Research Paper

The Effect of Spatially Varying Earthquake Input Motion on Earth Dams with Various Dimensions

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ABSTRACT

Seismic behavior of earth dams is significantly influenced by the nature of input motion. The implementation of identical motions at the base of the dams can yield unconservative dynamic responses. Therefore, spatially varying earthquake ground motion (SVEGM) should be considered in their seismic response analysis and design. This paper presents the nonlinear seismic analyses of earth dams subjected to SVEGM using finite difference method. Different models of earth dams are considered for this purpose. These models are different in dam height and foundation length. Different methods are available for the generation of SVEGM. A computer software is used for conditional generation of SVEGM input motion. For unconditional case, SVEGM is generated by a computer code developed in the present research based on spectral-representation-based technique. Two different coherency models are used for the generation of SVEGM. Results are expressed in terms of peak accelerations along the dam height and horizontal and vertical displacements of dam crest. The results indicate that generally the uniform input motions can produce higher values of peak accelerations along dam height and dam crest horizontal displacement than SVEGM excitation. However, the crest vertical displacement of smallest dam obtained by SVEGM input analysis is higher than that calculated by using uniform input analysis.

Keywords:
SVEGM; Earth dam; Coherency model; Conditional and unconditional simulation methods; Dynamic analysis

1. Introduction

Spatially varying earthquake ground motion (SVEGM) is referred to the variations in the amplitude and phase of earthquake recorded at different seismic recording stations over extended areas [1]. Given the large dimensions of earth dams, it is also difficult to define a 'realistic' earthquake motion scenario, based on the characterization of the motion at a single point [2-3]. The nonuniformity of excitations results from a variety of reasons, such as differences in the arrival times of seismic waves, the incoherence effect, and the site response effect. SVEGM can be caused by important factors that can be divided in three groups: wave passage effect, wave coherency loss, and site effects. The majority of coherency models were developed for soil sites whereas existing models for rock sites are limited.

Various SVEGM simulation techniques have been developed, covariance matrix decomposition, spectral representation method and ARMA (auto-regressive-moving-average) approximation, among others. Generally, most of SVEGM unconditional simulation methods involve calculations of the parametric power spectral density (or a response spectrum) and a spatial variability model. In these methods, parametric power spectral density (evolutionary or non-evolutionary) can be calculated either from existing models or from a predefined seismic ground motion time history (e.g., a recorded accelerogram) [1].

The conditional simulation of ground motions reported in the literature is based on the kriging (linear estimation theory) and Conditional Probability Density Function (CPDF) methods. In conditional simulation, frequency dependency of generated motions is explicitly taken into account by including frequency dependent spatial correlation function [4]. Vanmarcke and Fenton [5] conditionally simulated stationary segments of earthquake ground motion using the linear-estimation techniques called kriging, later extending the approach to account for time-varying ground-motion intensity and frequency content. Vanmarcke et al. [6] simulated properly correlated earthquake ground motions at an arbitrary set of closely spaced points, compatible with known or prescribed motions at other locations. These authors used linear-prediction estimators to generate a set of statistically independent, frequency-specific, spatial random processes. Their method is a significant improvement over conventional kriging techniques.

The conditional simulation of SVEGM can also be performed in the time domain. Jankowski and Wilde [4] proposed a simple method of conditional simulation of space-time variation of a ground motion. The frequency dependence of the spatial correlation function was simplified so that only the correlation of the predominant frequency of the earthquake was considered. Also, there have been several attempts in the recent years that have focused on simulating SVEGM at canyon site. Isari et al. [7] developed a new approach to generate SVEGM at topographic sites.

During the past years, the effect of SVEGM on long structures was evaluated. Harichandran et al. [8] compared the responses of long-span bridges using identical and general SVEGM excitations. Zhang et al. [9] analyzed the dynamic responses of multi-supported structures subjected to SVEGM.

Chen and Harichandran [10] evaluated the dynamic response of the Santa Felicia earth dam subjected to SVEGM and concluded that the ground motions with high incoherency can produce significant increase of the maximum shear stress in the stiff gravel of the stream bed. In a series of studies conducted at the International Institute of Earthquake Engineering and Seismology of Iran, Davoodi et al. [11], Sadreddini et al. [12], and Davoodi and Sadreddini [13-14] analyzed the effects of SVEGM on the response of the Marun and Masjed Soleyman embankment dams with two and three dimensional finite difference codes. The main topics of their studies are: effects of different coherency models, wave passage and loss of coherence effects, generation of SVEGM input motions considering code-defined spectra (for different soil classes) and various hazard levels of earthquakes (DBL and MCL) and the effects of SVEGM on the response of hypothetical earth dams with different crest length to height ratios (L/H). It is found that applying SVEGM results in reduction of acceleration values within the core of the dam. Also, the results indicated that the stress response within the dam body and core of dam can be significantly increased due to SVEGM.

