RISK ASSESSMENTS OF THE EARTHQUAKE-INDUCED PERMANENT DISPLACEMENTS IN EARTH DAMS

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SUMMARY

A simplified method is presented in this paper for investigating the risk of excessive permanent displacements of earth dams subjected to ground shakings. This procedure follows in general the Makdisi and Seed's, in addition, it allows one to consider the uncertainty encountered in the analysis.

An equivalent stationary motion model is used. Also, a probabilistic sliding block model is developed which make use of the ground motion model. To include the dynamic responses of earth dams during ground shaking, necessary response functions are formulated. An example is provided finally for illustrating the procedure.

INTRODUCTION

Newmark (Ref. 7) proposed in 1965 the concept of sliding blocks in an effort to illustrate that displacements rather than the pseudo-static factor of safety is the real controlling factor in assessing the seismic stability of earth dams.

Two simplified procedures, which adopted Newmark's sliding block concept, to assess the earthquake-induced permanent displacements in earth dams are currently available. These two procedures were proposed respectively by Sarma (Ref. 8) and Makdisi and Seed (Ref. 6). Although they differ in details, both methods contain essentially three steps:

1. Predetermine a set of possible yielding surfaces for analyses. For each yielding surface, estimate the limiting acceleration (A_c or $K_c g$ in the literature) that the soil wedge above the yielding surface can sustain.

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2. Perform dynamic analysis of the earth dam, as if the yielding surfaces did not exist. Then, calculate the average wedge acceleration above each yielding surface.

3. Treating each soil wedge as a rigid sliding block, and using the above obtained average wedge acceleration as support motion, calculate the permanent displacement associated with each yielding surface.

A decoupling assumption is implicitly made in this procedure. This assumption has been described and concluded to be acceptable by Lin and Whitman (Ref. 3).

To account for the uncertainty about the possible future motions, both methods utilized several ground motions as data base, and both derived some normalized expected permanent displacement relations for general applications. However, they used only a few ground motions in establishing such relations, as such, biases results may be given in applications. Moreover, the calculated displacements may scatter over a wide range due to variation in ground motions. This point is illustrated in Fig. 1. Accordingly, even if the displacement calculated is not biased, it alone does not provide sufficient information. The range of this scatter should also be quantified.

In view of the above problem, an alternative procedure is developed and presented in this paper. The basic idea underlies this procedure was evolved from the following understanding-- unless the erratic nature of the ground motion may properly be modelled, there is no way that the variation in the permanent displacement can be quantified. For this purpose, an equivalent stationary motion model is adopted. This ground motion model will be described first. A probabilistic sliding block model is also developed. This model, utilizing the adopted ground motion model, gives not only a better expected permanent displacement, but also its probability distribution. To make use of the now available probabilistic sliding block model, the spectral density function of the average wedge acceleration has to be evaluated. This formulation is also presented.

EQUIVALENT STATIONARY MOTION

The earthquake-induced permanent displacement is accumulated through all the slippages that occurred in a ground shaking. This can be viewed as a kind of fatigue problem. For fatigue type problem, the equivalent stationary motion model proposed by Vanmarcke and Lai (Ref. 10) has been found useful (Ref. 4). Only four parameters are required to completly described the damaging effect of a ground motion when using this model.

This model considers the ground to act as a one degree of freedom system, which modifies the highly erratic base rock motion into the shape as being recorded. This is, in other words, to use Kanai-Tajimi spectral density function $G_X(\omega)$, in describing the frequency content of the ground motions.

$$G_x(\omega) = \frac{G_o[1 + 4\ \xi_g^2 (\frac{\omega}{\omega_g})^2]}{1 - [(\frac{\omega}{\omega_g})^2]^2 + 4\ \xi_g^2 (\frac{\omega}{\omega_g})^2}$$

in which, three parameters G_o, ω_g, ξ_g are required to define the spectral density function. The fourth parameter needed is the equivalent stationary motion duration, S. The first three parameters may be replaced by the moments of the spectral density function. They may be the root-mean-square (r.m.s.), σ, the predominant frequency, Ω, and a measure of the frequency dispersion about the predominant frequency, i.e., the band-width, δ. In addition, S so defined is a function of Ω, σ, δ and Amax (Amax is the peak ground acceleration). Alternatively, Ω, σ, δ and Amax can be used in the equivalent stationary motion model to represent the motion.

All the parameters mentioned above are available for a large suite of ground motions (Ref. 2, Ref. 10).

PROBABILISTIC SLIDING BLOCK MODEL

The earthquake-induced permanent displacement is formed in a step-wise fashion, because the ground motion is changing directions all the time. Therefore, the final total permanent displacement, D, can be written as,

$$D = \sum_{i=1}^{N(S)} d_i$$

where, d_i is the displacement developed each time the earthquake-induced shear stress is larger than the resistance along a yielding surface; N(S) is the number of times such occasions should happen in the shaking duration.

