Hysteretic Damping in the Seismic Analysis of an Earth Dam

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ABSTRACT

A multi surface kinematic soil model[1] has been used to study the response of an earth dam to seismic loading. The finite element analysis has been run using different assumed shear stress/strain curves for the soil model. The variable hysteretic damping introduced by the curves is shown to have little effect on the computed peak accelerations, which are in good agreement with measured values. A more marked effect is observed in the peaks of the Fourier amplitude spectra which are shown to be more sensitive to the stress/strain curves.

INTRODUCTION

Dynamic analyses of soil structures require assumptions to be made as to the form of the stress/strain laws. Not only are displacements affected by the shape of the stress/strain curve, but also the amount of hysteretic damping generated by cycles of loading and unloading. In the present work, dynamic analysis of an earth dam[2] is used to demonstrate the influence of the shape of the stress/strain curve on the computed response.

The soil properties available for most analyses are often quite rudimentary and assumptions must be made before proceeding. For the analyses presented here, the only available data relating to the stress/strain curve of the soils were the initial stiffness and the effective shear strength parameters. For a given initial mean stress level, a curve can be generated between these limits such that it has the correct initial gradient and flattens out at approximately the correct shear stress level. This curve simulates the stress/strain response from initial loading to failure that might be measured in a triaxal compression or extension test. Such a curve can then be used to generate the parameters for a multi-surface model[1] suitable for implemetation in finite element codes for dynamic analysis of boundary problems.

The present report describes a method of curve generation in which changes of shape can be made without altering the initial gradient or seriously affecting the failure load. The curves are used in the dynamic analysis of an earth dam subjected to seismic loading, and the computed crest accelerations compared with the measured values for a variety of stress/strain curve shapes.

2. CURVE GENERATION

Consider a shear stress/strain curve of the form:

$$\bar{\varepsilon} = A\,q - B\ \ln\left[1 - \frac{q}{q_{ult}}\right] \qquad (1)$$

where

$\bar{\varepsilon} = \varepsilon_1 - \varepsilon_3$ shear strain

$q = \sigma_1 - \sigma_3$ shear stress

q_{ult} = ultimate value of q

A ,B = curve fitting parameters

The curve has the property that it passes through the origin (0,0) and is asymptotic to q_{ult}. In reality, failure conditions are reached at a finite amount of strain $\bar{\varepsilon}_{ult}$, so the asymptote is increased by $\frac{q_{ult}}{1 - TOL}$ where

$0 < TOL < 1$. Equation (1) can hence be rewritten as:

$$\bar{\varepsilon} = A\,q - B\ \ln\left[1 - q\,\frac{1-TOL}{q_{ult}}\right] \qquad (2)$$

We seek the values of A and B such that the following two conditions are
satisfied:

a) The initial gradient $\frac{d\,\bar{\varepsilon}}{d\,q} = \frac{1}{2\,G_o}$ at $q = 0$ where G_o is the initial shear modulus.

b) The curve must pass through the 'failure' point ($\bar{\varepsilon}_{ult}$,q_{ult})

The first condition leads to:

$$A + B\,\frac{(1 - TOL)}{q_{ult}} = \frac{1}{2\,G_o} \qquad (3)$$

and the second condition leads to:

$$\bar{\varepsilon}_{ult} = A\, q_{ult} - B \ln (TOL) \qquad (4)$$

From eqns. (3) and (4) we get:

$$A = \frac{1}{2\, G_o}\left[1 - \frac{(q_{ult} - 2\, \bar{\varepsilon}_{ult}\, G_o)\,(1 - TOL)}{q_{ult}\,(1 - TOL + \ln (TOL))}\right] \qquad (5)$$

and

$$B = \frac{q_{ult} - 2\, \bar{\varepsilon}_{ult}\, G_o}{2\, G_o\, (1 - TOL + \ln (TOL))} \qquad (6)$$

The curves in Figure 1 show typical q vs. $\bar{\varepsilon}$ relationships for different values of TOL as might be measured in a triaxal compression test. The assumed parameters were as follows:

$G_o = 10^4$ kPa

$q_{ult} = 269$ kPa ($\phi' = 35°$ $c' = 0$, cell pressure = 100 kPa)

$\bar{\varepsilon}_{ult} = 0.05$

For very small values of TOL, the curve becomes quite flat at the ultimate strain value $\bar{\varepsilon}_{ult}$. For higher values of TOL, the curve is still rising at $\bar{\varepsilon}_{ult}$ so the point ($\bar{\varepsilon}_{ult}$, q_{ult}) no longer corresponds to failure in the strict sense. It may be noted that all curves have the same initial gradient $2\, G_0$, and it is the change in shape of the curves at relatively low strain values that is of immediate interest in the present study.

