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Linear seismic response of arch dams to non-uniform excitations considering load combination effects

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Abstract

In the present paper, the effect of non-uniform excitation due to spatially varying earthquake ground motions (SVEGM) on linear responses of concrete arch dams is investigated. An iterative scheme is utilized to generate seismic ground motion time-histories at several locations along foundation boundaries that are compatible with prescribed target response spectra and are correlated according to a given coherence function including the wave propagation effect. A double curvature arch dam is selected as case study in which the reservoir is modeled as a compressible medium and the foundation is assumed to be massless. Various load combinations are considered based on the corresponding reservoir water levels and thermal loads. It is observed that using SVEGM leads to higher values in both tensile stresses and percentage of overstressed parts within the dam body in comparison with uniform excitation and therefore to be more realistic in calculating the dam response, this phenomenon should be incorporated in seismic analyses especially in high seismicity regions.

Keywords: Arch dam, linear analysis, non-uniform excitation, SVEGM.

1. INTRODUCTION

Since dynamic analysis of arch dams is usually complicated, seismic evaluation of these infrastructures have been traditionally done assuming that the input ground motion is uniform along the abutments. However, it has been understood for many years that the seismic motion in a canyon is spatially non-uniform. In fact, the realistic dynamic analysis of arch dams using spatially varying earthquake ground motion (SVEGM) should be performed for the purpose of safety assessment of existing dams. The term spatial variation of seismic ground motions denotes the differences in amplitude and phase of seismic motions reached to extended areas. Many researchers have worked on the effects of spatial variability on various engineering structures such as bridges, dams, tunnels and also various simulation techniques have been proposed for generating ground motion time-histories.

In dam engineering, limited works have been done on the seismic behavior under non-uniform excitations. The effect of a spatially varying ground motion on the response of earth-fill dams have been investigated in past few years. Three-dimensional nonlinear seismic analysis of concrete faced rock-fill dams subjected to scattered P, SV and SH waves considering the dam-foundation interaction effects was studied by Seiphoori et al. [1]. Results of analyses indicated that due to applying the scattered motion to the canyon, the response of the dam and its concrete face slab increases significantly. In addition, Chen and Harichandran [2]; Bayraktar et al. [3]; Haciefendioglu [4] ,Haciefendiolu and Soyluk [5] studied the behavior of earth-fill and rock-fill dams due to spatially variation ground motions considering various parameters.

Alves and Hall [6] analyzed the effect of spatially variable excitations on the nonlinear response of Pacoima dam using recorded data. Results showed that the response to uniform input is more severe in some ways, but the major difference with non-uniform input is the importance of the pseudo static component in the response, which can cause large deformations and stresses along the abutments of the dam. Bilici et al. [7] studied the stochastic dynamic response of dam-reservoir-foundation systems to spatially varying earthquake ground motions. To do so, the Sariyar gravity dam in Turkey was selected for numerical example and the ground motion was applied to each support point of the 2D finite element model. They concluded that spatially varying earthquake ground motions have important effects on the stochastic dynamic response of coupled systems. A nonlinear seismic analysis of concrete gravity dams with spatially variation ground motion under the dam body including dam-reservoir-foundation interaction was conducted by Mirzabozorg et al. [8]. In addition, Mirzabozorg et al. [9] studied the nonlinear seismic responses of concrete arch dams considering wave passage along the reservoir bottom and sides. In both studies, the results showed that the non-uniform excitation lead to crack profiles, which are different from those obtained under the uniform excitation. Chopra and Wang [10] computed the response of two arch dams to spatially varying ground motions recorded during earthquake using a developed linear analysis procedure including dam-water-foundation rock interaction effects. In another research, Wang and Chopra [11] used the sub-structure method for seismic analysis of arch dams including the effects of dam-water-foundation rock interaction to consider spatial variations in ground motions along the canyon. It was demonstrated that spatial variations in ground motion can have significant influence on the earthquake-induced stresses in the dam. This influence obviously depends on the degree to which ground motion varies spatially along the dam-rock interface. Thus, for the same dam, this influence could differ from one earthquake to the next, depending on the epicenter location and focal depth of the earthquake relative to the dam site. The seismic response of concrete gravity dams subjected to spatially varying ground motions was examined by Huang [12]. It was shown that spatially variable excitations generate larger openings at the heel of the dam and more severe slipping at its toe and may have significant consequence for the global dam stability during an earthquake. The effects of spatially varying earthquake ground motion on random hydrodynamic pressures were investigated by Bayraktar et al.[13] considering dam-reservoir-foundation interaction utilizing the Lagrangian approach. It was observed that the spatially varying earthquake ground motion affects the mean of maximum values of random hydrodynamic pressures considerably. Sohrabi-Gilani and Ghaemian [14] studied the seismic responses of Karun III arch dam subjected to multiple support excitations. They found that non-uniform ground acceleration can have extensive effects on the dam behavior and increases the responses. Pseudo static displacement is the dominant part of the total displacement for points near the dam foundation interface; however, the dynamic displacement is more significant for the middle part of the dam. Mirzabozorg et al. [15] studied the effects of wave passage and incoherency models on nonlinear seismic response of arch dams. In the present paper, an iterative scheme is utilized to generate seismic ground motion time-histories at several locations along the foundation boundaries that are compatible with prescribed response spectra; are correlated according to a given coherence function; include the wave propagation effect; and finally have specified duration of strong ground motion. In other word, a spectral-based simulation is used to generate sample functions of a non-stationary, multi-variate stochastic process with evolutionary power. Double curvature Dez arch dam is selected as numerical example and modeled based on as-built drawings to investigate SVEGM effects on the linear response of the dam. Reservoir is modeled as a compressible medium based on Eulerian approach and foundation rock is assumed to be massless.

