Spatial correlation effects on seismic response of structures

O. Ramadan[I] and M. Novak[II]

ABSTRACT

The effects that spatial randomness of ground motion may have on seismic response of large structures to earthquakes are discussed. It is outlined how spatial randomness of this motion can be incorporated in the analysis. Spatial correlation of seismic ground motion may have important consequences for extensive structures such as long dams, pipelines, large buildings etc. Usually, such structures are examined using a two-dimensional finite element analysis of its "slice". However, lack of spatial correlation of the ground motion along the longitudinal axis of the structure may result in bending and shear stresses that are very significant. This is demonstrated using the example of the horizontal seismic response of a long, concrete gravity dam. Soil-structure interaction is accounted for in the analysis.

INTRODUCTION

The performance and safety of earthquake-resisting structures can be enhanced by improving the understanding and representation of earthquake ground motions. One aspect of these motions, relevant for the analysis of extended structures such as tunnels, pipelines, large dams and multi-supported long bridges, is spatial variability. This means that the ground motion and the resulting dynamic loads may not be perfectly coherent (synchronized) in space. This property reduces the total load in the structure in some cases while in others it can produce a type of response that remains completely unforeseen if spatial correlation is not accounted for. This paper outlines a procedure that makes it possible to account for spatial correlation of ground motions and soil-structure interaction, using an example of the horizontal response of a large gravity dam. The paper complements an earlier study by Novak and Suen (1987) which was limited to the vertical response and used a technique different from the one employed here.

[I] Research Assistant, Faculty of Engineering Science, The University of Western Ontario, London, Ontario N6A 5B9

[II] Professor, Faculty of Engineering Science, The University of Western Ontario, London, Ontario N6A 5B9

While structural response to incoherent ground motions can be conveniently analyzed in terms of random vibration (Novak & Hindy, 1979; Hindy & Novak, 1980; Novak and Suen, 1987), the deterministic approach is more common. For the latter approach, time histories of ground motions are needed. These can either be actual motions recorded in seismic events or digitally simulated motions generated to fit specified spectra. In this study, horizontal ground motions are generated using the technique due to Shinozuka et al. (1988). The motions generated are stationary, spatially two-dimensional and homogeneous with zero mean and match a prescribed power spectral density. The motion components feature two independent random phase angles uniformly distributed between 0 and 2π. The time envelope function is applied on the simulated stationary ground motions to convert them into nonstationary ones.

The stationary time histories are generated to fit the local power spectral density represented by the modified Kanai-Tajimi acceleration spectrum (Clough & Penzien, 1975), i.e.

$$S_{u_g}(\omega)=S_o \frac{[1+4\xi_g^2(\frac{\omega}{\omega_g})^2]}{[1-(\frac{\omega}{\omega_g})^2]^2+4\xi_g^2(\frac{\omega}{\omega_g})^2} \cdot \frac{(\frac{1}{\omega_f})^4}{[1-(\frac{\omega}{\omega_f})^2]^2+4\xi_f^2(\frac{\omega}{\omega_f})^2} \tag{1}$$

in which S_o is the white-noise bedrock acceleration spectrum, ω_g, ω_f are resonance frequencies, and ξ_g, ξ_f are damping ratios. One of the advantages of this spectrum is that the corresponding spectrum of ground displacements, which will be needed, does not feature a singularity at frequency $\omega = 0$.

The power spectral density by Eq. 1 is used in the double series expression for the generated ground motion with the frequency ω replaced by

$$\omega = g(k_1,k_2) = \alpha\sqrt{k_1^2 + k_2^2} \tag{2}$$

in which k_1, k_2 are the wave numbers of non-dispersive waves in the directions x and z, respectively, and α is the wave phase velocity.

MATHEMATICAL MODEL

The Dam

The dam is assumed to have a large aspect ratio (length/width), and is modelled by N beam elements (Fig. 1). The mass, m, and the polar mass moment of inertia, I, associated with rocking are lumped at the element nodes. Water behind the dam is not considered. Horizontal translations perpendicular to the dam longitudinal axis and rotations about this axis (rocking) are allowed, resulting in bending of the dam and its twisting. The horizontal joint rotations are eliminated through static condensation leaving the model with 2(N+1) degrees of freedom. In the example, the dam is assumed to be of constant cross-section as may be adequate for a rectangular canyon.

