ_V' is defined as the ratio of the pore water pressure (u_d) to the total overburden pressure (σ_V'), ϕ_i is internal frictional angle of soil, k_{h_i} and k_{v_i} are horizontal and vertical seismic coefficients at the center of the i'th slice, respectively. Buoyancy acting on soil below the water table is considered in this analysis, while below the water table, earthquake load acts on soil mass, not on the amount given by subtracting buoyancy from soil weight.

5) The seismic reliability of embankments is obtained at the circular arc slip surface described in Step 4) using PEM method introduced by Rosenblueth (Ref. 4).

The failure probability is given by

$$P_F=\mathrm{P}(R\leq S)=\Phi\left(\frac{\overline{S}-\overline{R}}{\sqrt{\sigma_R^2+\sigma_S^2}}\right) \tag{3}$$

in which $\overline{S}$ is mean value of load, $\overline{R}$ is mean value of resistance, σ_S^2 is variance of load and σ_R^2 is variance of resistance. Φ is normalized Gaussian distribution function. In Eq. (3), R and S are assumed to be mutually independent.

In this study, the following assumptions are introduced. If a few field data of random variable X are obtained, the distribution of X can be approximated by the sample mean $\overline{X}$ and the sample variance σ_X^2. Since field data are a few, $\overline{X}$ and σ_X^2 have statistical uncertainties; $\overline{X}$ is considered to be a variable with mean $\overline{\overline{X}}$ and variance $\sigma_{\overline{X}}^2$, and σ_X^2 with mean $\overline{\sigma_X^2}$ and variance $\sigma^2_{\sigma_X^2}$. For a few data, therefore, the distributions have statistical uncertainties, too. The concept of statistical uncertainty is shown in Fig. 4. It has become clear from the preparatory study that the effect of the variance of sample mean on the failue probability is greater than that of the variance of sample variance. Therefore the variance of sample variance is ignored and the sample variance is assumed to be deterministic in this study. The mean value $\overline{\overline{X}}$ and variance $\sigma_{\overline{X}}^2$ of sample mean $\overline{X}$ can be estimated by the sample mean and the sample variance, respectively. The distribution of failure probability of the embankment is calculated using the present method.

CASE STUDY

A typical model of embankment used in this study is summarized in Table 1. The acceleration is assumed to be a Gaussian distribution. As regards the mean $\overline{A_S}$ of maximum horizontal acceleration A_S, the attenuation law proposed by Public Works Research Institute, Ministry of Construction (PWRI) (Ref. 5) is employed. The COV V_{A_S} of A_S and the COV $V_{\overline{A_S}}$ of mean of A_S are assumed to be 0.21 and 0.11, respectively. The value of COV V_{A_S} is taken from the statistical data in Tokyo area investigated by Goto and Kameda (Ref. 6).

An example of the analytical results for the model embankment is shown in Fig. 5, in case that $\overline{A_S}$ is 200 (gal). $V_{\overline{\phi}}$ and $V_{\overline{C}}$ denote the COVs of the mean of internal frictional angle and cohesion, respectively. The mean and the variance of failure probability of the embankment can be calculated using Eq. (3). The analytical results show that the effects of $V_{\overline{C}}$ and $V_{\overline{\phi}}$ on the failure probability are great as shown in Fig. 5. The effect of $V_{\overline{C}}$ on P_F is greater than that of $V_{\overline{\phi}}$. The mean value of failure probability for $V_{\overline{C}}=0.3$, $V_{\overline{\phi}}=0.2$ and $V_{\overline{k_h}}=0.11$ is 0.14. The failure probabilities of $\overline{P_F}+\sigma_{P_F}$ and $\overline{P_F}-\sigma_{P_F}$ are 0.2 and 0.08, respectively. In this way, the reliability of embankments with statistical uncertainty can be evaluated even if the number of sampling field data is not enough. The mean value of failure probability of the embankment subjected to pore water pressure build up in soil is shown in Fig. 6. Solid and segmented lines denote the failure probabilities in case that pore water pressure rises and dose not rise, respectively. Figure 6 shows that the value of the solid line is greater than that of the segmented line for all $\overline{A_S}$ values. The results suggest that the embankment will be damaged in lower horizontal acceleration level in case that pore water pressure rises.