2. GENERATION OF SVEGM

The spatial variation of ground motion records can be attributed to the three main mechanisms as shown in Figure 1, reported by Shinozuka and Deodatis [16]:

In the present paper, an iterative algorithm proposed by Deodatis [17] and Saxena [18] was used to generate differential acceleration time-histories at several prescribed locations along foundation boundaries. The methodology is described as follows, by considering that the acceleration time-histories at a specified number of locations on the ground surface constitute a multi-variate, non-stationary stochastic process (non-stationary stochastic vector process).

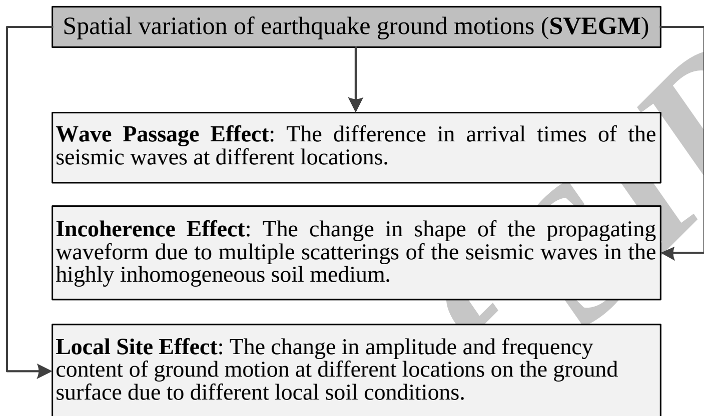


Figure 1 Main mechanisms of SVEGM

2.1. SIMULATION OF N-VARIATE NON-STATIONARY STOCHASTIC PROCESS

This section outlines the algorithm which simulates non-stationary ground motion time-histories based on a prescribed spectral density matrix (Kim and Feng [19]). The vector process is assumed to be a non-stationary with evolutionary power as summarized in Figure 2.