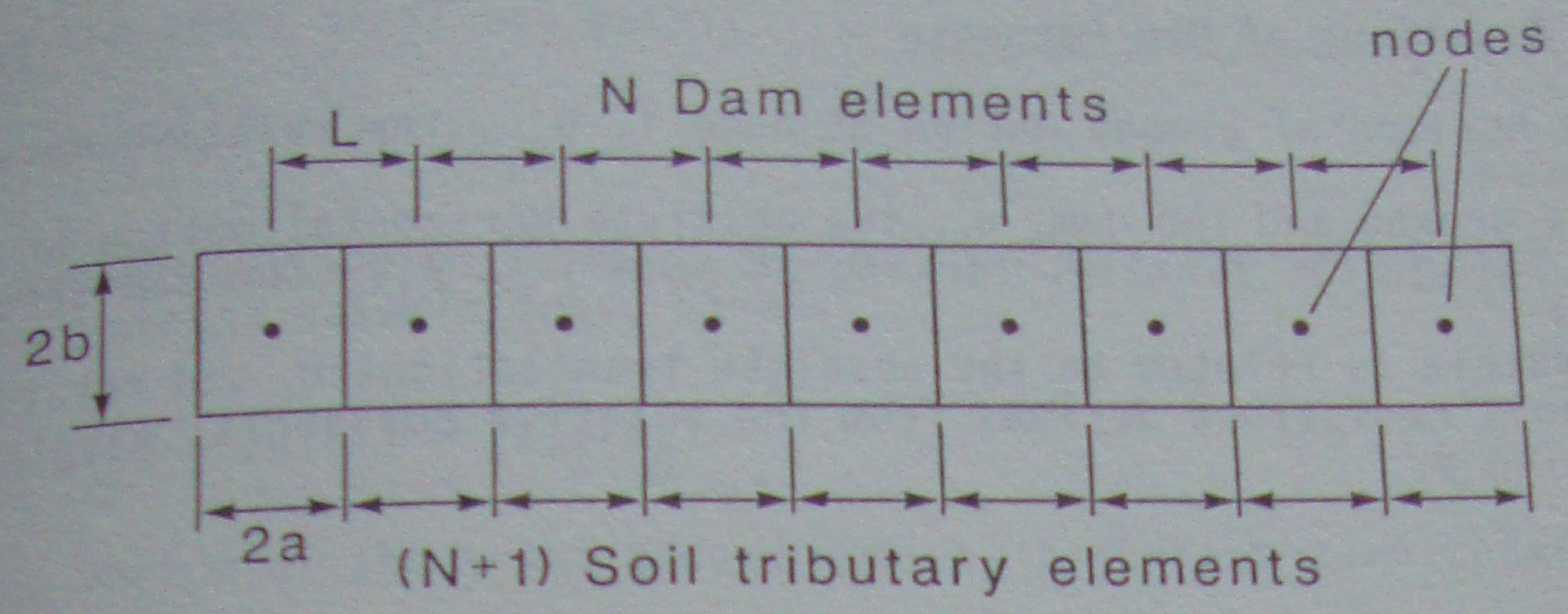

Figure 1. Schematic of dam elements and soil tributary elements

Material damping of the dam is hysteretic, i.e. frequency independent, and is introduced using complex Young's and shear moduli with material damping ratio β.

Soil Reactions

Soil-structure interaction is incorporated in the analysis through the complex, frequency dependent soil stiffness matrix, established for a sequence of rectangular tributary areas indicated in Fig. 2. The soil stiffness matrix associated with horizontal translations is obtained by inversion of the dynamic flexibility matrix which describes the displacements of the tributary areas due to unit harmonic loads distributed over the areas 2a x 2b on the surface of a viscoelastic halfspace. Coupling is considered. The horizontal displacements so generated can be written as

$$u(x,y) = \frac{F}{2G}\,[f(x,y)+i\;g(x,y)] \tag{3}$$

in which F = amplitude of the harmonic load taken as unity, G = shear modulus of the soil, and f,g = complex compliance functions evaluated using the solution of the stress boundary value problem. These functions were calculated following Gaul's (1977) solution. The part of the soil stiffness matrix stemming from horizontal translations is first calculated at the dam base and then transferred to the nodal points of the dam elements placed on the longitudinal axis passing through the dam centre of gravity. This couples the horizontal translation and rocking of the dam elements. The rocking soil stiffness matrix linking the rotations of individual soil elements was investigated in an analogous way. It turns out that the soil rotations do not propagate from the source very far but diminish quickly with distance. Therefore, the rocking soil stiffness matrix was evaluated in a simpler way using the well known solution for rocking of a strip footing. The torsional soil stiffness associated with the rotation in the horizontal plane is neglected because it is adequately accounted for by the horizontal translations when the dam elements are sufficiently small relative to the dam length.

Governing Equations of Dam Response

Denote the horizontal ground motion at node i, u_{g_i}, the relative motion between the ground and the dam, u_i, the absolute horizontal motion of the dam $U_i = u_i + u_{g_i}$ (Fig. 2); finally, rocking at node i is ψ_i. The dam structural stiffness matrix is related to the absolute translations U_i and rotations ψ_i, while the soil resistance derives from the relative horizontal displacements u_i and rocking ψ_i.