3. PARAMETER IDENTIFICATION AND DYNAMIC ANALYSES

The finite element mesh shown in Figure 2 represents a 2-D section of the Long Valley Dam, near Bishop California[3]. The dam is well instrumented, and provided a quite comprehensive set of acceleration records following a series of earthquakes in May 1980 [4].

As shown in Figure 2, the mesh is split into nine element groups with properties relating to initial stiffness and strength. These properties were used to generate stress/strain curves for each group as described previously, from which parameter identification [5] for the multi-surface model could be performed.

Using measured accelerations at the abutments of the dam, the mesh was subjected to the same accelerations along its base and sides in the horizontal and vertical directions. The dynamic response of the dam to these input accelerations was computed using a program called DYNAFLOW[6]. The resulting accelerations at the crest of the dam were then compared with the measured values from accelerogram records. Only the results in the horizontal (upstream/downstream) direction are presented here. For further details of the analyses performed on this dam, the reader is referred to reference 2.

In the present study, the analyses were repeated three times by altering the value of TOL in the curve generation phase, while keeping all other parameters constant.

4. RESULTS

Figures 3,4 and 5 show the computed acceleration of the crest of the dam in the upstream/downstream direction for the first 12 seconds of input motion. The Fourier amplitude spectra for the computed and measured values are also presented. In each case, the computed values (solid lines) are superimposed onto the measured values (dashed lines).

Figure 3a with TOL = 0.001 gives computed values of acceleration that consistently overestimate the amplitudes of the measured values. The Fourier amplitudes in Figure 3b agree closely in frequency content, but the energy associated with the computed values at the fundamental frequency is considerably overestimated.

Figures 4a and 4b show the same analyses with TOL = 0.1. The softer stress/strain curves used to generate the model parameters have resulted in greater hysteretic damping, leading to computed accelerations that are in better agreement with the measured values. The increased energy dissipation that has occured is particularly clear in the Fourier amplitude plot, where the peak value of 0.442 g-sec has been reduced by 47% from its value of 0.836 g-sec corresponding to the TOL = 0.001 analysis.

Further softening of the stress/strain curves by letting TOL = 0.9 has the expected effect of even greater damping and energy loss as shown in Figure 5. Although the maximum crest acceleration of about 0.4g is closely reproduced, the overall response is over-damped with the computed values underestimating the measured acceleration amplitudes. In this case, the Fourier amplitude peak of 0.274 g-sec has been reduced by 67% compared with the TOL = 0.001 analysis.

5. CONCLUSIONS

A multi-surface kinematic soil model has been used to analyse the response of an earth dam to seismic loading. The 2-D finite element mesh used in the analysis included nine different soil types to reflect the varying properties of the dam materials. The soil properties provided from the site investigation involved the elastic modulus as a function of confinement, and the shear strength parameters. A logarithmic function was used to generate the stress/strain curves for each of the soil types, and a parameter was included which allowed the shape of the curves to be varied. The effect of three different curves on the response of the dam to the same earthquake has been presented.

Generally speaking, excellent agreement was obtained between the computed and measured accelerations at the crest of the dam in both the time and frequency domains. However, the variable hysteretic damping introduced by the different curves was shown to have a marked effect on the peaks of the computed Fourier amplitude spectra.

From a design standpoint, conservative estimates of the response of the dam would be obtained by using smaller values of the curve fitting parameter TOL, as this would lead to a stiffer response at working stress levels. Although the curve generation method described in this paper gives the analyst flexibility in portraying the stress/strain behaviour of the soil, it is no substitute for actual soil test data which should be used whenever available.

6. REFERENCES

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7. ACKNOWLEDGEMENTS

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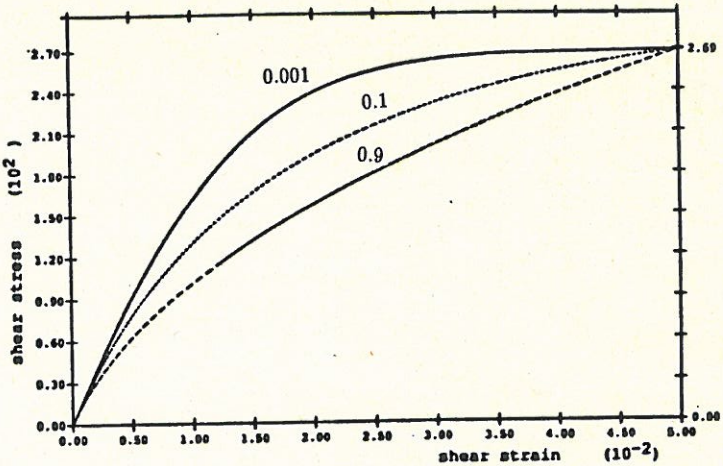

