Stochastic seismic response of Keban dam by the finite element method

Mehmet Akköse, Süleyman Adanur, Alemdar Bayraktar *, A. Aydın Dumanoğlu

Karadeniz Technical University, Department of Civil Engineering, 61080 Trabzon, Turkey

Abstract

In this study, stochastic seismic response of a rock-fill dam is investigated by finite element method. The Keban dam constructed in Elazıg, Turkey is chosen as a numerical example. The interaction of the rock-fill dam with the reservoir is neglected, but not the foundation rock. The properties of the dam materials were taken from the dam project and assumed to be linearly elastic, homogeneous and isotropic in the analysis.

A stationary and ergodicity assumption are made for stochastic seismic analysis. The E–W component of the Erzincan Earthquake recorded on March 13, 1992, Erzincan, Turkey is chosen as a ground motion since it occurred nearby the dam site. The component considered is applied to the dam in the horizontal direction.

The seismic response of the Keban dam subjected to the Erzincan Earthquake is also obtained by the deterministic method. The results obtained from stochastic and deterministic analysis are compared to each other. It is seen that the results obtained from the stochastic analysis are smaller than those from the deterministic analysis.

© 2006 Elsevier Inc. All rights reserved.

Keywords: Stochastic response; Rock-fill dam; Finite element method; Seismic ground motion

1. Introduction

Rock-fill dams are constructed for various purposes such as irrigation, energy production, flood control and recreation. A serious damage on these dams has not been recorded in the literature due to an earthquake ground motion [1]. Accordingly, it can be said that rock-fill dams are highly resistant to seismic loads. The satisfactory seismic behaviour of these dams is due to the capacity of the rock-fill body.

Ozkan [1] and Gazetas and Dakoulas [2] have presented comprehensive reviews on theoretical methods for estimating the dynamic response and the performance of earth and rock-fill dams subjected to strong earthquake ground motions. Several factors such as liquefaction effects, non-linear material behaviour, and permanent deformations affect the dynamic response of earth and rock-fill dams during the earthquakes. Linear and
non-linear earthquake responses of earth and rock-fill dams including these factors were carried out by many researchers [3–6]. These studies were performed by using the deterministic methods. In recent years, the stochastic seismic responses of earth dams have also been investigated by only a limited number of researchers [7,8]. However, it can be seen from the literature review that a few works on stochastic response of rock-fill dams to ground motion have been studied. Therefore, the objective of this study is to determine the stochastic seismic response of a rock-fill dam using the finite element method.

2. Stochastic analysis formulation

An acceleration–time history of ground motion recorded at one point is used as seismic input in the deterministic method. In the stochastic method, however, recorded ground motions appropriate to the site are characterized as statistically. Since the ground motion caused by seismic disturbance is random, the best way to characterize the random excitation statistically is to employ a power density function and autocorrelation function. Once, the power spectral density function or the autocorrelation function of the seismic input is known, the cross power spectral density function can be determined easily.

In this study, only the final expression for the cross power spectral density function will be given. Detailed expressions for this function are explained elsewhere [9–11]. If a single ground acceleration record is used for the input, cross power spectral density function, $S_{ij}(w)$, can be determined by using the equation of motion of the system as [12,13]

$$S_{ij}(w) = S_{in}(w) \sum_{r=1}^{N} \sum_{s=1}^{N} \psi_{ir} \psi_{js} H_{ir}(w) H^{*}_{js}(w),$$

where $w$ is the frequency, $H(w)$ is the frequency response function, $S_{in}(w)$ is the power spectral density function of the ground motion, $N$ is the number of modes which are considered to contribute to the response, $\psi_{ir}$ is the contribution of the $r$th mode to $U_j(t)$ displacement and * denotes the complex conjugate.

