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STOCHASTIC DYNAMIC RESPONSE OF AN EMBANKMENT DAM TO NON-UNIFORM GROUND MOTIONS

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ABSTRACT

The effect of the spatial variation of earthquake ground motion (SVEGM) on dynamic response of multiple-support structures can be important. The objective of this paper is to investigate the seismic response of an embankment dams subjected to multiple-support excitation. To this end, the response of Marun embankment dam to uniform and non-uniform excitations were analyzed using a random vibration approach. The spatially varying ground motion is modelled considering both incoherence and wave passage effects. It was observed that the stress components calculated from the varying earthquake ground motions are larger than those at the uniform ground motion.

Kywords: SVEGM, Embankment dam, stochastic dynamic response.

1. INTRODUCTION

It is very common in engineering practice to assume that all supports of structures experience identical ground motion during an earthquake. This assumption is sufficient for structures with small bases, but may not be adequate for extended structures such as dams, tunnels, bridges and pipelines. Spatial variability of seismic ground motion can be mainly attributed to the following three mechanisms: 1) difference in arrival times of seismic waves at different locations, commonly known as the "wave passage effect," 2) loss of coherence of seismic waves due to multiple reflection and refraction as they propagate through the highly inhomogeneous soil medium, referred to as the "incoherence effect," and 3) change in the amplitude and frequency content of seismic ground motion due to different local soil conditions, known as the "local soil effect".

These ground motion spatial variations may significantly influence the structural responses. The seismic response of embankment dams to multi-support excitation has been studied in the past few years by various methods. Dumanoglu and Severn [1] studied the dynamic response of an embankment dam subjected to asynchronous input motions with varying travelling velocities. They concluded that if the velocity of travelling waves decreases, the horizontal and vertical stresses at a cross section close to the base increase appreciably. Haroun and Abdel-Hafiz [2] studied the effects of amplitude and phase difference of an earthquake motion on the seismic response of a long earth dam. They concluded that the dam response can be sensitive to the assumed spatial variation of ground motion along its base. Chen and Harichandran [3] analyzed the stochastic response of the Santa Felicia earth dam to SVEGM including the incoherence and wave passage effects. They concluded that the shear stresses of stiff material near the base of the dam can be significantly increased due to SVEGM. Bayraktar et al. [4] studied the seismic response of the Torul concrete-faced rockfill (CFR) dam, constructed in Turkey to asynchronous base excitation by considering dam-reservoir interaction. They observed that all stress components (horizontal, vertical, and shear stresses) near the base of the dam increase considerably when travelling wave velocity decreases. Haciefendioglu[5] investigated the effect of transient stochastic analysis on nonlinear response of earth and rock-fill dams to SVEGM. It was observed that the incoherence effect has generally more significant influence on the response of earth and rock-fill dams, comparing with the wave-passage effect. Davoodi and Javaheri[6] studied the stochastic response of the Masjed soleyman earth dam to SVEGM. In their study the earth dam was analyzed using 2D finite element model. They concluded that SVEGM can decreases safety factors of assumed landslides.

This paper investigates the effects of SVEGM on the stochastic response of Marun rock fill dam using random vibration method. To this end, ANSYS finite element program was established. For comparison purpose, the seismic response of the dam was evaluated under both identical and spatially variable excitations. The SVEGM model used in this study includes both incoherence and wave-passage effects. The incoherence and wave-passage effects are respectively examined by considering the Harichandran and Vanmarcke coherency model and by using the wave velocity of 1840 m/sec.

2. DESCRIPTION OF THE DAM

The Marun rockfill dam is constructed on Marun River in 19km north of Behbahan in Khuzestan province, Iran. This dam has a maximum height of 165m above its rock foundation, crest length of 345m and crest width of 15m. This dam consists of an impervious clay-core between shells made of rockfill and Alluvium materials. The maximum cross-section of the dam and its material zones are shown in Figure1. Table 1 lists the material properties used in this study.