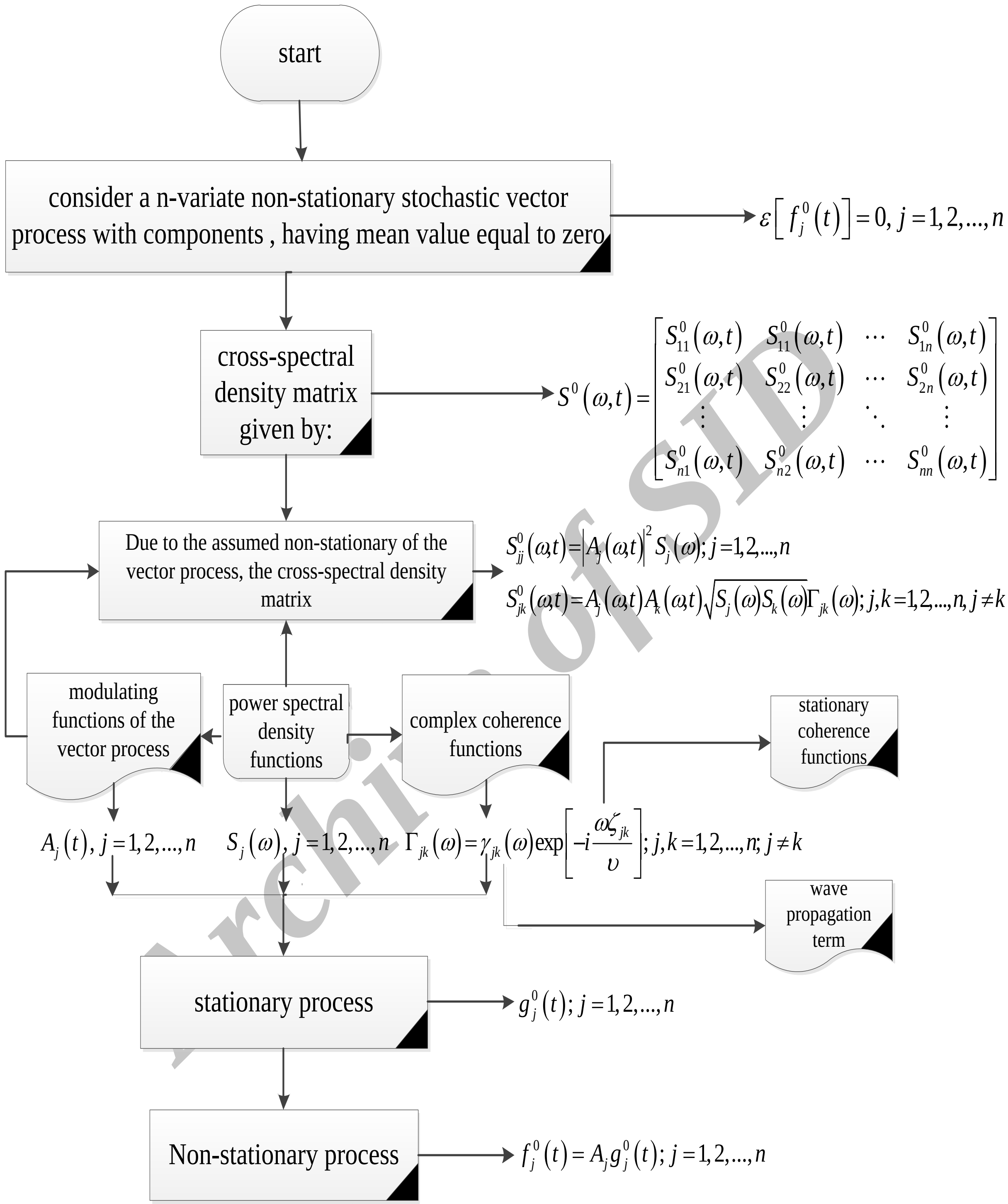
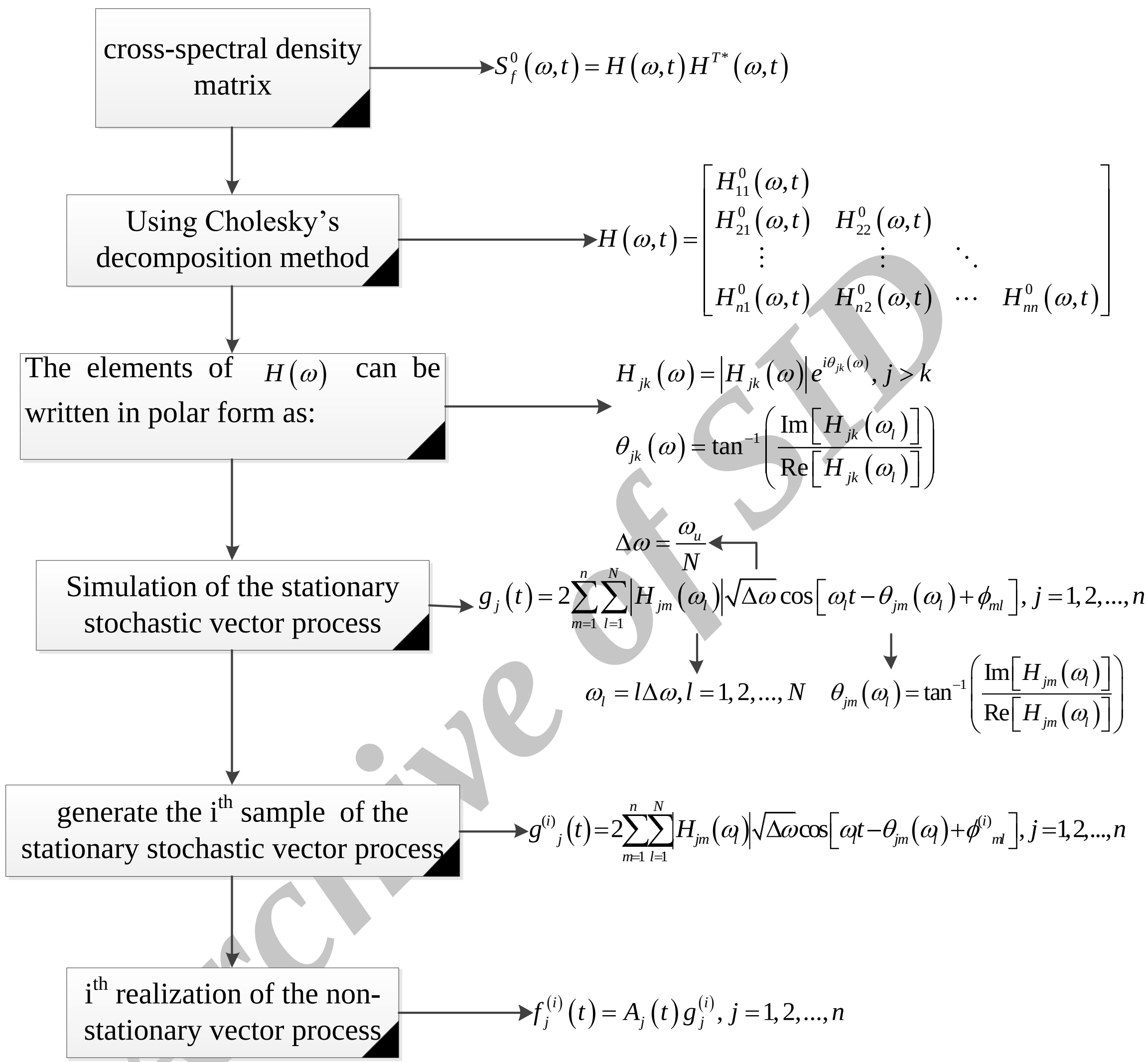


Figure 2: Simulation of n-variate non-stationary stochastic process

2.2. SIMULATION PROCEDURE

Figure 3 shows the procedure to simulate samples of an n-variate non-stationary stochastic function $f_j^0(t);\ j=1,2,...,n$.



ϕ_{ml} is n sequences of independent random phase angles distributed uniformly over the interval $[0,2\pi]$

ω_u represents an upper cut-off frequency beyond which the elements of the cross-spectral density matrix, maybe assumed to be zero for anytime instant t.

Figure 3: Simulation procedure of non-stationary vector process

3. DEVELOPING NUMERICAL MODEL AND LOAD COMBINATIONS

Dez arch dam was selected as numerical example. Its total height is 203m but the height of the main body (without concrete saddle) is 186m. Crest length is 240m;thickness at the crest level is 4.5m and its maximum thickness at the base is 21m. General view and also downstream faceofthe dam is shown in Figure 4 [20].