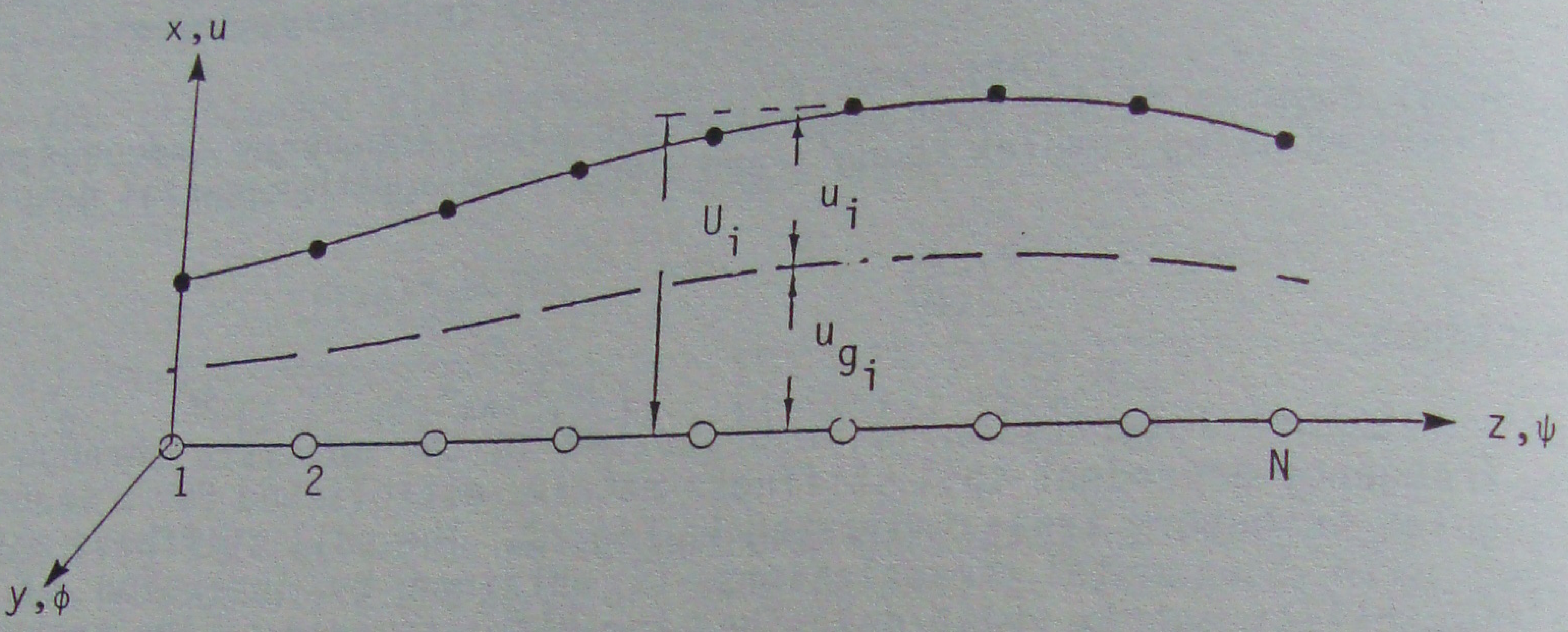

Figure 2. Dam displacements

Using the lumped mass matrix, the governing equations are

$$[\,M\,]\{\ddot{Y}\} + [k]_s\{Y\} + [k]_f\{y\} = \{0\} \tag{4}$$

in which the displacement vectors are written as

$$\{Y\} = [U_1 U_2 \ldots U_{N+1}\ \psi_1 \psi_2 \ldots \psi_{N+1}]^T = [\{U\}\ \{\psi\}]^T \tag{5}$$

$$\{y\} = [u_1 u_2 \ldots u_{N+1}\ \psi_1 \psi_2 \ldots \psi_{N+1}]^T = [\{u\}\ \{\psi\}]^T \tag{6}$$

The mass matrix is diagonal and lists all lumped masses, m, and mass moments of inertia, I, and the structural stiffness, $[k]_s$, condensed with regard to rotation, ϕ, is standard. The foundation stiffness matrix can be written as

$$[k]_f = \begin{bmatrix} [k_{uu}]_f & [k_{u\psi}]_f \\ [k_{\psi u}]_f & [k_{\psi\psi}]_f \end{bmatrix} \tag{7}$$