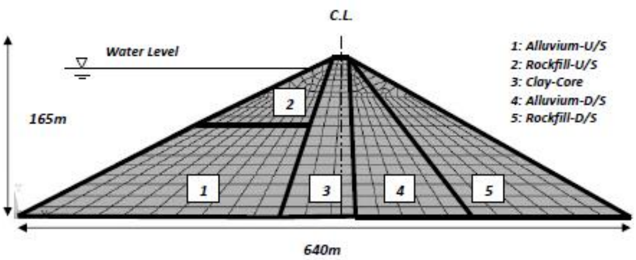

Figure 1. *Dimention, Meshing and Material regions in ANSYS computer program*

Table-1. *Properties of material used in this study*

Material	γ(kN/m^3)	Ex106(kN/m^2)	ν
Alluvium-U/S	20.5	1.06-4.21	0.42
Rockfill-U/S	21	1.00-2.50	0.38
Clay-Core	21.3	0.20-1.04	0.40
Alluvium-D/S	20.5	1.48-3.57	0.42
Rockfill-D/S	21	0.87-2.61	0.38

2D finite element model with shell elements is used for the numerical analysis. The analysis of dam performed for first impounding stage by using ANSYS finite element software. The elastic modulus of dam materials is assumed to vary with depth due to increase of confining pressure. Free vibration analysis of dam model performed before spectral analysis to verification of the finite element model.

The first 10 natural frequencies ranging from 1.5 to 3.5 Hz are compared favorably with those reported by Jafari and Davoodi [7].

3. Finite element modeling and random vibration theory

The dynamic equation of motion of a structure discretized using the finite element method may be written in the partitioned from [8]:

$$\begin{bmatrix} M_{ff} & M_{fr} \\ M_{rf} & M_{rr} \end{bmatrix} \begin{bmatrix} \ddot{u}_f \\ \ddot{u}_r \end{bmatrix} + \begin{bmatrix} C_{ff} & C_{fr} \\ C_{rf} & C_{rr} \end{bmatrix} \begin{Bmatrix} \dot{u}_f \\ \dot{u}_r \end{Bmatrix} + \begin{bmatrix} K_{ff} & K_{fr} \\ K_{rf} & K_{rr} \end{bmatrix} \begin{Bmatrix} u_f \\ u_r \end{Bmatrix} = \begin{Bmatrix} F \\ 0 \end{Bmatrix} \tag{1}$$

Where [M], [C], [K] are the mass, damping and stiffness matrices respectively; $\{\ddot{u}\}, \{\dot{u}\}, \{u\}$ are the vector of total acceleration, velocities and displacement respectively. The subscript f denotes the response degrees of freedom and r denotes the ground degrees of freedom. The free displacement u can be decomposed into pseudo static and dynamic part as :

$$u = u_d + u_s \tag{2}$$

The pseudo-static displacement u_s may be obtained from Eq. (1) by excluding the first two terms on the left-hand side of the equation and by replacing $\{u_f\}$ by $\{u_s\}$;

$$\{u_s\} = -\left[K_{ff}\right]^{-1}\left[K_{fr}\right]\{u_r\} = [A]\{u_r\} \tag{3}$$

Where:

- $[A] = -\left[K_{ff}\right]^{-1}\left[K_{fr}\right]$

Substituting Esq. (3) and (2) into Eq. (1) the equation of motion of the dynamic component of the response degrees of freedom can be written as:

$$\left[M_{ff}\right]\{\ddot{U}_d\} + \left[C_{ff}\right]\{\dot{U}_d\} + \left[K_{ff}\right]\{U_d\} \simeq \{F\} - (\left[M_{ff}\right][A] + \left[M_{fr}\right])\{\ddot{U}_r\} \tag{4}$$

Using well-known modal analysis approach and $\{U_d(t)\} = [\phi]\{y(t)\}$ decouples the above equation to yield;

$$\ddot{Y}_J + 2\xi_J\omega_J\dot{Y}_J + \omega_J^2 Y_J = G_J \tag{5}$$

In which j is number of mode shape chosen for evaluation, Y_j are generalized displacement, ω_j and ξ_j are the natural circular frequency and modal damping ratio. The modal loads G_i are defined by;

$$G_j = \{\Gamma_j\}^T\{\ddot{U}_r\} + \Upsilon_J \tag{6}$$

Where modal participation factors are given by;

$$\{\Gamma_j\} = -(\left|M_{ff}\right|[A] + \left[M_{fr}\right])^T\{\phi_j\} \tag{7}$$

Using the theory of random vibrations, the power spectral density function (PSD) of the response can be computed from the input PSD's with the help of transfer functions for single DOF systems H (ω) and by using mode superposition techniques. The response PSD's for ith DOF are given by adding three below terms:

For dynamic part;

$$\sigma_{zd}^2 = \sum_{j=1}^{n}\sum_{k=1}^{n}\psi_j\psi_k\int_{-\infty}^{+\infty}(\sum_{l=1}^{r}\sum_{m=1}^{r}\Gamma_{lj}\Gamma_{mk}H_j^*(\omega)H_k(\omega)S_{lm}(\omega))d\omega \quad (8)$$

Pseudo-Static Part;

$$\sigma_{z_s} = \sum_{l=1}^{r}\sum_{m=1}^{r}B_lB_m\int_0^{\infty}\frac{1}{\omega^4}S_{lm}(\omega)d(\omega) \quad (9)$$

Covariance Part;

$$Cov(u_s,u_d) = -\sum_{j=1}^{n}\sum_{l=1}^{r}\psi_jB_l\int_0^{\infty}\frac{1}{\omega^2}\sum_{m=1}^{r}\Gamma_{mj}H_J(\omega)S_{lm}(\omega)d(\omega) \quad (10)$$

Where:

n = no. of modes, r = no. of support DOF, ψ_j= response z from the *j*th mode, B_l= response z due to a unit displacement of support DOF *l*, Γ_{lj}=*l*th element of the participation vector Γ_j, $H_J(\omega) = (\omega_J^2 - \omega^2 + 2i\omega_j\xi_j\omega)^{-1} = jth$ modal frequency response function, and $S_{lm}(\omega) =$ cross SDF of acceleration along the DOF *l* and *m.*

4. INPUT GROUND MOTION MODEL

In the stochastic analysis approach, the total mean-square responses depend on the cross power spectral density function of ground acceleration. In this study the power spectral density function of ground acceleration characterizing the earthquake process is assumed to be the following form of filtered white noise ground motion model modified by Clough and Penzien (1993):

$$S_a(\omega) = S_0\frac{1+4\xi_g^2(\frac{\omega}{\omega_g})^2}{[1-(\frac{\omega}{\omega_g})^2]^2+4\xi_g^2(\frac{\omega}{\omega_g})^2}\times\frac{(\frac{\omega}{\omega_f})^4}{[1-(\frac{\omega}{\omega_f})^2]^2+4\xi_f^2(\frac{\omega}{\omega_f})^2} \quad (11)$$

Where ω_g , ξ_g are the resonant frequency and damping ratio of the first filter, ω_f , ξ_f are those of the second filter, and S_0 is the amplitude of the white-noise bed rock acceleration. The parameters of the ground motion model are determined according to the E-W component of the 1994 Northridge earthquake. Figure 2 shows the acceleration time history and the power spectrum of the selected ground motion. For multi support excitation, the dam foundation is divided into four regions. The cross-spectral density function of the earthquake ground motion, between support points A and B is expressed as:

$$S_{AB} = S(f)|\gamma(v,\omega)|e^{i\varphi(v,f)} \quad (12)$$

Where$|\gamma(v,\omega)|$ denotes the coherency function, S (f) is the power spectral density function of the earthquake ground motion and υ is separation distance between stations A, B. In this paper the incoherence effect is examined by considering the Harichandran and Vanmarcke coherency model. This model is based on the study of four events recorded by the SMART-1 array in Taiwan:

$$|\gamma(v,\omega)| = Aexp(\left[-\frac{2v}{\alpha\theta(f)}(1-A+\alpha A)\right] + (1-A)exp\left[-\frac{2v}{\alpha\theta(f)}(1-A+\alpha A)\right] \quad (13)$$

Where

- $\theta(f) = k\left[1 + (\frac{f}{f_0})^b\right]^{1/2}$

In which A, α, κ, f_o and b are the model parameters and f is frequency in Hertz. The model parameters were estimated by Harichandran and Wang (1990) as, A=0.736; α = 0.147; k = 5210; f_0 = 1.09 and b=2.78. As for other multiple-parameters models, this model can be made to match a broad range of coherency applications.