A 3D finite element model was developed for dynamic analysis of dam-reservoir-foundation system. The dam body was modeled using 792 eight-node solid elements in three layers through the thickness and also mass-less foundation was simulated using 3770 eight-node solid elements and extended to at least twice the height of dam body in all directions.Moreover,3660 eight-node fluid elements were used in reservoir domain extended in upstream direction about 5 times of the dam body height. Fluid elements have three translational degrees of freedoms (DOFs) and one pressure DOF at each node in which translational DOFs are activated only at nodes that are on the interface with solid elements. Isotropic elasticity of mass concrete and Poisson's ratio in static and dynamic conditions are 40GPa, 0.2, 46GPa and 0.14, respectively and concrete density is 2400kg/m^3. Isotropic elasticity of foundation rock in saturated and unsaturated conditions is assumed as 13GPa and 15GPa, respectively and Poisson's ratio is taken 0.25. 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 [21].

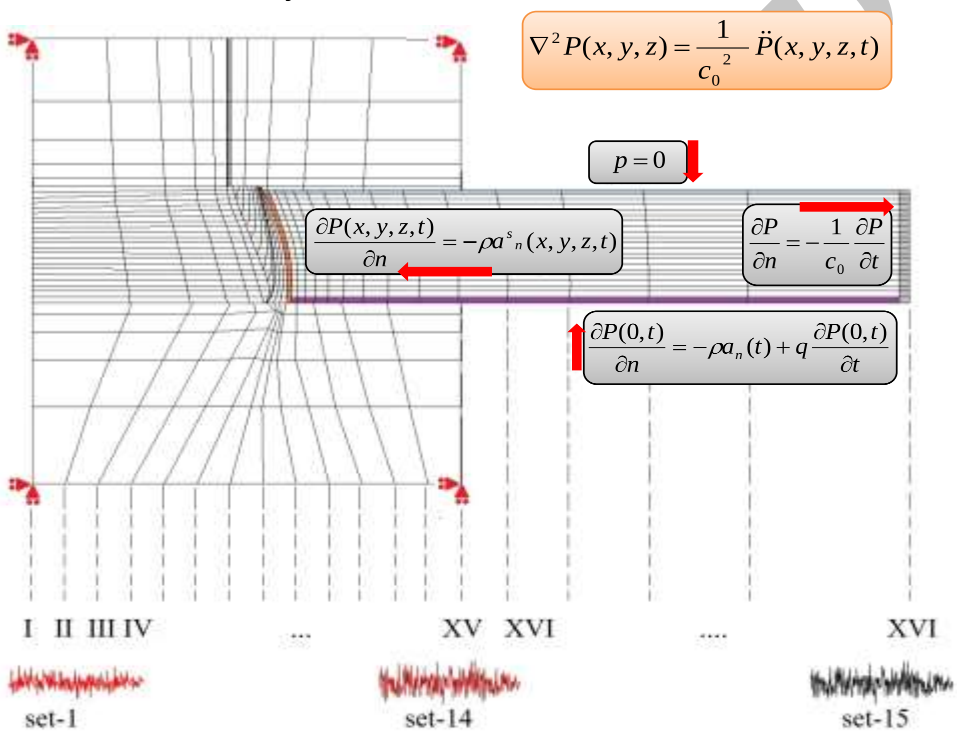


Figure 4 Section view of finite element model of the coupled system and mechanism of non-uniform excitation along the foundation and reservoir boundaries

Two main load combinations are considered in the present study based on USACE [22] and FERC [23]. In the first one, reservoir level is assumed to be in normal water level (NWL) and summer temperature conditions is applied to the dam body. In the second load combination, minimum water level (MWL) is assumed in conjunction with winter temperature in Dez dam site. Other applied loads on the system are dam body self-weight and seismic load in uniform and non-uniform conditions at various performance levels. Table1 summarizes the load combinations considered in the present study.

Thermal load applied on the structure was extracted from calibrated thermal transient analyses conducted using the data recorded at the dam site taking into account solar radiation on the exposed surfaces of the dam body [21].

As can be seen in Table 1, two seismic excitation levels are considered to investigate the ground motion intensity effects; base level (DBL) and maximum credible level (MCL). Horizontal and vertical acceleration response spectra at these levels are shown in Figure 5 in log-log scale. In the case of non-uniform excitation, the system is excited at foundation boundaries using 14 sets of simulated ground motions compatible with desired target spectrum. Based on the presented formulation in previous sections, a computer program in MATLAB environment was provided for generating non-uniform ground motions. The Newmark-β time integration method is utilized to solve the coupled problem of dam-reservoir-foundation model. Moreover, structural damping is taken to be 5% of critical damping in all cases.