Denoting the total stiffness matrix

$$[k] = [k]_s + [k]_f \tag{8}$$

the governing equation in terms of absolute motion, preferred here because of subsequent stress calculations, becomes

$$[\,M\,]\{\ddot{Y}\} + [k]\{Y\} = [k]_f\{y_g\} \tag{9}$$

where the vector of the input ground motion, featuring zero rotations, is

$$\{y_g\} = [u_{g_1} \;\; u_{g_2} \ldots u_{g_{N+1}} \;\; 0 \; 0 \ldots 0_{N+1}]^T = [\{u_g\} \; \{0\}]^T \tag{10}$$

With the notations by Eqs. 5 to 10, and partitioning Eq. 8 as in Eq. 7, the governing equation, Eq. 9, can be rewritten in a partitioned form, i.e.

$$\begin{bmatrix} [m] & \\ & [I] \end{bmatrix} \begin{Bmatrix} \{\ddot{U}\} \\ \{\ddot{\psi}\} \end{Bmatrix} + \begin{bmatrix} [k_{uu}] & [k_{u\psi}] \\ [k_{\psi u}] & [k_{\psi\psi}] \end{bmatrix} \begin{Bmatrix} \{U\} \\ \{\psi\} \end{Bmatrix} = \begin{bmatrix} [k_{uu}]_f & [k_{u\psi}]_f \\ [k_{\psi u}]_f & [k_{\psi\psi}]_f \end{bmatrix} \begin{Bmatrix} \{u_g\} \\ \{0\} \end{Bmatrix} \tag{11}$$

Because of the frequency dependence of the soil stiffness matrix these equations are solved by Fast Fourier Transform in the frequency domain (complex response analysis), transforming first the simulated ground motions generated digitally. For each harmonic component further condensation with regard to $\{\psi\}$ is implemented to save on computing time.

EXAMPLE

To illustrate the type of response the above procedure yields, a long, concrete gravity dam with a cross-section similar to that of the Koyna Dam in western India is analyzed. The dam is 103 m high with a crest length of 853 m. Its cross-section, assumed to be constant, is shown in Fig. 3. The dam specific mass and Young's modulus are 2300 kg/m^3 and 30000 MPa, respectively. The Poisson's ratio is 0.2. The foundation rock is basalt with a shear wave velocity of 1218 m/s (4000 ft/s) and Poisson's ratio equal to 0.3. Further data on this dam are given in Novak and Suen (1987). The ground motion is generated by Eq. 1 with $\omega_f = 0.1\,\omega_g$, $\xi_f = \xi_g = 0.6$, $\omega_g = 15.71\ s^{-1}$, and the envelope function shown in Fig. 4. The dam is divided into ten equal elements.

The ground motions are simulated at the eleven nodes in the direction X with the dam lying along the axis Z and the wave phase velocity of 1400 m/s. The duration of the ground motions is 10 s. The simulated ground motions are shown in Fig. 5. The maximum ground acceleration is 0.15g. The correlation