To the authors' knowledge, there is no comprehensive study about the effect of SVEGM on seismic response of earth dams with various dimensions using time history analysis. To this end, in this paper the effect of SVEGM on dynamic response of earth dams with different height and foundation length is studied. SVEGM is generated using two different methods: conditional an unconditional simulation.

2. SVEGM

The important factors creating the spatial variability of seismic ground motions can be divided in three groups [15]:

a) Wave Passage Effects: It denotes the difference in the arrival times of waves at different spatial stations. The time delay between two locations induced by wave passage will result in a deterministic phase differences of the earthquake ground motions.
b) Incoherence Effects: is caused by the refraction and the reflection of seismic wave that occur along the seismic wave propagation path (Figure 1).
c) Local Site Effects: This term refers to the

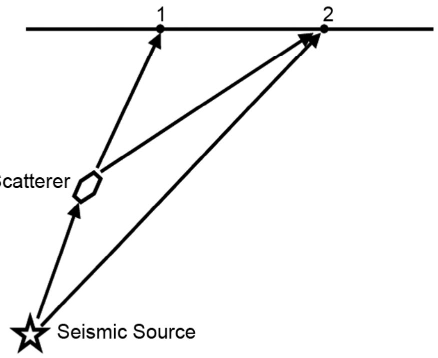

Figure 1. Incoherence effect [1].

difference in local site conditions at each station that can change amplitude and frequency content of seismic ground motion.

2.1. Coherency

The coherency of the seismic motions is a complex number and can be obtained from the ratio of the smoothed cross spectrum of the time series between the two stations *j* and *k*, to the corresponding power spectra [1]:

$$\bar{\gamma}_{jk}^{M}(\omega) = \frac{\bar{S}_{jk}^{M}(\omega)}{\sqrt{\bar{S}_{jj}^{M}(\omega)\bar{S}_{kk}^{M}(\omega)}} \tag{1}$$

The square of the absolute value of the coherency, the coherence:

$$\left|\bar{\gamma}_{jk}^{M}(\omega)\right|^{2} = \frac{\left|\bar{S}_{jk}^{M}(\omega)\right|^{2}}{\bar{S}_{jj}^{M}(\omega)\bar{S}_{kk}^{M}(\omega)} \tag{2}$$

is a real number assuming values $0 \le \left|\bar{\gamma}_{jk}^{M}(\omega)\right|^{2} \le 1$. The absolute value of the coherency:

$$\left|\bar{\gamma}_{jk}^{M}(\omega)\right| = \frac{\left|\bar{S}_{jk}^{M}(\omega)\right|}{\sqrt{\bar{S}_{jj}^{M}(\omega)\bar{S}_{kk}^{M}(\omega)}} \tag{3}$$

is termed the lagged coherency. Its real part, $\Re[\bar{\gamma}_{jk}^{M}(\omega)]$, is commonly referred to as the unlagged coherency, and its phase:

$$\bar{\varphi}_{jk}^{M}(\omega) = \tan^{-1}\left(\frac{\Im[\bar{\gamma}_{jk}^{M}(\omega)]}{\Re[\bar{\gamma}_{jk}^{M}(\omega)]}\right) = \tan^{-1}\left(\frac{\Im[\bar{S}_{jk}^{M}(\omega)]}{\Re[\bar{S}_{jk}^{M}(\omega)]}\right) \tag{4}$$

is the smoothed phase spectrum [1].

The lagged coherency can be described as a linear transfer function (degree of linear correlation at each frequency) to which the earthquake ground motions at the two stations are related [1].

In this study, SVEGM time histories are generated using conditional and unconditional simulation techniques. The generated motions are used as input excitations at the foundation base to perform its nonlinear dynamic analysis. In the following, a brief description of two methods is provided.