Table 1. Definition of load combinations

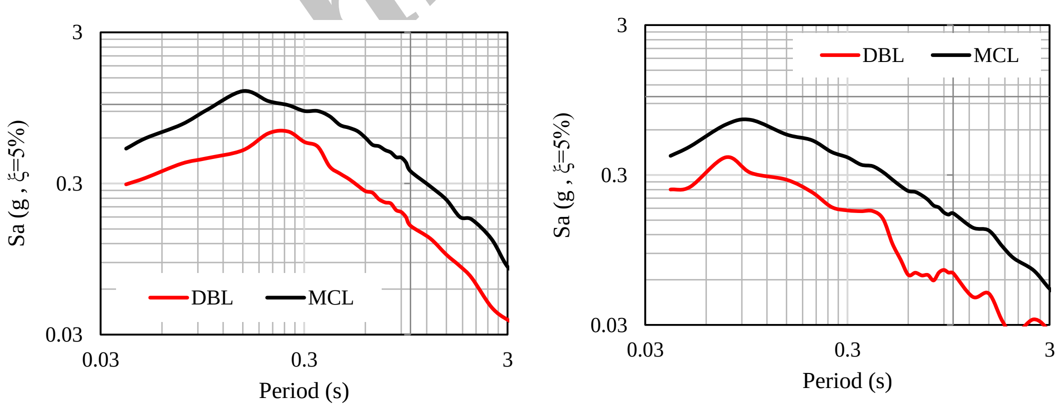
NO.	Abbreviation	Dam self-weight	Hydrostatic pressure	Temperature loading	Seismic level	Seismic type
1	S-DBL-U	Considered	NWL*	Summer	DBL†	Uniform
2	S-DBL-NU	Considered	NWL	Summer	DBL	Non-uniform
3	S-MCL-U	Considered	NWL	Summer	MCL§	Uniform
4	S-MCL-NU	Considered	NWL	Summer	MCL	Non-uniform
5	W-DBL-U	Considered	MWL**	Winter	DBL	Uniform
6	W-DBL-NU	Considered	MWL	Winter	DBL	Non-uniform
7	W-MCL-U	Considered	MWL	Winter	MCL	Uniform
8	W-MCL-NU	Considered	MWL	Winter	MCL	Non-uniform

* Normal Water Level

** Minimum Water Level

† Design Base Level

§ Maximum Credible level



(a) (b)

Figure5: Acceleration response spectrum of seismic excitation levels, (a) horizontal component; (b) vertical component

4. RESULTS AND DISCUSSION

4.1 DISPLACEMENT

In this section the time-historiesof crest displacement at mid-pointfor various load combinations are compared with each other.The crest displacement in the downstream direction is 11mm under static loads due to minimum water level and winter temperature, whereas the value reaches to 20.5mm for normal water level and summer temperature. As it is clear in Figure 5, the frequency content for both uniform and non-uniform excitations are the same butthe extreme values in non-uniform excitation is less than uniform onein both downstream (DS) and upstream (US) directions.Comparing two load combinations shows that displacement values for normal water level is more than minimum water level. The differences between uniform and non-uniform excitations for NWL are less than those of MWL. Generally, increase of seismic excitation level leads to slump of displacement time-history diagram of non-uniform excitation with respect to uniform one.

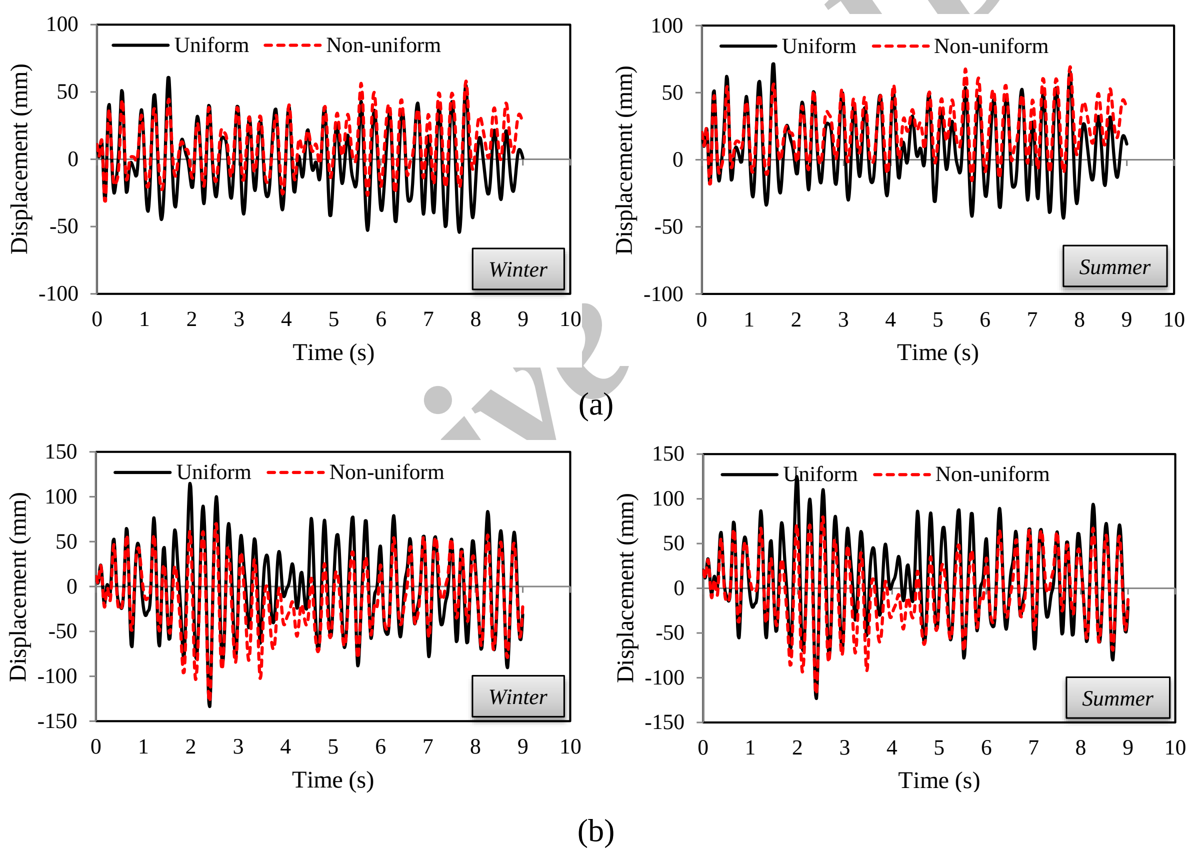
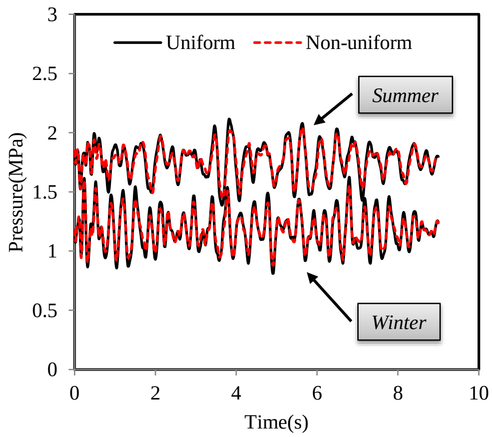