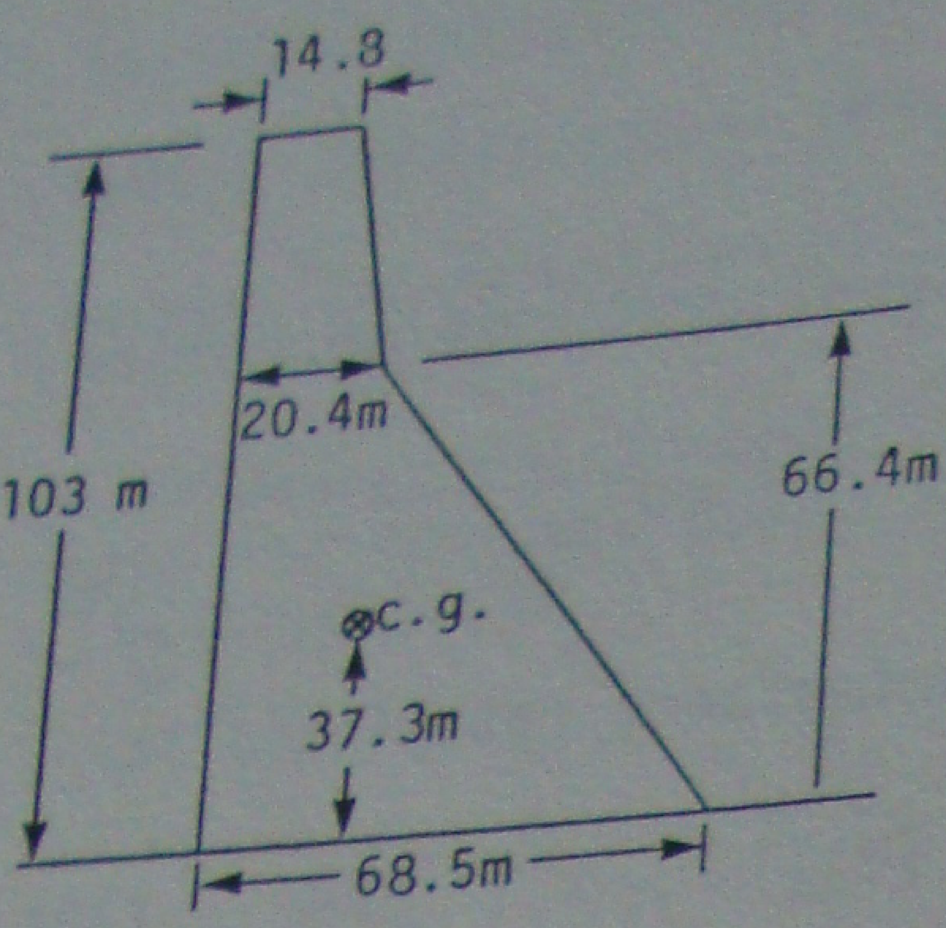

Figure 3. Dam cross-section

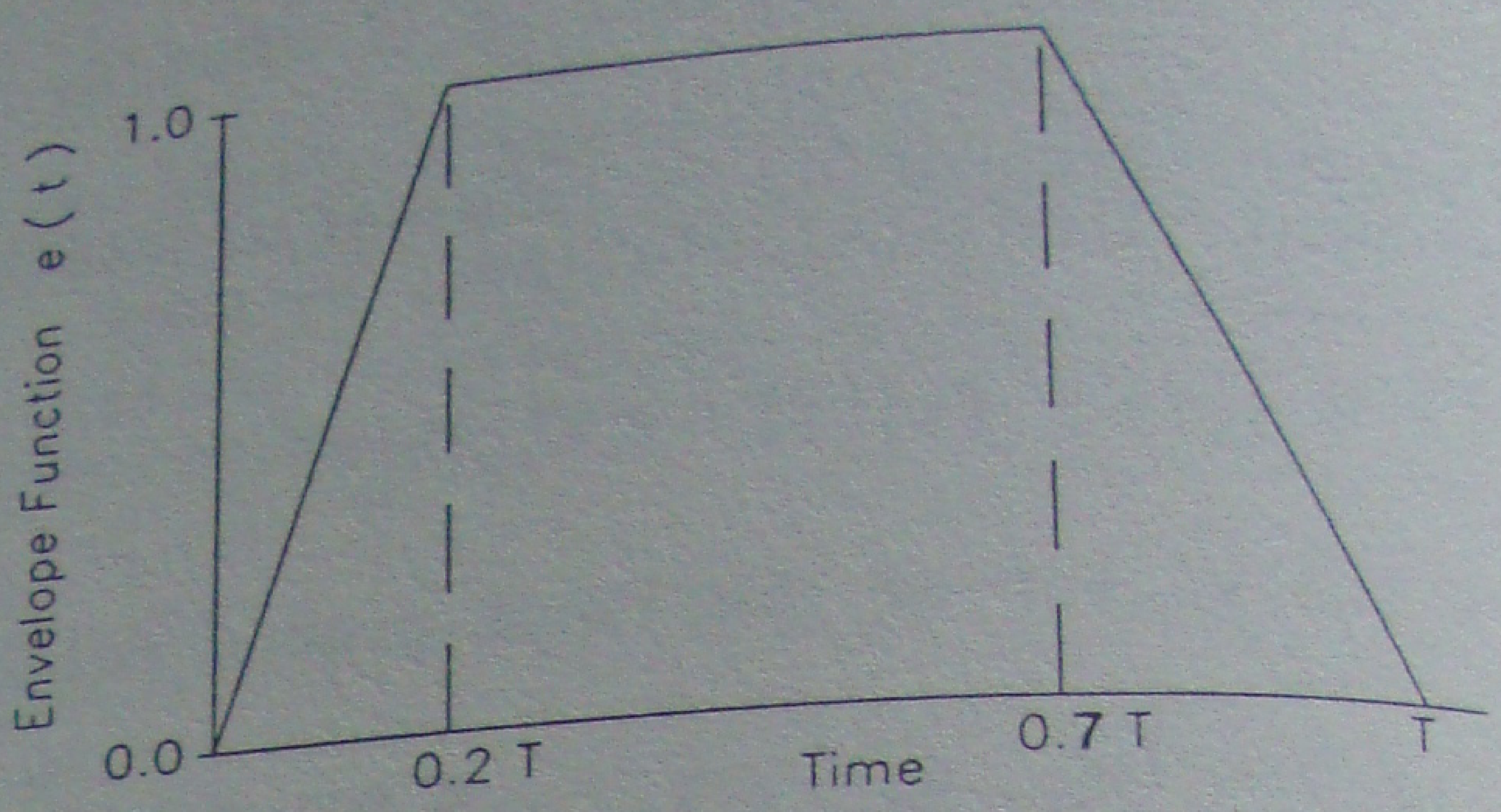

Figure 4. Envelope function

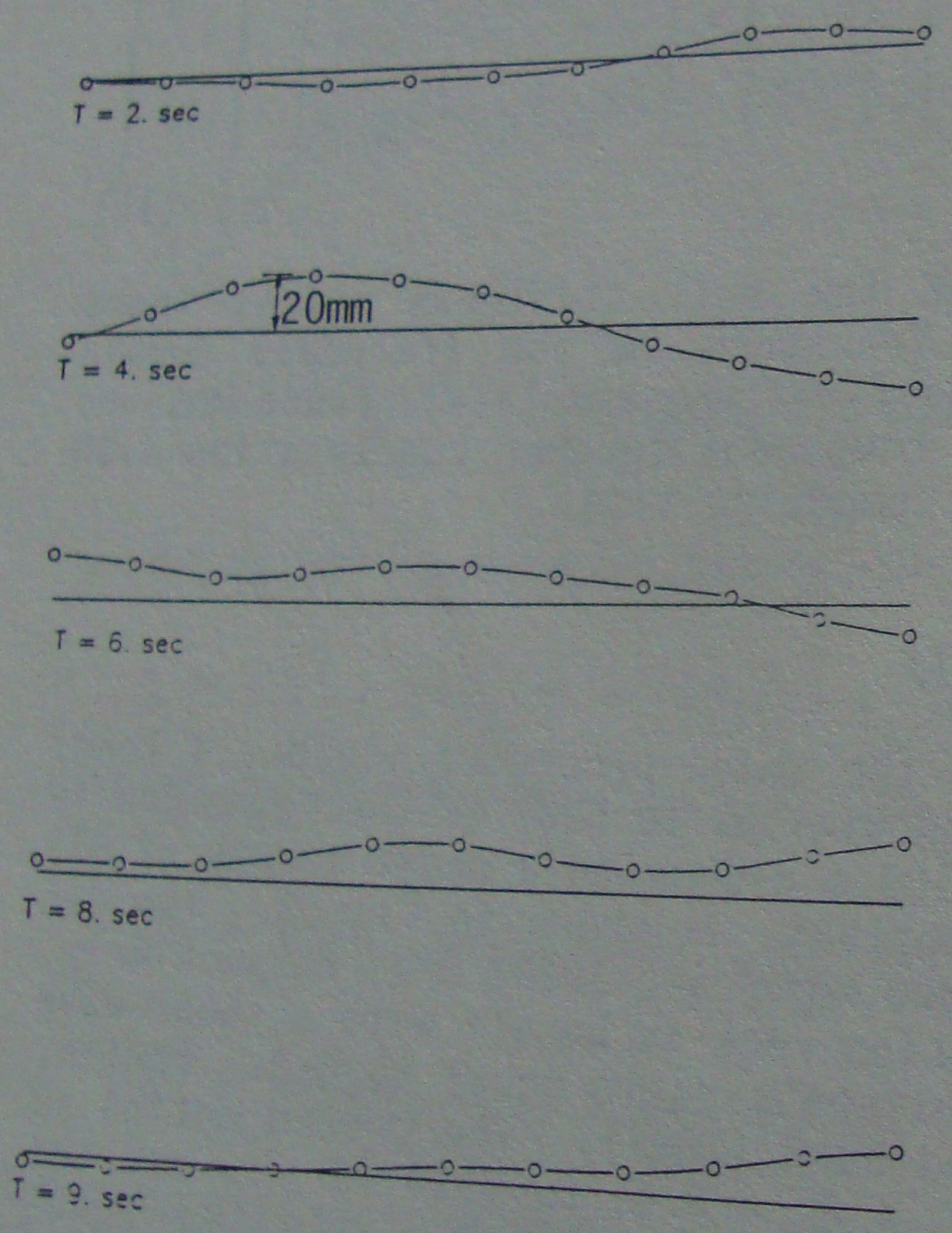

Figure 5. Simulated ground motions

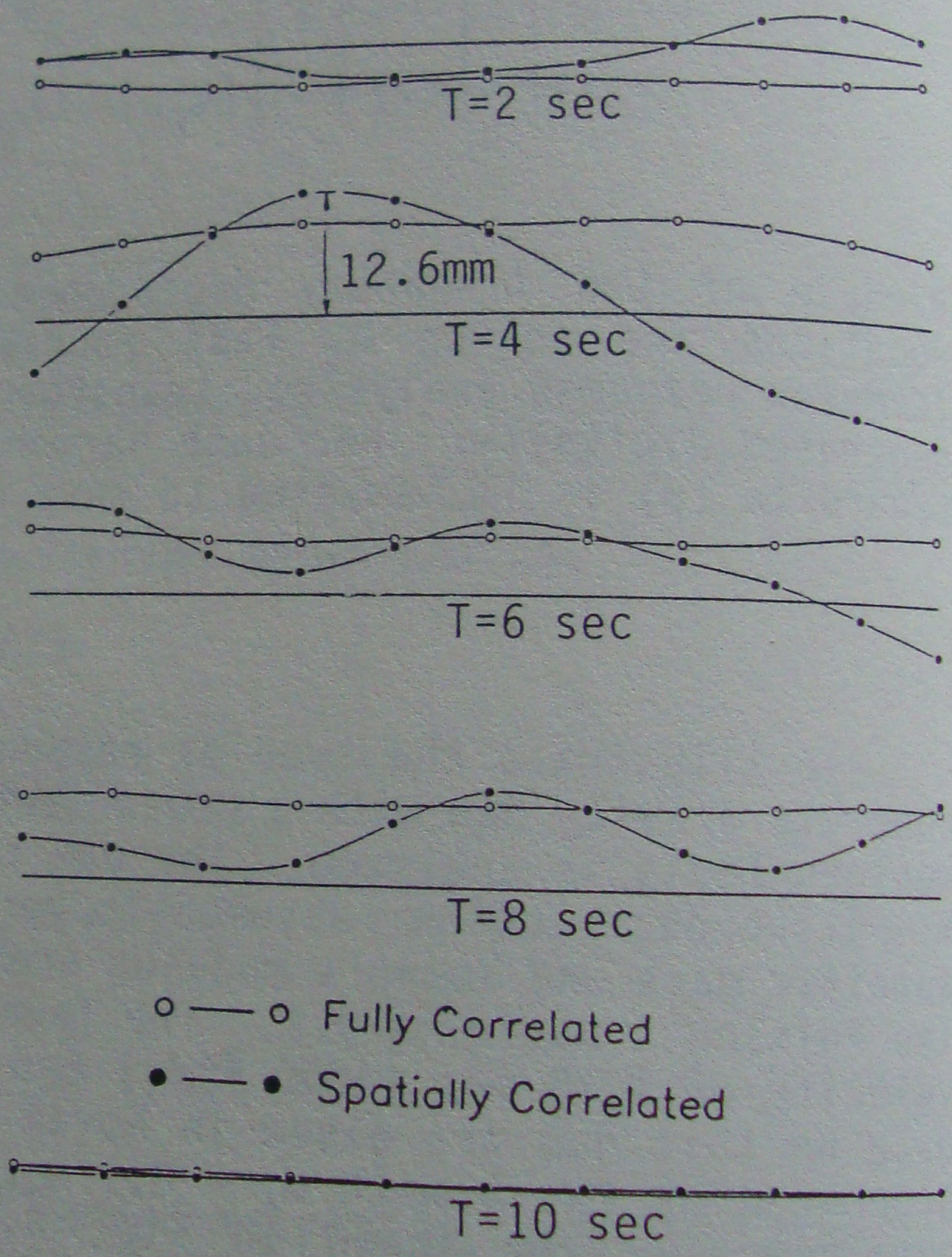

Figure 6. Dam horizontal response

coefficients between the node 1 and the nodes 2 to 11 are 0.96, 0.85, 0.73, 0.60, 0.48, 0.35, 0.22, 0.10, 0.0 and -0.08. These correlation coefficients suggest a correlation length close to the dam length. The dam response to this ground motion is shown in Fig. 6 in which the response to fully correlated ground motions is also plotted for comparison, as in the subsequent figures. The bending of the dam due to the lack of ground motion coherence is obvious. For fully correlated ground motions, the dam moves almost as a rigid body. Notice also that the maximum dam displacement due to incoherent ground motions exceeds the response to fully correlated excitation. The torsional moments associated with the dam response are displayed in Fig. 7 while the bending moments are shown in Fig. 8. These moments are much higher for the incoherent ground motion than for the fully correlated one. Under the usual plane strain assumptions, these moments would be all equal to zero. The maximum bending and combined shear stresses are 1.24 and 0.36 MPa for the incoherent ground motions and only 0.26 and 0.09 MPa for the fully correlated ground motions, respectively. The actual level of the stresses depends, of course, on the actual ground motion intensity, frequency content and degree of coherence.

