Nonlinear seismic response of high concrete arch dams subjected to foundation non-uniform excitation

Hasan Mirzabozorg, Assistant professor, K. N. Toosi University of Technology, Tehran, mirzabozorg@kntu.ac.ir
Masomeh Akbari, Graduate student, K. N. Toosi University of Technology, Tehran, masomeh.akbari@gmail.com
M. Amin Hariri Ardebili, Graduate student, K. N. Toosi University of Technology, Tehran, amin_hariri@sina.kntu.ac.ir
M. Sadreddini, Ph.D. candidate, Islamic Azad University-Science and research branch, Tehran, ali_civil75@yahoo.com

Paper Reference Number:
Name of the Presenter: Masoumeh Akbari

Abstract

Uniform excitation is an assumption that has often been made for structural analysis of arch dams. However, it has been recognized for many years that the ground motion is non-uniform during the canyon. In this paper, non-uniform excitation due to spatially varying ground motions on nonlinear responses of concrete arch dams are investigated. A high arch dam was selected as numerical example, reservoir was modelled as incompressible material and foundation was supposed as mass-less medium. This study was used Monte-Carlo simulation approach for generating spatially non-uniform ground motion. In the present method, random seismic characteristics due to incoherence and wave passage effects were investigated and finally their effects on structural response were compared with uniform excitation for design base level (DBL) earthquakes. Based on the results, non-uniform input leads to some differences than uniform input. Moreover using non-uniform excitation increase stresses on dam body.

Key words: Concrete arch dam, Incoherency effect, Non-uniform excitation, Wave passage effect

1. Introduction

Seismic analysis of long span structures have been done with uniform excitation, whereas the motion of the ground changes, in both amplitude and frequency, as the earthquake waves travel with a finite speed away from their source. Variations in the ground motion arise mainly from three sources, e.g.; the wave passage effect, the incoherence effect and the site-response effect (Der-kiureghian, 1996). In this paper wave passage and incoherence effects were considered as non-uniform input sources. Many researchers have investigated the response of long span structures to asynchronous support excitations. Effect of asynchronous and multiple supports input in analysis of beams and bridges have been considered by Harichandran et al. (1996). They studied the effect of spatial variability of ground motion on existing long span suspension bridges. Allam and Datta (2004) were presented a non-stationary random vibration response evaluation of a cable-stayed bridge model subjected to spatially variable excitations. Zhang et al. (2009) investigated a random vibration algorithm for the seismic response analysis which accurately accounts for the spatial variability effects of wave passage, incoherence and site-response.

Although a lot of works have been done in seismic analysis of concrete arch dams, a limited of them has been investigated effects of asynchronous input on the seismic behaviour of dams. Bayraktar et al. (1996 and 1998) were analyzed the effect of wave propagation on the response of Sariyar concrete gravity dam. They reported that horizontal, vertical and shear stresses in the foundation generally increased with the decreasing propagation velocity. Maeso et al. (2002) investigated behaviour of an arch dam subjected to incident body (P-, SV- and SH-) and surface (Rayleigh) waves. Alves and Hall (2006) analyzed the effect of spatially variable excitations on the nonlinear response of Pacoima dam using seismic data. Results were showed that for uniform excitations stresses and joint opening were largest in the centre part of the dam away from the abutments. The stresses along the abutments and in the centre of the downstream face of the dam were dominated by non-uniform excitation.

In this study Monte-Carlo simulation approach was used for generating spatially non-uniform ground motion for nonlinear analysis of a high concrete arch dam. DEZ dam was selected as numerical example to investigate wave travelling and incoherence effects in dam-reservoir-foundation system. Reservoir was modelled as incompressible material and foundation was supposed as mass-less medium. In addition all contraction and peripheral joints were modelled based on as-built drawings.