APPLICATION TO FIELD EMBANKMENTS

The damage on the levees along Mogami river caused by the 1964 Niigata earthquake and along Yoshida river caused by the 1978 Miyagi prefecture-off earthquake are taken here. Nine embankments on similar alluvial deposit are analyzed. Table 2 presents numerical results for nine embankments in which $V_{\bar{C}}$ and $V_{\bar{\phi}}$ are assumed to be 0.14 and 0.1, respectively. Damage level denotes the damage scale of the embankment subjected to earthquake motions. F_S is the safety factor of the embankment defined by Eq. (2). The damage levels proposed by PWRI are grouped into three classes, in which α is large, β moderate and γ small in damage classes, respectively. The relationship between damage levels and the failure probabilities of embankments is shown in Fig. 7. The results indicate that the damage levels are related to the distributions of failure probability of embankments. In other words, the mean value of failure probability of embankments for damage level α is greater than that for other damage levels, in general. Moreover, the scattered shape of the distribution of failure probability for large mean value $\overline{P_F}$ of failure probability is narrower than that for small $\overline{P_F}$. Despite a few statistical data, sufficient information for seismic reliability of embankments can be obtained using the porposed method.

CONCLUSIONS

The developed probabilistic method is applied to the model embankment and the embankments in Niigata city during the 1964 Niigata earthquake and those in Sendai city during the 1978 Miyagi prefecture-off earthquake. The effects of uncertainties in load and resistance on the damage assesment, and comparision between the failure probability and the damage scale of embankments are discussed.

The results obtained in this study are summarized as follows;

(1) The method of reliability analysis of embankment considering uncertainties and randomness of soil strength and seismic load is proposed using Point Estimate Method.

(2) The uncertainty of cohesion of soil gives greater influence on the analytical results than other parameters such as internal frictional angle of soil.

(3) The method involves pore water pressure build up processes. The result suggests that the embankment will be damaged in lower horizontal acceleration level in case that pore water pressure rises.

(4) The method is applied to the embankments during past earthquakes. The failure probability of embankments is related fairly well to the damage scale proposed by PWRI.

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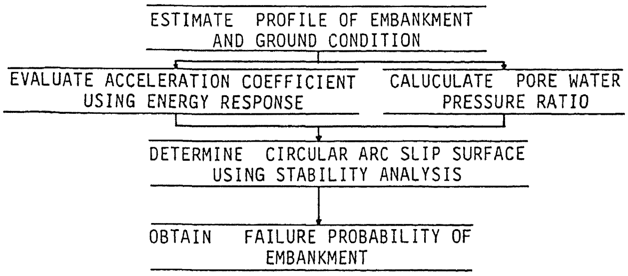

Fig.1 Analytical procedure.

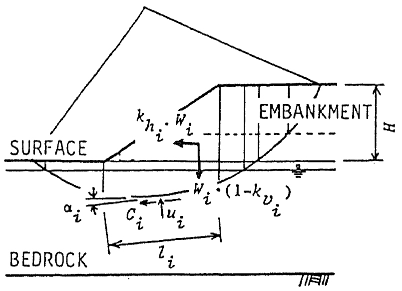

Fig.3 Model of embankment.

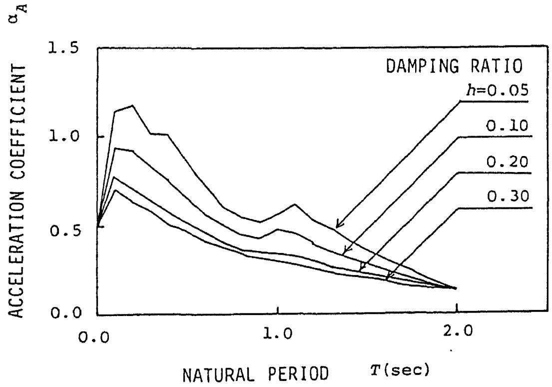

Fig.2 Spectra of acceleration coefficient using energy response.

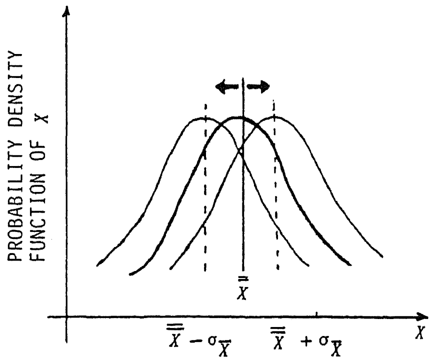

Fig.4 Concept of statistical uncertainty for $\bar{x}$.