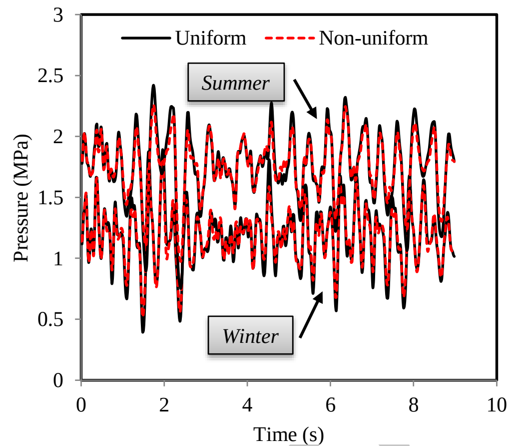
Figure 5: Time-history of the crest displacement in the stream direction for (a) DBL; (b) MCL

4.2 HYDRODYNAMIC PRESSURE

Figure 6 compares the hydrodynamic pressures at the base point of crown cantilever obtained from uniform and non-uniform excitations for two performance levels. Due to initial water level, the hydrodynamic pressure time-history in summer load combination starts at higher point. There is good agreement between hydrodynamic pressures in uniform and non-uniform excitation but it seems that uniform excitation leads to higher values.



(a)



(b)

Figure 6: Hydrodynamic pressures time-history at the base of crown cantilever

(a) DBL;(b)MCL

4.3STRESSENVELOPE

Figures 7 to 10 represent non-concurrent envelopes of principal stresses extracted from uniform and non-uniform analyses on the upstream and downstream faces of the dam body. Comparing winter and summer load combinations reveals that operating dam in minimum water level increases the area with maximum first principal stress in comparison with the summer condition that is more evident in middle parts of the upstream face and central parts of the downstream face. As can be seen, in uniform excitation, the area with high values of the first principal stress are seen in upper parts of the body near the abutments while in non-uniform case they shift to the lower parts of the downstream face. In both DBL and MCL, using non-uniform excitation leads to stress concentration at lower parts of the left side in vicinity of the dam-foundation interface. For the third principal stress, the area with high values shifts to the lower parts of the downstream face due to non-uniform excitation. Generally, it can be understood that the models based on non-uniform excitation leads to higher stresses especially in dam-foundation interface.

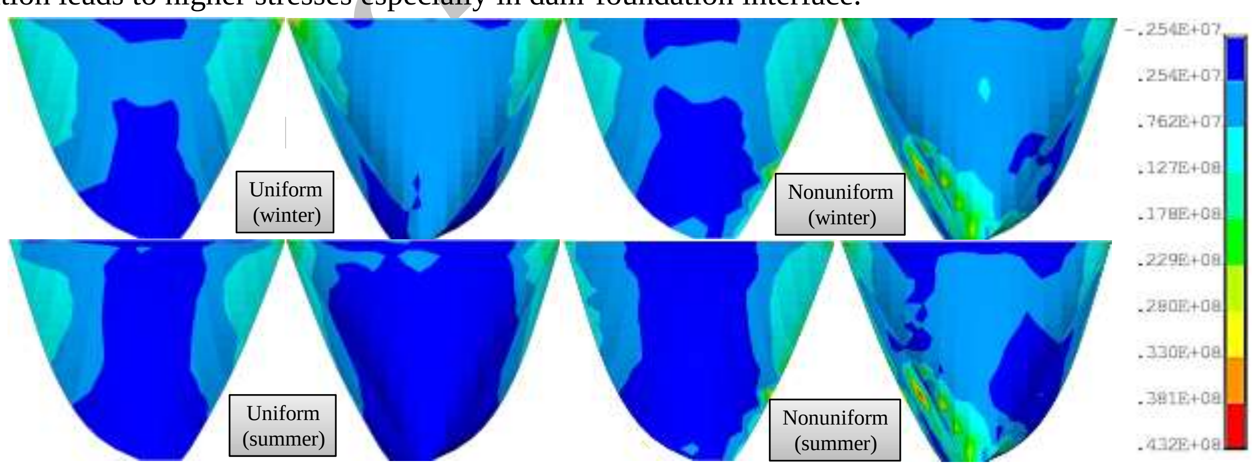


Figure 7: Non-concurrent envelope of maximum first principal stresses on the upstream and downstream faces of the dam body for DBL (Pa)