2. Generation of Spatially Variation Ground motions

2.1 m-Variant Non-stationary Stochastic Ground motion Process

Following the spectral-representation methodology (Shi-nozuka and Deodatis, 1988) and considering the 1D-mV (one-dimensional, m-variant) non-stationary ground motion stochastic vector process (Cacciola and Deodatis, 2010) and corresponding cross-spectral density matrix with evolutionary power spectrum given by:

$$\mathrm{S}^0(\omega,t)=\begin{bmatrix} S_{11}^0(\omega,t) & S_{12}^0(\omega,t) & \dots & S_{1m}^0(\omega,t) \\ S_{21}^0(\omega,t) & S_{22}^0(\omega,t) & \dots & S_{2m}^0(\omega,t) \\ \vdots & \vdots & \ddots & \vdots \\ S_{m1}^0(\omega,t) & S_{m2}^0(\omega,t) & \dots & S_{mm}^0(\omega,t) \end{bmatrix}_{m\times m} \tag{1}$$

Specifically for the case of earthquake ground motion, the elements of the cross-spectral density matrix with evolutionary power can be expressed in the following special form:

$$S^0_{jj}(\omega,t)=|A_j(\omega,t)|^2 S_j(\omega)\ ;\ j=1,2,\ldots,m$$
$$S^0_{jj}(\omega,t)=A_j(\omega,t)A_k(\omega,t)\sqrt{S_j(\omega)S_k(\omega)}\Gamma_{jk}(\omega)\ ;\ j\neq k\ \&\ j,k=1,2,\ldots \tag{2}$$

where $A_j(\omega,t)$ and $S_j(\omega)$ $(j=1,2,\ldots,m)$ are the (non-separable) modulating function and the (stationary) power spectral density function of component $f_j^0(t), (j=1,2,\ldots,m)$ respectively and $\Gamma_{jk}(\omega)$ $(j,k=1,2,\ldots,m;\ j\neq k)$ is the complex coherence function between $f_j^0(t)$ and $f_k^0(t)$.

For the special case of uniformly modulated non-stationary stochastic vector process, the modulating functions are independent of the frequency, that is:

$$A_j(\omega,t)=A_j(t)\ ;\ j=1,2,\ldots,m \tag{3}$$

In such a case, the three components of the non-stationary stochastic vector process are expressed as:

$$f_j^0(t)=A_j(t)\,g_j^0(t)\ ;\ j=1,2,\ldots,m \tag{4}$$

where $g_j^0(t); j=1,2,\ldots,m$ are the components of a stationary stochastic vector process. And cross-spectral density matrix given by:

$$S^0(\omega)=\begin{bmatrix} S_1(\omega) & \sqrt{S_1(\omega)S_2(\omega)}\Gamma_{12}(\omega) & \cdots & \sqrt{S_1(\omega)S_m(\omega)}\Gamma_{1m}(\omega) \\ \sqrt{S_2(\omega)S_1(\omega)}\Gamma_{21}(\omega) & S_2(\omega) & \cdots & \sqrt{S_2(\omega)S_m(\omega)}\Gamma_{2m}(\omega) \\ \vdots & \vdots & \ddots & \vdots \\ \sqrt{S_m(\omega)S_1(\omega)}\Gamma_{m1}(\omega) & \sqrt{S_m(\omega)S_2(\omega)}\Gamma_{m2}(\omega) & \cdots & S_m(\omega) \end{bmatrix} \tag{5}$$

2.2 Simulation Formula for m-Variant Non-stationary Stochastic Process

According to the algorithm presented by Deodatis (1996), in order to simulate the1D-mV non-stationary ground motion vector process, $f_0(t)$ the evolutionary cross-spectral density matrix $S_f^0(\omega,t)$ is first decomposed at every time instant t using Cholesky's method into the following product:

$$S_f^0(\omega,t)=H(\omega,t)H^{T*}(\omega,t) \tag{6}$$

where H(ω,t) is a lower triangular matrix and the superscript T denotes the transpose of a matrix. H(ω,t) is written as:

$$H(\omega,t)=\begin{bmatrix} H_{11}(\omega,t) & 0 & \cdots & 0 \\ H_{21}(\omega,t) & H_{22}(\omega,t) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ H_{m1}(\omega,t) & H_{m2}(\omega,t) & \cdots & H_{mm}(\omega,t) \end{bmatrix} \tag{7}$$