The first step toward a complete formulation of D is to control the four parameters of the motion to be fixed, and examine the variation of D due to the change in motion details. This is equivalent to derive first a conditional distribution of D. And the distribution of D can readily be obtained through total probability formulation. This conditional distribution, at a given A_c, $P(D\ A_c, Amax, \Omega, \sigma, \delta)$ has been identified (Ref. 2) to be lognormal. The mean and the standard deviation for this conditional distribution can be obtained from the following equations:

$$E[D \mid A_c, Amax, \Omega, \sigma, \delta] = E[N(S)]\,E[d]$$

where $E[d]$possess the following form

$$E[d] = \frac{\sigma^2}{2\ A_c\Omega^2}\, g(\frac{Ac}{\sigma}) f(\delta)$$

in which $f(\delta)$ and $g(A_c/\sigma)$ are derived through simulations. $g(A_c/\sigma)$ is presented in Fig. 2; while $f(\delta) = 1 + 7.11(\delta - 0.2)^2$.

$E[N(S)]$ is derived using up-crossing rate from random vibration theory,

$$E[N(S)] = \nu_r^+ S$$

where ν_r^+ is the up-crossing rate at $r = Amax/\sigma$ level. Considering the ground motion to follow the Gaussian distribution, ν_r^+ is

$$\nu_r^+ = \frac{\Omega}{2\pi} \exp\left(-\frac{r^2}{2}\right)$$

As for the coefficient of variation, it is found to be

$$V[D \mid A_C,\ Amax,\ \Omega,\ \sigma,\ \delta] = F(r)\sqrt{\frac{2}{\nu_r^+ S}}$$

where, $F(r)=0.38+0.62[1-\exp(-r^2/2)]$. When r is large, F(r) approaches one , and the coefficient of variation may also be found by treating N(S) and d as independent random variables. The above formulations has also been verified by the results from 140 earthquake motions (Ref. 2).

RESPONSE FUNCTIONS FOR EARTH DAMS

If the spectral density function of the average wedge acceleration can be found, the permanent displacements for earth dams can be obtained by utilizing the above model for sliding blocks. Considering the large damping associated with earth structures when subjected to severe ground shakings, the response of earth dams can be treated as stationary when the ground motion is so treated. Then, what is need in addtion to the above derived formulations is the response functions.

Earth dams are modelled as composed of one dimensional shear slices, the absolute acceleration response function for a soil wedge up to depth z (Fig. 3) is,

$$H_{a,ave}(z,\omega) = \sum_k C_k(z) \frac{-\omega^2}{(\omega_k^2 - \omega^2) + 2i\omega\omega_k \xi_k}$$

where, k is kth mode. involved; $C_k(z)$ is $\frac{4H\ J_1(\beta_k z/H)}{z\ \beta_k^2\ J_1(\beta_k)}$, and $C_k(0) = \frac{2}{\beta_k J_1(\beta_k)}$; J_k is the Bessel function of the kth kind; β_k is the kth root of J_0. If the modulus of the soil is considered to vary with depth, the $C_k(z)$ will be different. The response function for such type of model (i.e., Ref. 1) has been presented by Lin (Ref. 2).

The spectral density function of the wedge acceleration up to depth z then is,

$$G_{a,ave}(z,\omega) = \left| H_{a,ave}(z,\omega) + 1 \right|^2 G_x(\omega)$$

Calculating the moments of $G_{a,ave}(z,\omega)$ as in the case for ground motions, the r.m.s., the predominant frequency and the band-width. Using these moments as input, from the probabilistic sliding block model, the conditional distribution of the permanent displacement can readily be obtained.

To account for the nonlinear behavior of soil, an equivalent linear approach used in the computer program FLUSH (Ref. 5) is adopted. This approach assumes that the ratio between the average strain and the r.m.s. strain equals that of the ground accelerations. From this, the average strain level can be calculated. Thereby, the modulus can be modified. Finally, a strain compatible modulus is reached.

AN EXAMPLE

A homogeneous dam of 110 m height, with shear wave velocity 300 m/sec is used to illustrate the present procedure. Assuming that the yielding surface extending from the top to the bottom is the most critical one, and it has a safety factor of 1.3 under static condition. At stake is the question-- what is the risk of the excessive permanent displacement , say, greater than 10 cm, for the soil wedge along this yielding surface? Assuming that the material of this dam belongs to the sand catergory of Ref. 6. Also, the dam is seated on rock.