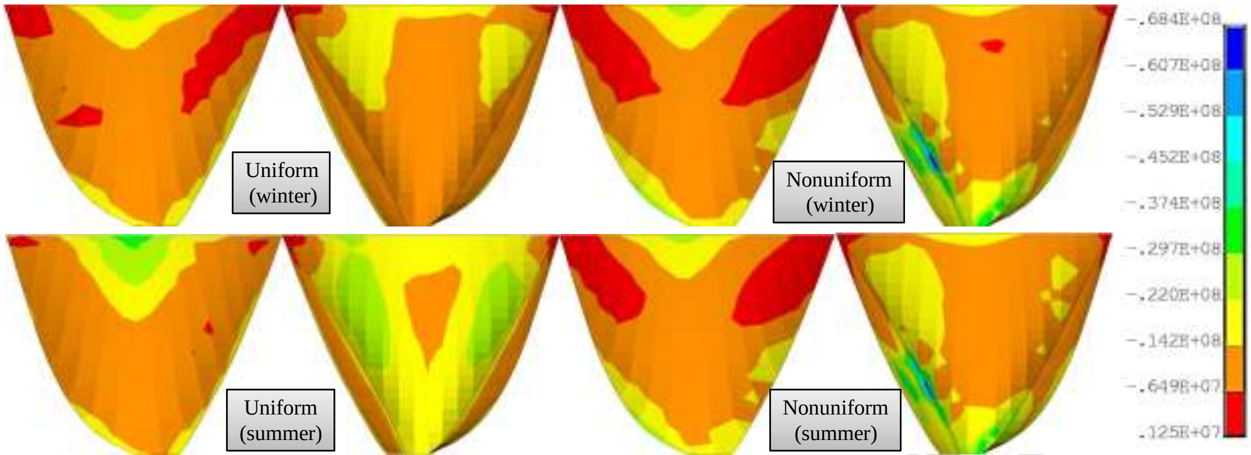


Figure 8: Non-concurrent envelope of minimum third principal stresses on the upstream and downstream faces of the dam body for DBL (Pa)

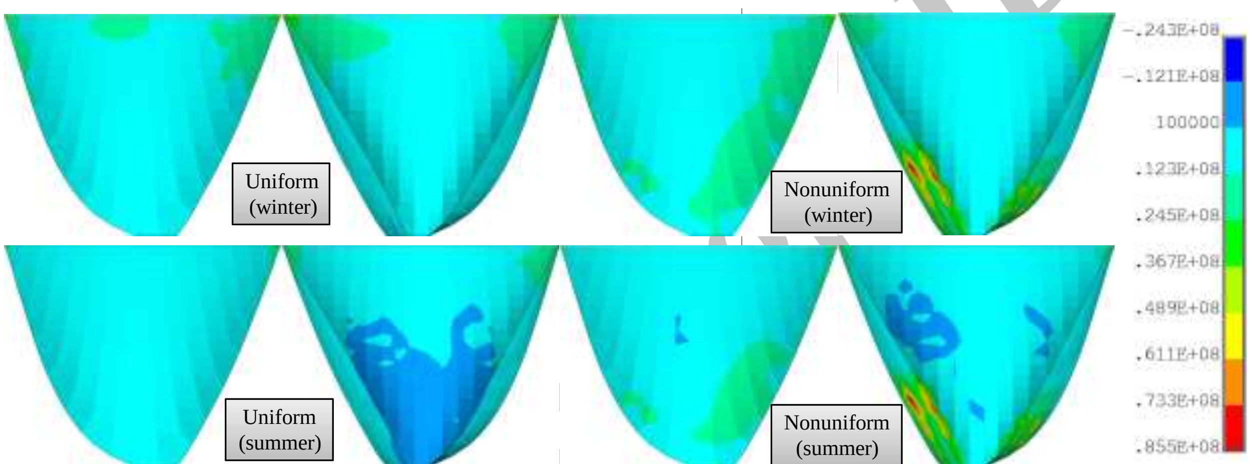


Figure 9: Non-concurrent envelope of maximum first principal stresses on the upstream and downstream faces of the dam body for MCL (Pa)