Once the cross-spectral density matrix, $S_f^0(\omega,t)$, is decomposed according to Eqs. 6~7, the non-stationary ground motion vector process $f_j^0(t), j = 1,2,\ldots,m$ can be simulated by the following series as N→ ∞

$$f_j(t) = 2\sum_{r=1}^{m}\sum_{s=1}^{N}\left|H_{jr}(\omega_l,t)\right|\sqrt{\Delta\omega}\cos\left[\omega_s t - \theta_{jr}(\omega_l,t) + \Phi_{rs}\right] \text{ ; j=1,2,…,m} \quad (8)$$

where;

$$\theta_{jk}(\omega,t) = \tan^{-1}\left(\frac{\mathrm{Im}\left[H_{jk}(\omega,t)\right]}{\mathrm{Re}\left[H_{jk}(\omega,t)\right]}\right) \quad (9)$$

3. Numerical Modeling of Dam-Reservoir-Foundation System

DEZ arch dam with 203m height in Iran was selected as numerical example. Crest length is 240m, thickness at the crest level is 4.5m and its maximum thickness at the base is 21m. Finite element idealization prepared for the dam, foundation rock and reservoir is shown in Fig. 1, which consists of 792 solid elements for modelling dam and concrete saddle (Pulvino), 3770 solid elements for simulation of mass-less foundation rock and 3660 fluid elements in reservoir domain. Far-end boundary of the foundation is at the distance from the dam which is about 2 times the height of the dam body in all direction. It is note worthy that all contraction and peripheral joints were simulated based on as-built drawings using 3D node-to-vode contact elements (Hariri et al., 2011).

The concrete dam is assumed to be with following material properties; $\rho_d = 2400\,Kg/m^3, \upsilon_d = 0.2$ *and* $E_d = 40GPa$. The foundation material is assumed to be $\upsilon_d = 0.25$ and same density. In addition, reservoir water density is assumed 1000kg/m^3, sound velocity is 1440m/s in water and wave reflection coefficient for reservoir around boundary is supposed 0.8, conservatively.

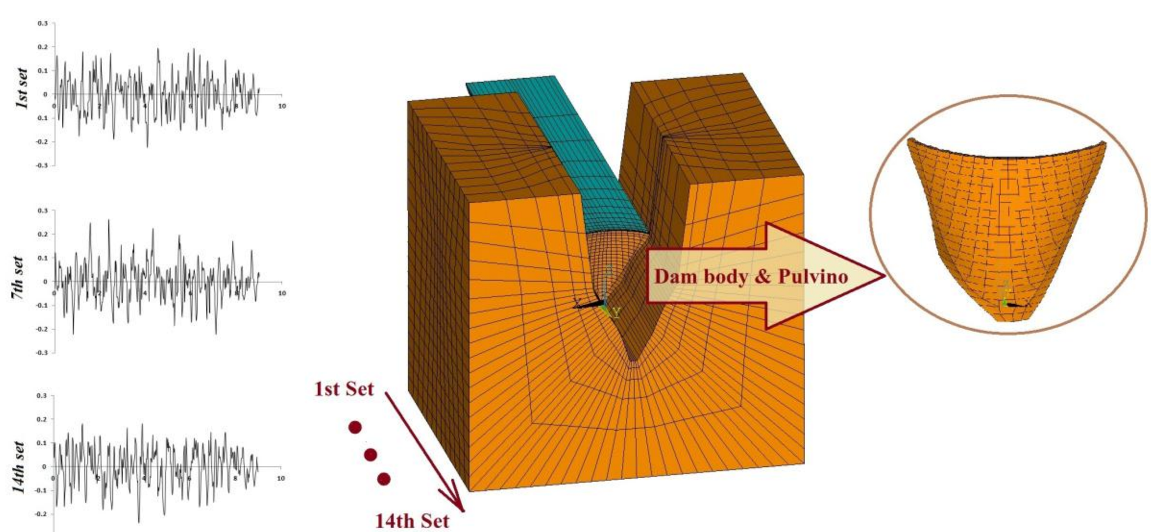
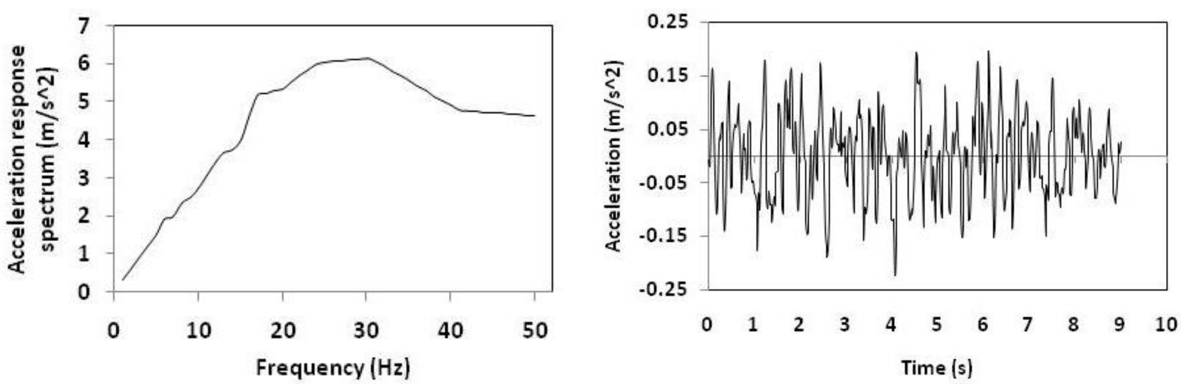