Figure 1. Stress/strain curves with TOL = 0.001 , 0.1 , 0.9

Group	E_0(kPa)	ν_0	ϕ'	c'(kPa)	
1	1.6E5	0.3	40	0	drained
2	2.1E5	0.3	40	0	drained
3	4.0E5	0.45	39	45	undrained
4	5.0E5	0.45	39	45	undrained
5	5.5E5	0.45	39	45	undrained
6	5.9E5	0.45	39	45	undrained
7	6.2E5	0.45	39	45	undrained
8	6.5E5	0.45	39	45	undrained
9	4.9E6	0.3			elastic

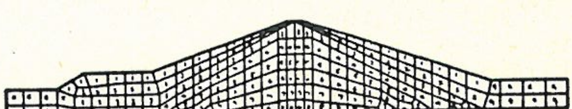

Figure 2. Mesh layout and properties for dam analyses

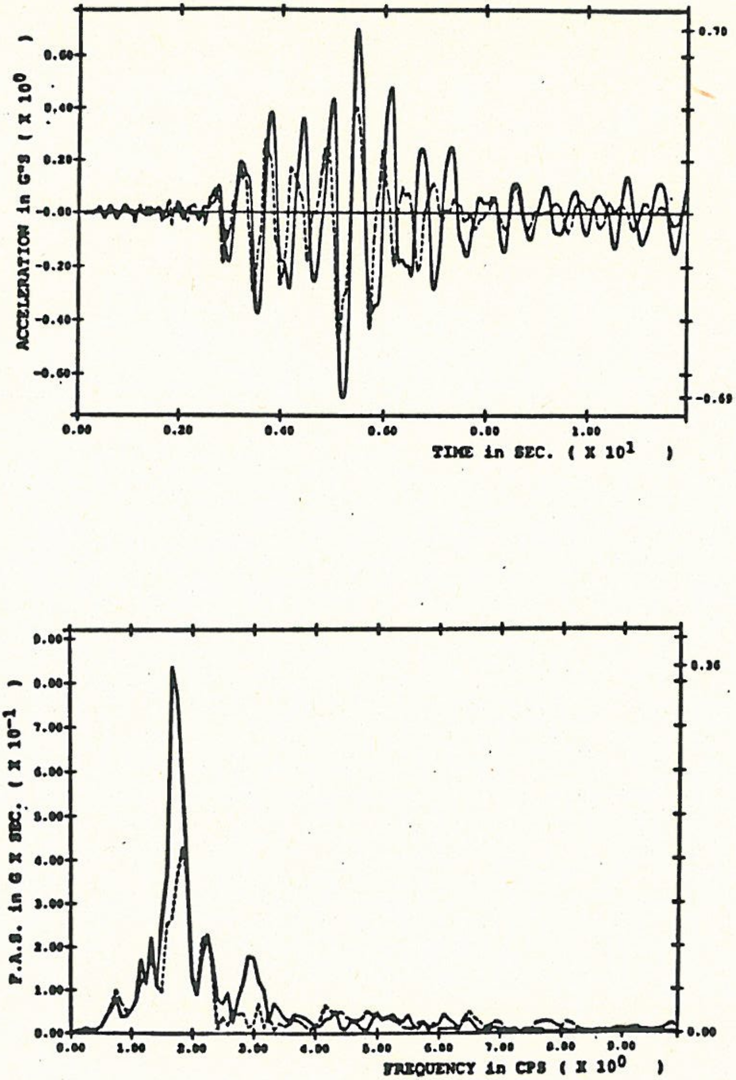

Figure 3. Crest response with *TOL* = 0.001
(solid=computed, dashed=measured)
a) Accelerations b) Fourier spectra