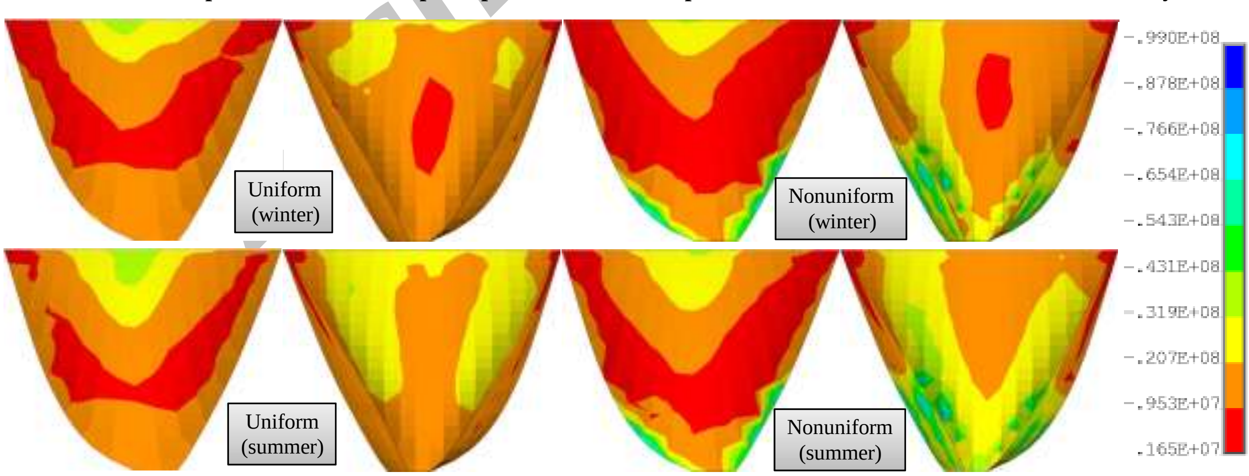


Figure 10: Non-concurrent envelope of minimum third principal stresses on the upstream and downstream faces of the dam body for MCL (Pa)

5. DISCUSSION

USACE [22] proposed a systematic methodology in order to performance assessment of concrete dams using linear analysis. This methodology is based on factors such as displacements, stresses, demand-capacity ratio, cumulative inelastic duration and percentage of overstressed areas on the dam body faces. This guideline proposed criteria for both gravity and arch dams so that if they have been satisfied in terms of abovementioned factors extracted from a linear analysis, the analyser is permitted to use the linear elastic method for safety evaluation of the dam; and if not, nonlinear dynamic analysis is required. The most important factor is percentage of overstressed areas on both faces of the dam body. USACE [22] represents that if the overstressed areas on the face is limited to 20% of the total area of that face, the analyser is permitted to use linear elastic method for safety evaluation of the dam. As can be seen in Figure 11,in all cases the percentage of overstressed areas are more than 20% and so the coupled system needs to be modelled considering material and joint nonlinearity effects for more accurate evaluation. However, in all cases exciting the dam using non-uniform seismic input leads to higher overstressed areas in comparison to the case with uniform excitation, especially in lower parts of the dam near the dam-foundation interface.

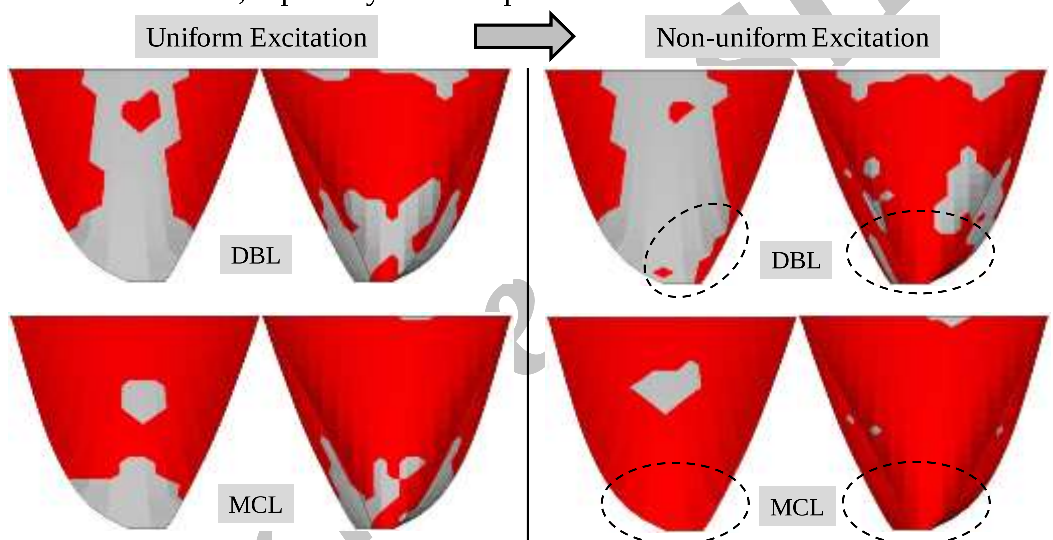


Figure 11: Overstressed areas of the dam under uniform and non-uniform excitations

6. CONCLUSION

In this paper, effects of non-uniform excitation due to wave passage and incoherency effect on linear response of a high concrete arch dam are studied. An iterative scheme is utilized to generate seismic ground motion time histories that are compatible with prescribed response spectra; correlated according to a given coherence function; include the wave propagation effect; and finally have specified duration of strong ground motion. A double curvature arch dam was selected as numerical example, reservoir was modeled as a compressible material and foundation rock was modeled as a mass-less medium. Two main load combinations (summer and winter conditions) were studied based on the corresponding reservoir water levels and thermal loads.
The conclusions drawn from this study can be written as:

a. The response of the finite element model of arch dam to non-uniform excitation is substantially different from the response to uniform excitation. As a result, crest displacement and hydrodynamic pressures in non-uniform excitation is less than those in uniform excitation.
b. Comparing winter and summer load combinations reveals that operating dam in minimum water level increases the area with maximum first principal stress in comparison with the summer condition.
c. In uniform excitation, the area with high values of the first and third principal stress are observed in upper parts of the body near the abutments while in non-uniform case they shift to the lower parts of the downstream face.
d. The models based on non-uniform excitation leads to higher stresses especially on the dam-foundation interface.
Spatial variations of ground motion are typically ignored in dam engineering practice while it should be taken into account in the seismic evaluation of concrete arch dam.

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