Fig 1: Finite element model of coupled system and time-history of non-uniform ground motions at various locations of foundation

4. Loading

Applied loads on the system are dam body self-weight, hydrostatic pressure in Normal Water Level (NWL) and seismic load. In addition, thermal load corresponding to summer condition is applied on the dam body. It is worthy to note that thermal load applied on the structure has been extracted from calibrated thermal transient analyses conducted using real data at the dam site taking into account solar radiation on exposed surfaces of the dam body (Hariri et al., 2011). Acceleration response spectrum of DBL for horizontal direction is shown in Fig. 2. Also time-history of horizontal component of generated ground motion for uniform excitation is shown in this figure. It is notable that in the case of uniform excitation exerted ground motion in all areas are the same with the first set of non-uniform excitation.

In non-uniform ground motion the system is excited at foundation boundaries using 14 sets of simulated ground motion records compatible with DBL spectrum in upstream-downstream direction. Based on presented formulation in previous step, a computer program was developed for generating non-uniform ground motions. The program is capable of producing different non-uniform acceleration time-histories considering wave-passage and incoherence effects according to target spectrum and solving the general equation of differential support motion. The first effect is raises by the limited wave propagation velocity, depending on their relative distances away from the source. The second effect is due to reflections and refractions of seismic waves through the soil during their propagation that leads to change in amplitude and frequency away from their source. β-Newmark method is utilized to solve the coupled nonlinear problem of dam-reservoir-foundation model. Moreover structural damping is taken to be 5% of critical damping.



(a) (b)

Fig 2: (a) Acceleration response spectrum for horizontal component of DBL, (b) Horizontal component of acceleration time-history in uniform excitation,

5. Results and discussion

5.1 Displacement

In this section results of displacement obtained from uniform and non-uniform analyses are compared with each other at crest point of crown cantilever. Based to Fig. 3, although general trend of displacement time-history is similar in both cases, in non-uniform excitation maximum displacement is happened at t=2.9s and in uniform excitation the maximum value is belongs to t=5.1s. In addition uniform excitation leads to higher value than non-uniform input.

5.2 Principal Stresses

Fig. 4 shows time-history of principal stresses at crest point of central cantilever based on uniform and non-uniform analyses. As it is clear using non-uniform excitation leads to higher values in first principal stress (S1) and lower values in third principal stress (S3) for considered point. The general trend of stress variation for both excitations is almost same.