2.1. Spectral moments

Statistics related to the structural behaviour for a stationary process can be determined by using the zeroth, the first and the second spectral moments of the output process [11]. Spectral moments, which can be expressed in terms of power spectral density function and frequency, may be calculated as follows [12]

$$\lambda_{m,ij} = 2 \int_{0}^{\infty} w^m S_{ij}(w) \, dw, \quad m = 0, 1, 2,$$

where $m = 0, 1, 2$ is the zeroth, the first and the second spectral moments, respectively. These parameters will then be used while obtaining the mean of maximum value, variance and frequency of occurrence [13–15].

2.2. Expected maximum value

The expected maximum value is considered to be the most important parameter in the stochastic analysis of structures affected by seismic loads. In the stochastic analysis the expected maximum value ($\mu$) is the mean value of all maximum values. The expected maximum value, which depends on the peak factor and the root-mean-square response, can be expressed as

$$\mu = p \sqrt{\lambda_0}.$$  

Standard deviation of $\mu$ is expressed as

$$\sigma = q \sqrt{\lambda_0},$$

where $\lambda_0$ is the zeroth spectral moment defined by Eq. (2), $p$ and $q$ are the peak factors, which are the functions of the duration of the motion and the mean zero crossing rate, respectively [16].
2.3. Occurrence frequency

Frequency of occurrence is described as the average number of times that the line \( y(t) = 0 \) is crossed by the response in a unit of time. For Gaussian process of zero average, the average number of times in the zero level crossed by the process in a unit of time is expressed as

\[
v = \frac{1}{\pi} \sqrt{\frac{\lambda_2}{\lambda_0}}
\]  

(5)

Because the zero level is crossed two times for each cycle, frequency of occurrence for the response process will be equal to \( v/2 \) as

\[
f_0 = \frac{v}{2} = \frac{1}{2\pi} \sqrt{\frac{\lambda_2}{\lambda_0}}
\]  

(6)

where \( \lambda_2 \) is the second spectral moment defined by Eq. (2).

3. Numerical application and discussions

In this study, the Keban dam constructed in Elazıg, Turkey (Fig. 1) is chosen as a numerical example to investigate the stochastic seismic response of a rock-fill dam by the finite element method. Fig. 2 shows the vertical cross-section of the Keban dam. The finite element mesh of the dam is shown in Fig. 3. The Keban dam is 163 m high from riverbed. The crest has a length of 1097 m. The main purpose of the dam is to regulate river flow and supply energy. In the finite element mesh of the dam, there are 326 nodes and 286 quadrilateral elements. The dam is treated as a plane strain problem. The interaction of the rock-fill dams with the reservoir has generally neglected [17,18]. Therefore, the interaction with the reservoir is accordingly ignored, but not the foundation rock.

Materials in the dam section can be grouped in three main categories: compacted rock-fill placed at various lifts, the impervious clay core flanked by transition filters and a concrete core at the bottom of the dam. The properties of these materials taken from the dam project are as follows: For the compacted rock-fill, elasticity modulus \( E = 1.632 \times 10^{10} \text{ N/m}^2 \), mass density \( \rho = 2120.29 \text{ kg/m}^3 \), and Poisson’s ratio \( v = 0.36 \); for the impervious clay core, elasticity modulus \( E = 1.015 \times 10^{10} \text{ N/m}^2 \), mass density \( \rho = 2089.70 \text{ kg/m}^3 \), and Poisson’s ratio \( v = 0.45 \); for the concrete core, elasticity modulus \( E = 2 \times 10^{10} \text{ N/m}^2 \), mass density \( \rho = 2446.48 \text{ kg/m}^3 \), and Poisson’s ratio \( v = 0.15 \). The elasticity modulus, mass density and Poisson’s ratio of the foundation rock

Fig. 1. The Keban dam constructed in Elazıg, Turkey.
are taken as $1.379 \times 10^{10} \text{N/m}^2$, 2689.09 kg/m$^3$, and 0.24, respectively. The materials used in this study are assumed to be linearly elastic, homogenous and isotropic.