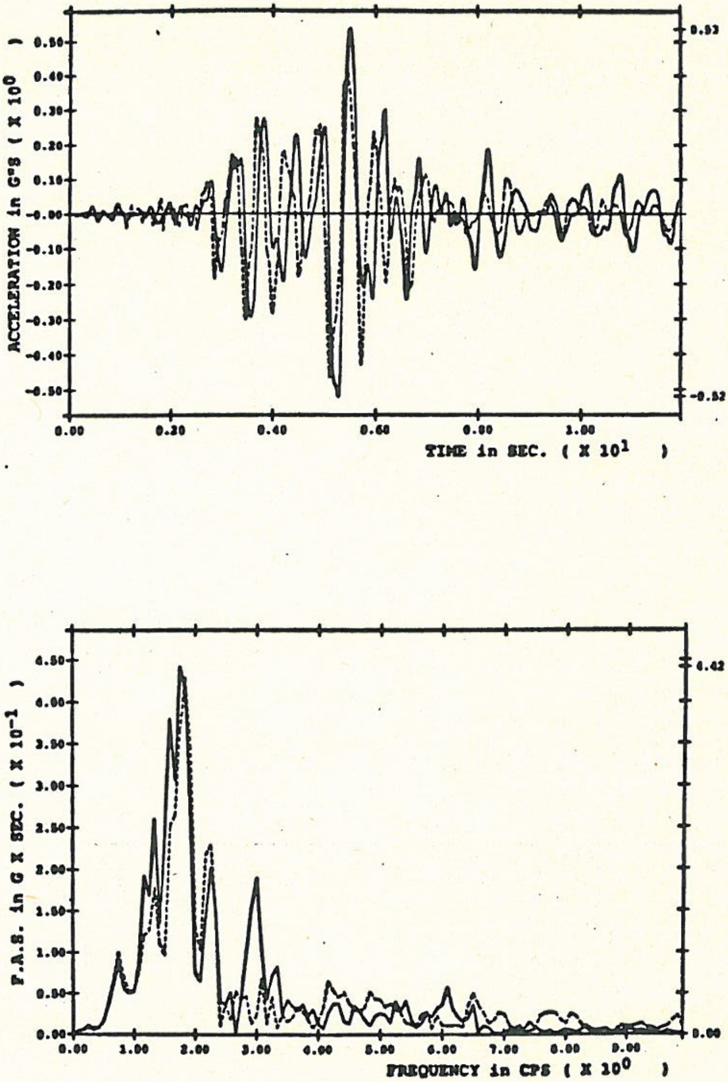

Figure 4. Crest response with *TOL* = 0.1
(solid=computed, dashed=measured)
a) Accelerations b) Fourier spectra

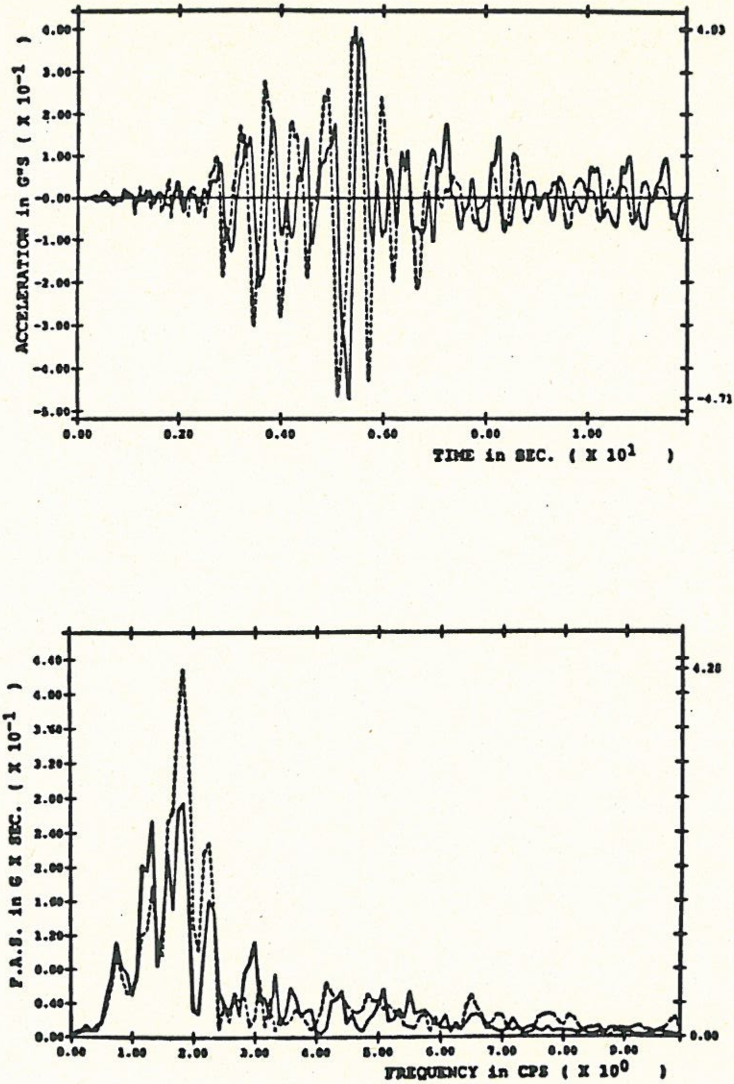

Figure 5. Crest response with *TOL* = 0.9
(solid=computed, dashed=measured)
a) Accelerations b) Fourier spectra