5.2 Stress Envelope

Figs. 5 and 6 display non-concurrent envelopes of principal stresses extracted from uniform and non-uniform analyses on upstream and downstream faces of the dam body for DBL. As can be seen, in non-uniform excitation, maximum S1 is 9.69MPa which occurred in the lower part of the dam body at the connection between dam and Pulvino, but in uniform excitation this value decreases to 3.85MPa which occurs at the left part of upstream face. Neglecting over stress points in non-uniform excitation, it can be seen that the area with high stress in upstream face shifted from left parts in uniform excitation to lower parts in non-uniform excitation. In uniform excitation minimum S3 is belongs to central part of upstream face and some areas in dam-Pulvino interface and its value is -14.3MPa. In non-uniform excitation the general pattern is similar to uniform, except that minimum S3 is -17.8MPa in central part of upstream face in vicinity of crest. According to these figures it’s easy to find that difference between uniform and non-uniform inputs for S1 (that can be interpreted as tensile stress) are intensive than S3 (or compressive stress).

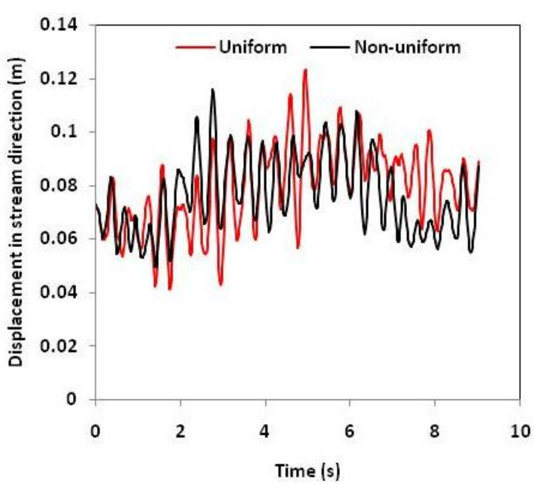


Fig 3: Time-history of crest displacement in stream direction

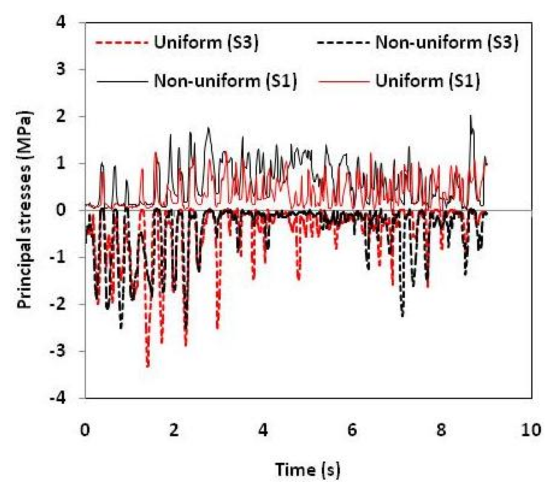
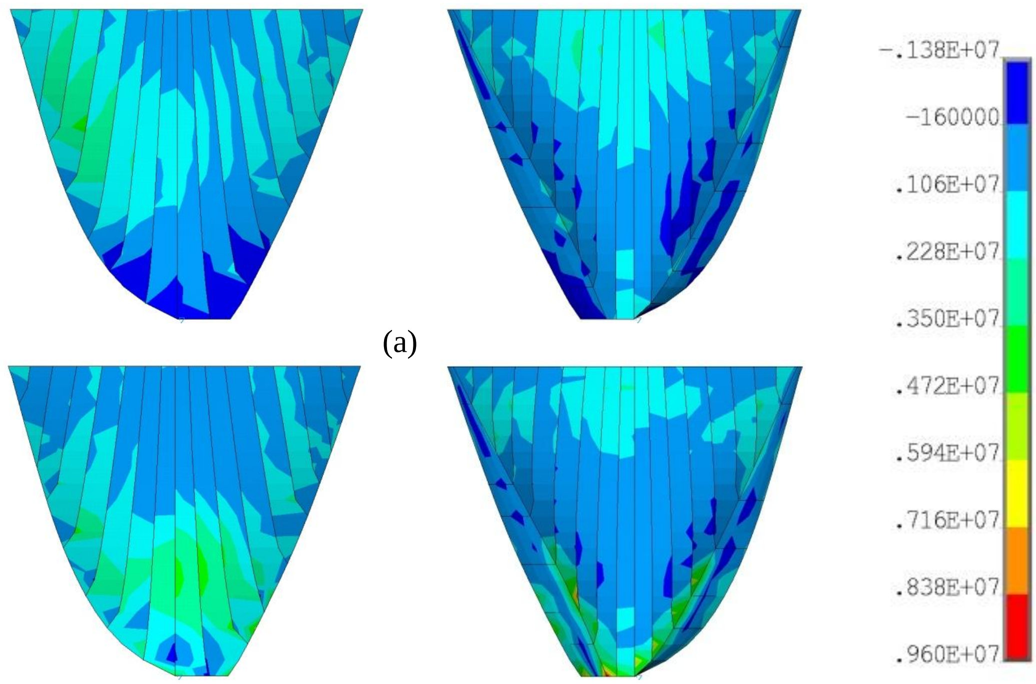