To begin with, the ground motions have to be defined. Parameters of ground motions derived upon rock site records are used for this problem. From 36 rock site records, the dispersion of ground frequencies, ω_g, is shown in Fig. 4 (Ref. 2). This is taken as the possible ω_g encountered at the site. Whereas the value of ξ_g is concluded not important, its mean value is used, which is 0.22. For the ratio σ/Amax, data obtained from 140 records of various site condition is used, and shown in Fig. 5. In evaluating the dynamic response, 10% damping is used for all the four modes considered. The resulting expected permanent displacement with respecte to possible peak accelerations is demonstrated in Fig. 6. Combining with the results from hazard analysis (Fig. 7), the distribution can be defined. The analysis yields:

$E[D] = 0.17$ cm
$P_r(D > 10\text{cm}) = 0.0034$

CONCLUSIONS

Limited analyses show that the present procedure give compatible results with that obtained by time domain integration when the input ground motions are the same. It has the flexibility that allows one to tackle his problem to the desired sophistication. It also constitutes the basis for dealing with the question--"what is the probability that the permanent displacement should exceed X cm in Y year?"

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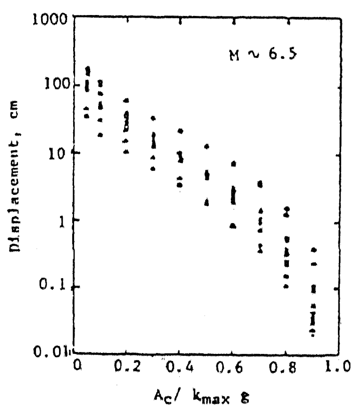

Fig. 1 Scatter in the Permanent Displacement due to Variation in the Ground Motions (Ref. 6).

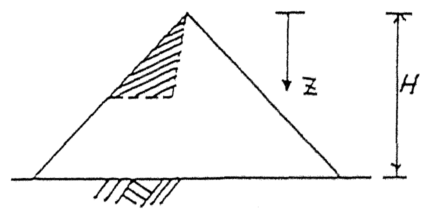

Fig. 3 The Soil Wedge and the Triangular Dam Used.

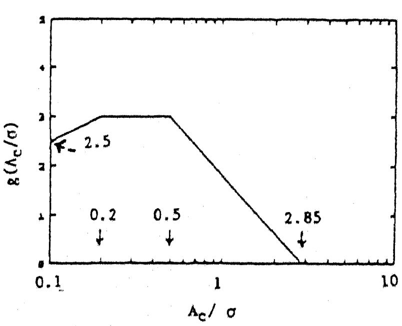

Fig. 2 The Plot of Function $g(A_c/\sigma)$.

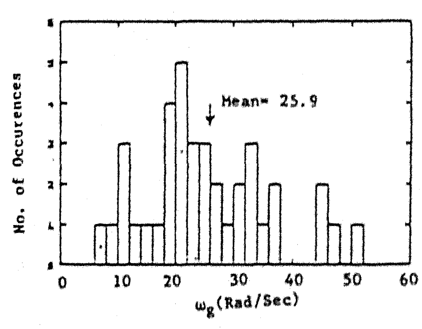

Fig. 4 The Range of ω_g deived from Rock Site Records.

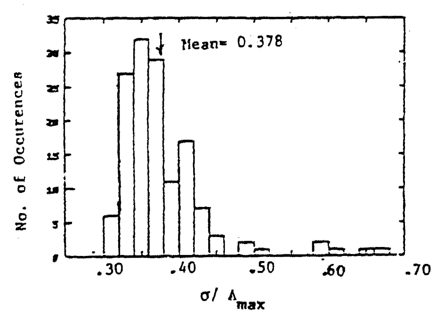

Fig. 5 The Variation of σ/Amax Obtained from 140 Records on Various Sites.

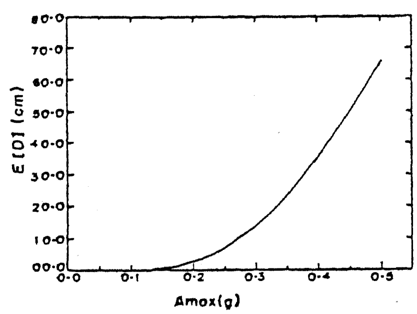

Fig. 6 Expected Displacement v.s. Amax for the Example.

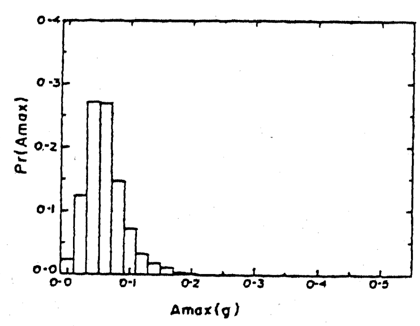

Fig. 7 Seismic Hazard for the Example Site.

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