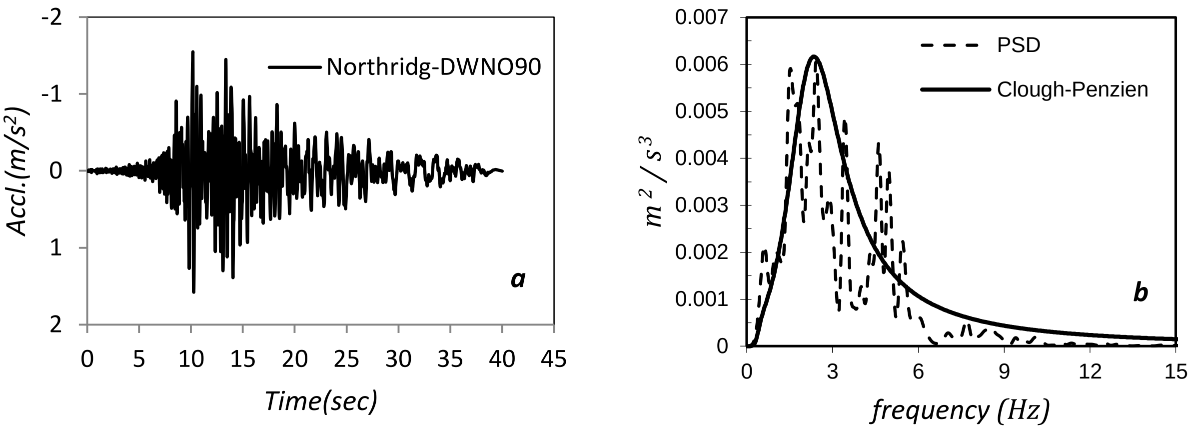

***Figure 2**. (a)Acceleration time history of 1994 Northridge earthquake (b) Filtered spectral density function*

5. RESPONSE OF THE DAM TO SVEGM

This section compares the seismic responses of Marun dam to uniform and SVEGM excitations. Results will be presented in terms of stress fields for different loading cases. The contours of the one standard deviation (1σ) of stress responses are shown in figures 3 to 5 for identical and multi- support excitations. As can be seen, due to both kinds of input motions, the maximum of all stress components occur in the same locations on the dam body. In other words, the multi support excitation does not change the distribution pattern of stresses in the dam body except in horizontal stresses. It can be observed that in the case of multi-support excitation the magnitude of all stress components increase considerably. The latter can be explained by 82, 63 and 75% increase in maximum values of horizontal, vertical and shear stresses for multi-support excitation compare to those due uniform excitation.