Fig 4: Time-history of crest first and third principal stresses

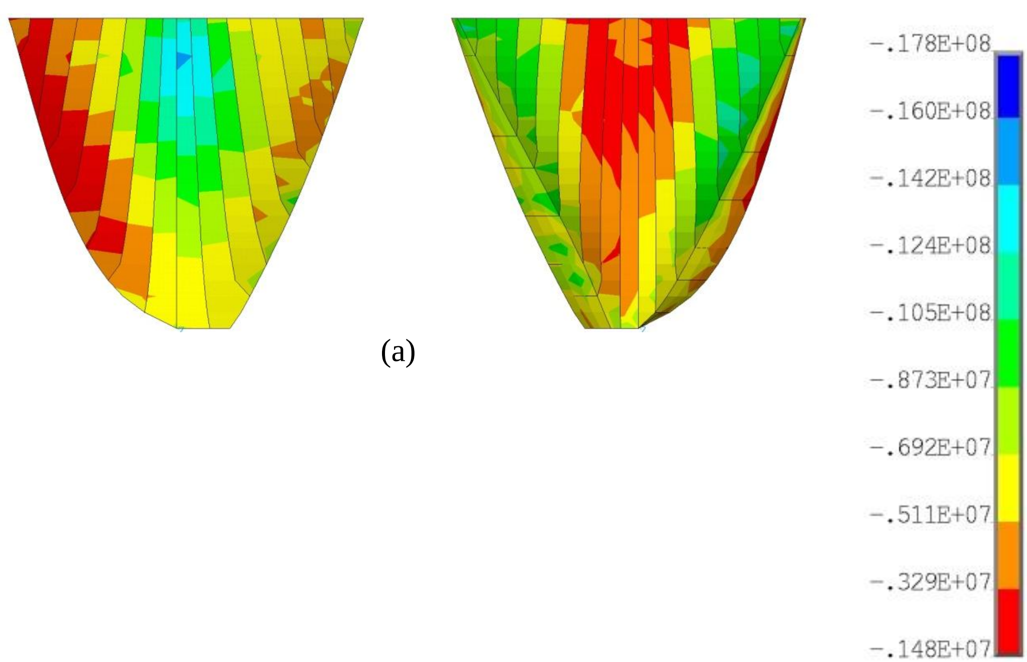
6. Conclusion

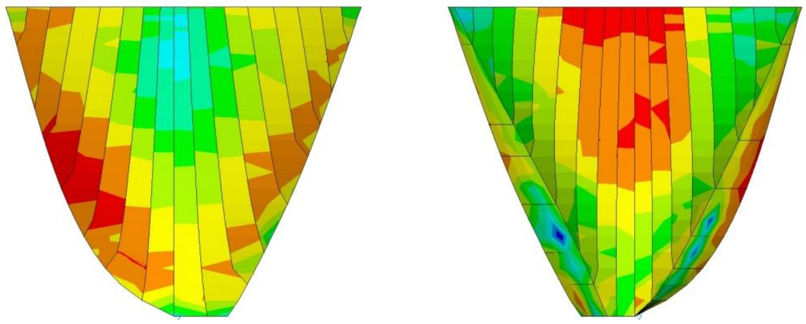
In this paper, effects of non-uniform excitation due to spatially varying ground motions on nonlinear responses of concrete arch dams are studied. In this study Monte-Carlo simulation approach was used for generating spatially non-uniform ground motion. It was observed that using non-uniform input leads to lower values for crest displacement in comparison with uniform excitation. Also it was concluded that differences between uniform and non-uniform excitations in first principal stress is more than third principal stress. Totally non-uniform excitation generates higher tensile and compressive stresses in dam body. The ratio of maximum tensile stress in non-uniform to uniform excitation in present study is 2.51 and the ratio for minimum compressive stress is 1.24. It is generally observed that the spatially varying earthquake ground motion model has important effects on the stochastic response of the dam-reservoir-foundation system. Therefore, to be more realistic in calculating the dam response, spatially varying earthquake ground motions should be incorporated in the analysis.



(b)

Fig 5: Non-concurrent envelopes of first principal stresses in upstream and downstream faces of dam body (Pa), (a) Non-uniform excitation, (b) Uniform excitation





(b)

Fig 6: Non-concurrent envelopes of third principal stresses in upstream and downstream faces of dam body (Pa), (a) Non-uniform excitation, (b) Uniform excitation

References

Alves, S.W. & Hall, J.F. (2006). Generations of spatially non-uniform ground motion for nonlinear analysis of a concrete arch dam. *Earthquake Engineering and Structural Dynamics*. 35, 1339-1357.

Alves, S.W. & Hall, J.F. (2006). System identification of a concrete arch dam and calibration of its finite element model. *Earthquake Engineering and Structural Dynamics*. 35, 1321-1337.