A stationary assumption where the statistical parameters are independent of time is made for the stochastic analysis. Besides, while calculating the statistics to represent the random process, like ensemble averages, some difficulties are encountered. The ergodicity assumption is made to overcome these difficulties and only one earthquake record is used in this study. Although earthquake motions are not completely stationary, these motions can be considered as stationary processes under certain conditions because of its analytical simplicity. Perhaps an earthquake ground motion is not stationary along the whole motion, but it is an acceptable approximation to consider the ground motion stationary along the duration’s where maximum structural responses take place. A stationary model simplifies the computations and gives satisfying results. The response of structural systems to stationary excitations is of wide engineering interest [14,19–22].

The E–W component of the Erzincan Earthquake recorded on March 13, 1992, Erzincan, Turkey is chosen as ground motion and given in Fig. 4 since it occurred nearby the dam site. The component considered is
applied to the dam in the upstream–downstream direction. The power spectral density (PSD) function of the Erzincan Earthquake is determined with the Fourier transforms of the autocorrelation function as shown in Fig. 5.

In this paper, the dynamic response of the Keban dam subjected to the Erzincan Earthquake is also obtained by the deterministic method. The results obtained from stochastic and deterministic analysis are compared to each other. The seismic responses of the Keban dam are obtained for a time interval of 0.00225 s.

3.1. Displacements

Mean of maximum values of displacements are calculated from stochastic seismic analysis. The absolute maximum values of displacements are obtained from deterministic dynamic analysis. Horizontal displacements along the core of the rock-fill dam at the marked nodes on line 1 (Fig. 3) obtained from stochastic and deterministic seismic analyses of the Keban dam are plotted in Fig. 6. Vertical displacements along the horizontal length of the dam at the marked nodes on line 2 and line 3 (Fig. 3) obtained from stochastic and deterministic seismic analyses of the dam are also plotted in Figs. 7 and 8, respectively. It is seen from
these figures that the expected maximum values of horizontal and vertical displacements obtained from stochastic dynamic analysis are smaller than the absolute maximum horizontal and vertical displacements obtained from deterministic dynamic analysis. It is also seen from Figs. 7 and 8 that the vertical displacements at the marked nodes on line 2 and line 3 decrease towards the core of the rock-fill dam.

The displacements obtained from the stochastic dynamic analysis can be verified by calculating the time-history of the horizontal displacements at the crest point (node 1) of the rock-fill dam as shown in Fig. 9. Taking the average of 15 maximum horizontal displacements shown in Fig. 9, the mean of maximum horizontal displacements can be calculated as 3.98 cm for the deterministic analysis. The expected maximum horizontal displacement obtained from stochastic dynamic analysis is 4.01 cm as shown in Fig. 5. The maximum displacement obtained by averaging, which is 3.98 cm, is very close to 4.01 cm obtained from the stochastic analysis. This shows the correctness of the displacements obtained from the stochastic analysis.

3.1.1. Frequencies of occurrence of displacements

The frequency of occurrence of horizontal displacements along the core of the rock-fill dam at the marked nodes on line 1 of the rock-fill dam (Fig. 3) are calculated using Eq. (6) and depicted in Fig. 10. The values of
frequency of occurrence along the line 1 vary between 1.67 and 1.74. It can be seen by comparison of Figs. 6 and 10 that the frequency of occurrence decrease with increasing displacement values.

Frequency of occurrence of the displacements obtained from the stochastic seismic analysis can be verified. For this purpose, a time interval between 3.6 and 4.3 s of the time-history of the crest displacements in Fig. 9 where maximum horizontal displacement is occurred is zoomed as shown in Fig. 11. Since the period is defined as the time required to complete one cycle, it is taken the time interval between $t_1 = 3.68775$ and $t_2 = 4.27725$

![Fig. 11. Determination of value of occurrence period of the maximum horizontal displacement of the dam crest.](image)

![Fig. 12. Horizontal, vertical, and shear stresses on section I–I of the rock-fill dam.](image)
shown in Fig. 11 in order to compute the period of the maximum horizontal displacement. Difference between $t_1$ and $t_2$ is 0.5895 s. So, frequency of the maximum horizontal displacement can be calculated as 1.70 Hz from the deterministic seismic analysis. The value of frequency of occurrence of the horizontal displacement at the crest point (node 1) from stochastic dynamic analysis is obtained as 1.67 Hz. This also shows good accuracy of the results obtained from the stochastic dynamic analysis.