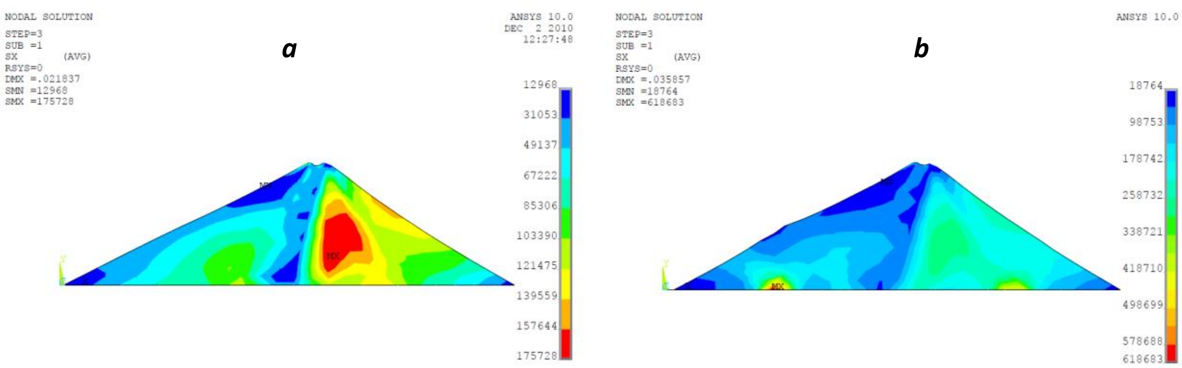

***Figure 3**. 1σ Contours of dynamic horizontal stress σx for: (a) identical; (b) multi support Excitation*

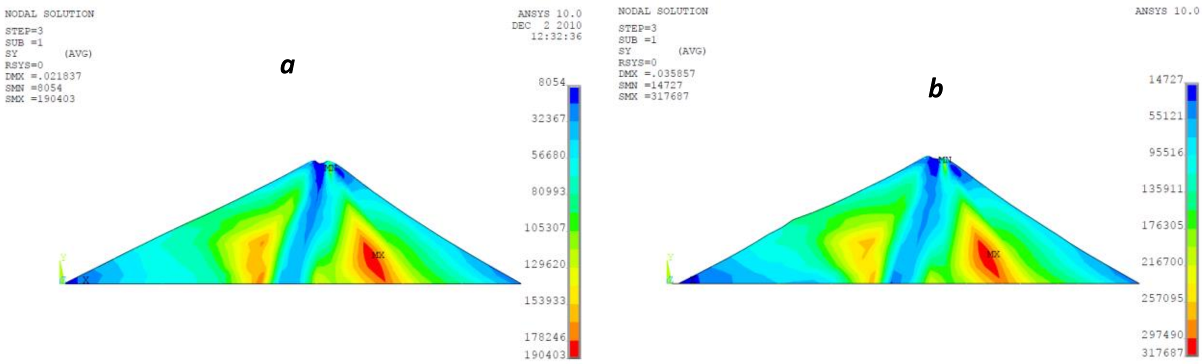

Figure 4. *1σ Contours of daynamic vertical stress σy for: (a) identical; (b) multi support Excitation*

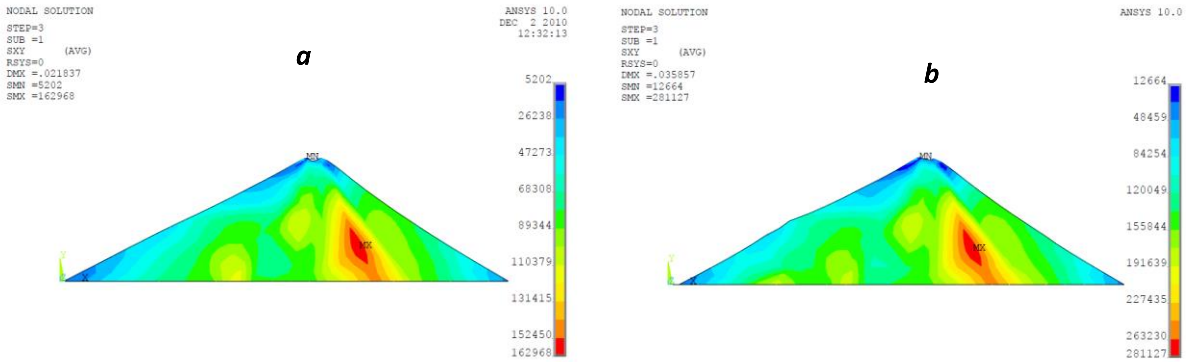

Figure 5. *1σ Contours of dynamic shear stress τxy for: (a) identical; (b) multi support Excitation*

For demonstration purpose, the stress responses are compared in Figure 6 at a horizontal cross section at the mid height of the dam. As can be seen, by moving from upstream to downstream the differences between identical and multi support excitation responses increase for horizontal stress component. This is while a constant difference can be observed for vertical and shear stress components. The variation of maximum shear stresses at mid-height of the dam is also compared for two loading cases in figure 6. As can be inferred, in unison with general trend, applying multi-support excitation increases considerably the maximum shear stresses.

Dynamic stability analysis was performed for upstream slip circle under identical and multi support excitations. The sliding surface is selected as critical sliding surface according to the report of consulting engineering reports [9] and is shown in figure 7. After adding the dynamic stresses to static one, local safety factor will be calculated by equation 14 for each element located on sliding surface**,** and then averaged on sliding surface.

$$F_S = \frac{q_f}{q} = \frac{\sigma_1+\sigma_3}{\sigma_1-\sigma_3} sin\varphi = \frac{p}{q} sin\varphi \qquad (14)$$

Table-2 has shows the factor of safety under identical and multi support excitation .Factor of safety under multi support excitation has 5.7% variance more than identical excitation. It shows that the assumption of identical excitation underestimates the factor of safety of the dam.