Allam, S.M. & Datta, T.K. (2004). Seismic response of cable-stayed bridge deck under multiple-component non-stationary random ground motion. *Earthquake Engineering and Structural Dynamics*. 33, 375-393.

Bayraktar, A. & Dummsnoglu, A.A. (1998). The effect of synchronous ground motion on hydrodynamic pressures. *Computer and structures*. 68, 271-282.

Bayraktar, A., Dummsnoglu, A.A. & Calayir, Y. (1996). Asynchronous dynamic analysis of dam-reservoir-foundation systems by the lagrangian approach. *Computer and structures*, 58, 925-935.

Cacciola, A.N. & Deodatis, G. (2010). A method for generating fully non-stationary and spectrum-compatible ground motion vector processes. *Soil Dynamics and Earthquake Engineering*.

Der Kiureghian, A. (1996). A coherency model for spatially varying ground motions. *Earthquake Engineering and Structural Dynamics*. 25(1), 99–111.

Deodatis, G. (1996). Non-stationary stochastic vector processes: seismic ground motion applications. *Probabilistic Engineering Mechanics*. 11, 149-168.

Hariri Ardebili, M. A., Mirzabozorg, M., Ghaemian, M., Akhavan, A. & Amini, A. (2011). Calibration of 3D FE model of DEZ high arch dam in thermal and static conditions using instruments and site observation. *6th International conference on dam engineering*. Lisbon, Portugal, 121-135.

Harichandran, R.S., Hawwari, A. & Sweidan, B.N. (1996). Response of long-span bridges to spatially varying ground motion. *ASCE-Structural Engineering*. 122(5), 476–484.

Maeso, O., Aznarez, J.J. & Dominguez, J. (2002). Effects of space distribution of excitation on seismic response of arch dams. *Journal of Engineering Mechanics-ASCE*. 128, 759-768.

Shinozuka, M. & Deodatis, G. (1988). Stochastic process models of earthquake ground motion. *Journal of Probabilistic Engineering Mechanics*. 3(3), 114-123.

Zhang, Y.H., Li, Q.S., Lin, J.H. & Williams, F.W. (2009). Random vibration analysis of long-span structures subjected to spatially varying ground motions. *Soil Dynamics and Earthquake Engineering*. 29, 620–629.