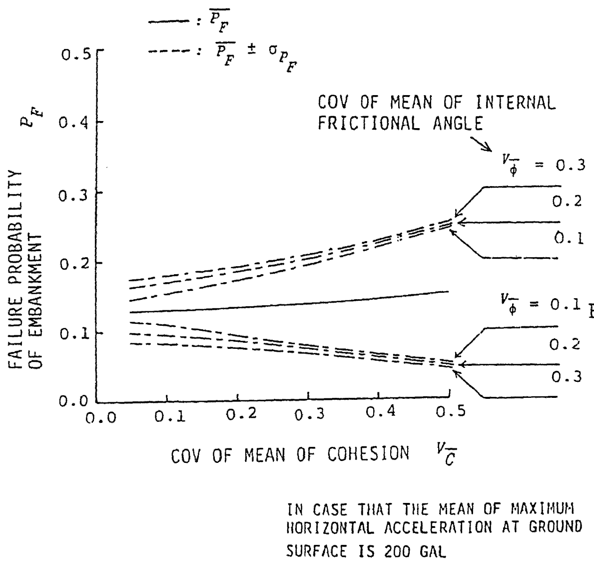

Fig.5 Relationship between P_F, $V_{\overline{C}}$ and $V_{\overline{\phi}}$.

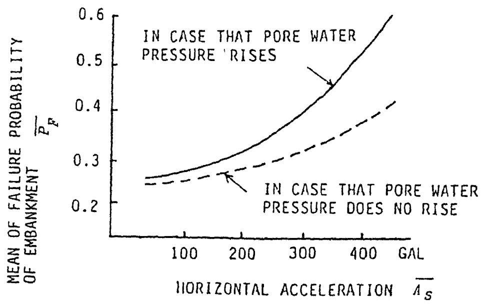

Fig.6 Relationship between $\overline{P_F}$ and $\overline{A_S}$ in case that pore water pressure rises and does not rise.

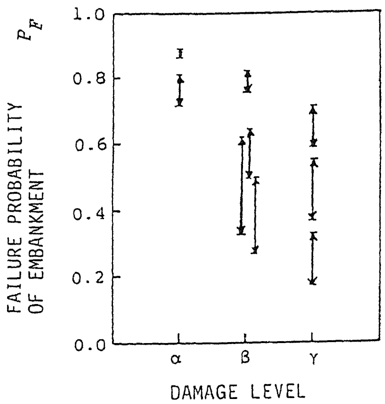

Fig.7 Relationship between P_F and damage level.

Table 1 Material constants of model embankment.

DEPTH OF WATER TABLE	-0.5 m	MAXIMUM DEPTH AT CIRCULAR SLIP ARC SURFACE	1.0 m
HEIGHT OF EMBANKMENT H	4.0 m		
GRADIENT OF SLOPE	1.5	THICKNESS OF GROUND	30.0 m

	UNDER WATER TABLE	IN GROUND	IN EMBANKMENT
MEAN OF COHESION $\overline{C}$ (tf/m^2)	0.54	1.31	2.09
COV OF C	0.27	0.27	0.27
MEAN OF INTERNAL FRICTINAL ANGLE $\overline{\phi}$ (°)	25	25	25
COV OF ϕ	0.19	0.19	0.19
COV OF SEISMIC COEFFICIENT AT GROUND SURFACE V_{k_h}	0.21	0.21	0.21
COV OF MEAN OF V_{k_h}	0.11	0.11	0.11
VELOCITY OF S WAVE V(m/sec)	200	200	100
DEGREE OF SATURATION (%)	100	80	60
UNIT WEIGHT (tf/m^3)			
IN DRY CONDITION	1.82	1.82	1.82
IN SATURATED CONDITION	2.23	2.15	2.06
NATURAL PERIOD T(sec)	0.6	0.6	0.1
DAMPING RATIO h			0.2
VOID RATIO	0.69	0.69	0.69

$1(tf/m^2)=9.8(kPa)$ $1(tf/m^3)=9.8(kN/m^3)$

Table 2 Analytical results of field embankments.

No.	DAMAGE LEVEL	F_S	$\overline{P_F}$	σ_{P_F}
1	α	0.858	0.760	0.045
2	γ	1.120	0.461	0.092
3	β	0.620	0.790	0.033
4	γ	0.918	0.652	0.063
5	β	1.075	0.473	0.146
6	α	0.390	0.878	0.013
7	γ	1.671	0.254	0.080
8	β	1.330	0.387	0.117
9	β	1.196	0.579	0.086