3.2. Stresses

The stress components, which are obtained from stochastic and deterministic dynamic analyses, are also compared with each other. The stress values are calculated at the middle points of the elements with a time interval of 0.0025 s. Sections I–I, II–II, and III–III shown in Fig. 3 are taken into account for comparison of the stress components, which are horizontal, vertical and shear stresses. The mentioned stress components on sections I–I, II–II, and III–III of the rock-fill dam are compared in Figs. 12–14, respectively. It can be seen from these figures that the expected maximum values of all stress components for all sections are smaller than the absolute maximum stresses obtained from deterministic dynamic analysis. It can also be seen from Fig. 12 that the stresses decrease towards the dam crest.

To verify the stresses obtained from the stochastic dynamic analysis, time-history of the horizontal stresses at the element A selected from the dam body is calculated from the deterministic dynamic analysis as shown in Fig. 15. Taking the average of 19 maximum horizontal stresses shown in Fig. 15, the mean of maximum horizontal stresses can be calculated as 350.37 kN/m$^2$ for deterministic analysis. The expected maximum horizontal stress obtained from stochastic dynamic analysis is 355.37 kN/m$^2$ as shown in Fig. 12(a). The maximum stress obtained by averaging, which is 350.37 kN/m$^2$, is very close to 355.37 kN/m$^2$ obtained from the stochastic analysis.

![Fig. 13. Horizontal, vertical, and shear stresses on section II–II of the rock-fill dam.](image-url)
3.2.1. Frequencies of occurrence of stresses

Values of frequencies of occurrence of horizontal stresses at section I–I of the rock-fill dam are depicted in Fig. 16. It can be seen from Fig. 16 that the value of frequency of occurrence of stochastic horizontal stress at the element A (Fig. 3) is obtained as 3.31 Hz. To verify the frequency of occurrence of the horizontal stress obtained from the stochastic dynamic analysis, a time interval between 3.7 s and 4.2 s of the time-history of horizontal stresses in Fig. 15 where maximum value is occurred is zoomed as shown in Fig. 17. It is taken the time interval between \( t_1 = 3.8205 \) and \( t_2 = 4.1130 \) shown in Fig. 17 in order to compute the period of the maximum horizontal stress. Difference between \( t_1 \) and \( t_2 \) is 0.2925 s. So, frequency of the maximum horizontal stress can be calculated as 3.42 Hz. These also show good accuracy of the results obtained from the stochastic dynamic analysis.

Fig. 14. Horizontal, vertical, and shear stresses on section III–III of the rock-fill dam.

Fig. 15. Time-history of horizontal stress of the element A.
4. Conclusions

Stochastic seismic response of a rock-fill dam by finite element method is investigated in this paper. The project values of the Keban dam were considered in the analyses. Frequencies of occurrence of expected maximum values of displacements and stresses are compatible with the results of the deterministic seismic analysis. It is observed that the displacement and stress results obtained from the deterministic dynamic analysis are greater than the mean of maximum values obtained from the stochastic dynamic analysis. Because the mean of maximum values obtained from the stochastic analysis is calculated by averaging all the maximum response values, it should be expected that the absolute maximum values obtained from the deterministic dynamic analysis would be greater than the mean of maximum values.

The horizontal displacements from both analyses increase along the dam height. The vertical displacements obtained along the horizontal length of the dam significantly decrease towards the core of the rock-fill dam for both analyses. The frequency of occurrences of horizontal displacements at the clay core decrease with increasing the values of displacements. The all stress components decrease towards the dam crest. The shear stresses obtained along the clay core are greater than the horizontal and vertical stresses.

To generalize these results, solutions must be obtained using many earthquake inputs and different rock-fill dam models.

References


[3] H.B. Seed, Considerations in the earthquake design of earth and rockfill dams, Geotechnique 29 (3) (1979) 215–263.