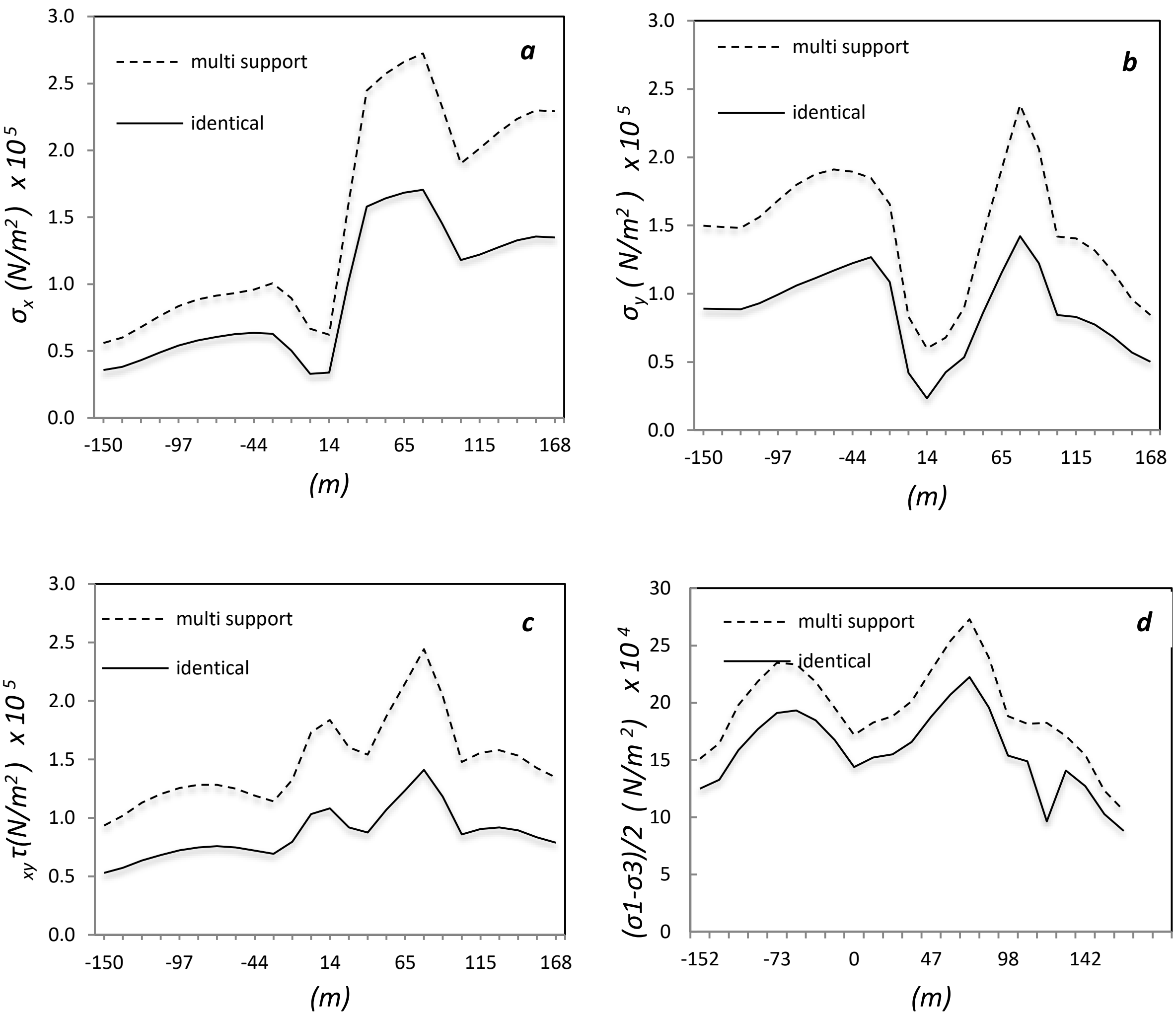

Figure 6. *Comparison of; (a): horizontal stress, (b): vertical stress,(c):shear stress , (d) and Max. Shear stress at mid height of dam for identical and multi support Excitation*

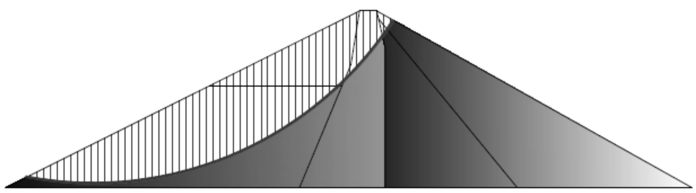

Figure 7. *Upstream slip circle for Marun dam*

Table-2. *Safety factor comparison for identical and multi support excitation*

Type of excitation	F_S(Safety factor)	Variance from uniform excitation
Identical	1.39	
Multi support	1.31	5.7%

6. CONCLUSIONS

The effect of SVEGM on the dynamic response of Marun dam was investigated using random vibration method. It was found that the spatially varying ground motions have important effects on the stochastic dynamic response of embankment dams. As a general trend, it was observed that the all stress components computed under multi-support excitations are significantly larger than those measured under identical ground motion. Also it was found that SVEGM can significantly increase the maximum shear stresses of embankment materials at the mid height of the dam and should be considered in the design. It can be concluded that neglecting the effects of multi-support excitations may lead to substantial underestimation of the seismic responses of embankment dams.

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