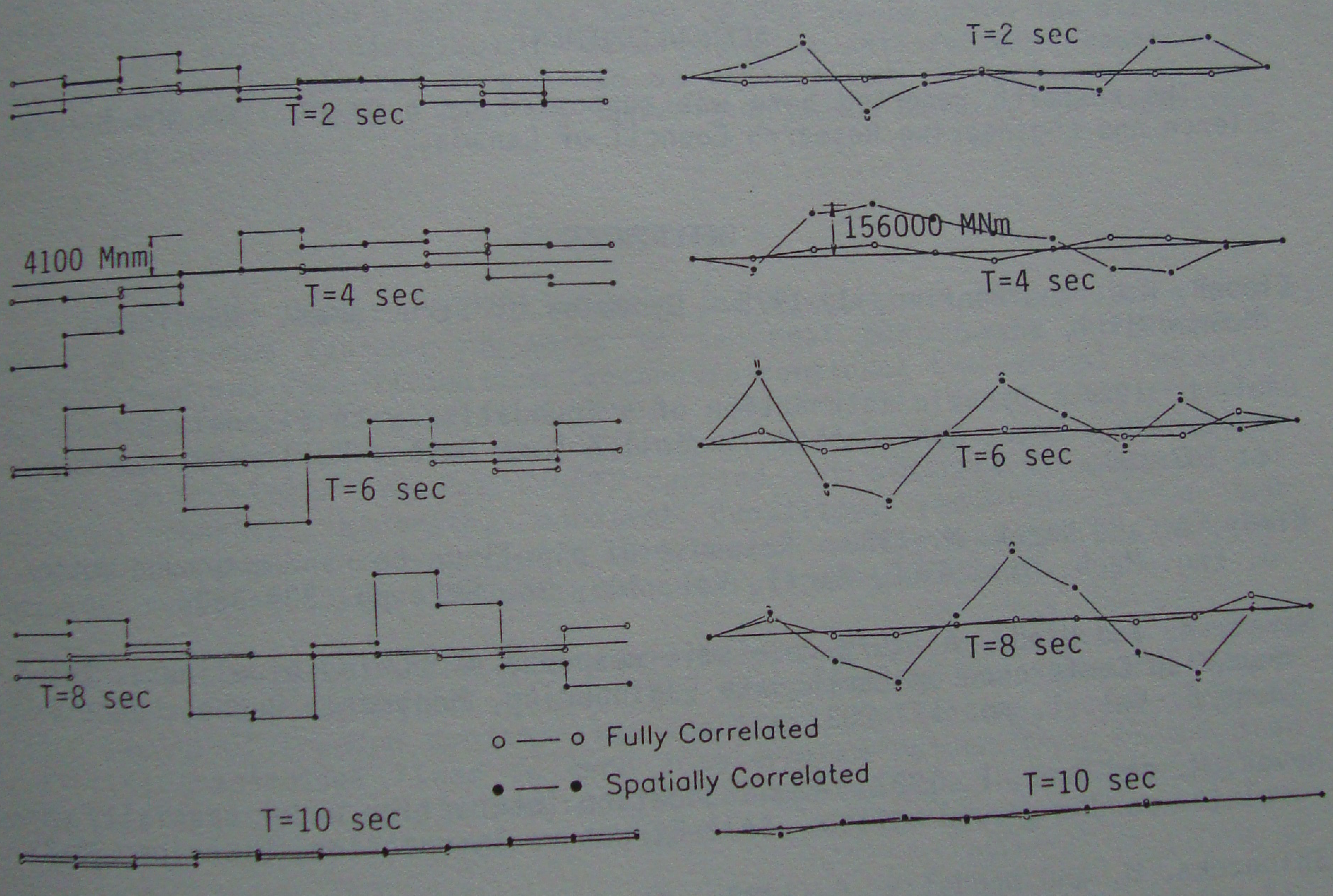

Figure 7. Dam torsional moments

Figure 8. Dam bending moments

The results shown are affected by soil-structure interaction. This can be recognized from the ratio of the Fourier spectrum of the dam horizontal response to the spectrum of the ground motion.

CONCLUSIONS

A solution which accounts for both spatial correlation of ground motion and soil-structure interaction in the seismic response analysis of large structures is presented and used to analyze a long concrete gravity dam. The following conclusions emerge:

1. While the dam responds almost as a rigid body to fully correlated ground motions, it bends and twists significantly due to ground motion incoherence.
2. The dam stresses are small under fully correlated motions but can be quite high even under moderately incoherent motions.
3. Absolute dam displacements may be increased by seismic motion incoherence.
4. Significant stresses in large structures may remain unforeseen if the ground motion is assumed to be fully correlated.

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