3. Unconditional Simulation of SVEGM

In this study, a MATLAB code is developed for generation of unconditional SVEGM based on spectral-representation-based technique proposed by Shinozuka et al. [16]. According to applied methodology, the stationary stochastic vector process $f_j(t)$ at each station *j* can be simulated by the following series:

$$\begin{aligned} f_j(t) = 2\sum_{m=1}^{j}\sum_{l=1}^{N}\left|H_{jm}(\omega_l, t)\right|\sqrt{\Delta\omega}\,\times \\ \cos\left[\omega_l t - \theta_{jm}(\omega_l, t) + \varphi_{ml}\right] \quad j = 1, 2, 3, 4, \ldots, M \end{aligned} \tag{5}$$

where:

$$\omega_l = l\,\Delta\omega \quad l = 1, 2, \ldots, N, \quad \Delta\omega = \frac{\omega_u}{N} \tag{6}$$

$$\theta_{jk}(\omega) = \tan^{-1}\left[\frac{\mathrm{Im}\,[H_{ik}(\omega)]}{\mathrm{Re}\,[H_{ik}(\omega)]}\right] \tag{7}$$

In Equations (5) to (7), *M* is the total number of spatial stations, $H(\omega, t)$ is a lower triangular matrix obtained by Cholesky decomposition of cross spectra density matrix at every time instant *t*, φ_{ml} are sequences of random phase angles uniformly distributed over the range $[0,2\pi]$, represents an upper cut-off frequency, ω_u is the resolution in the frequency domain, *N* is the total number of frequency samples and $\mathrm{Im}\,[H_{jm}(\omega,t)]$ and $\mathrm{Re}\,[H_{jm}(\omega,t)]$ are the imaginary and real parts of the $H(\omega,t)$ respectively.

By multiplying the generated stationary time histories by appropriate envelope functions, non-stationarity can be introduced.

In this study, the incoherence effect is examined by considering Harichandran and Vanmarcke [17] coherency model. This model has the following form:

$$|\gamma(\upsilon, f)| = A\exp\left[-\frac{2\upsilon}{\alpha\theta(f)}(1-A+\alpha A)\right] + (1-A)\exp\left[-\frac{2\upsilon}{\theta(f)}(1-A+\alpha A)\right] \tag{8}$$

$$\theta(f) = k\left[1+({}^{f}\!/\!{}_{f_0})^{b}\right]^{-1/2} \tag{9}$$

In which *A*, α, *k*, ω_o and *b* are the model parameters, ξ is separation distance between two stations and *f* is frequency in Hz. The parameters of the equation assume the values: $A = 0.626$, $\alpha = 0.022$, $k = 19700$ m, $\omega_o = 12.69$ rad/sec, and $b = 3.74$.

4. Conditional Simulation of SVEGM

SIMQKE-II generates a set of spatially correlated earthquake ground motions at an arbitrary number of points. Generated ground motions are statistically compatible with, or conditioned by, recorded ground motions at nearby points. Simulated motions become increasingly similar to the recorded motions as they become more correlated, and conversely, become statistically independent as their correlation drops to zero. Using the location of the field points, the covariance matrix and the power spectral density functions, the conditional SVEGM at desired stations can be generated [18].

Figure (2) shows the SIMQKE-II procedure for simulating spatially correlated earthquake ground motions at different spatial points.

Non-stationarity is introduced in conditional simulations by the time domain segmentation technique.

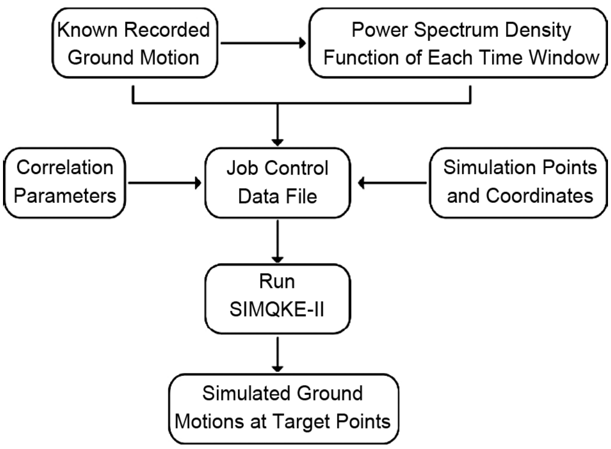

Figure 2. SIMQKE-II algorithm to simulate spatially correlated earthquake ground motions [19].

The exponentially decaying isotropic frequency-dependent spatial correlation function is used:

$$\rho(r_{ij}) = \exp\left\{-\frac{\omega|r_{ij}|}{2\pi cs}\right\} \tag{10}$$

where r_{ij} is the relative position vector, *c* is the shear wave velocity in the medium, and *s* is a scale parameter. The parameters of the equation assume the values: $c = 1100$ m/sec, $s = 5$.

5. FLAC Dynamic Numerical Modeling

In the finite difference method (FDM) based on equations that are called finite difference approximations, every calculation is performed in terms of the field variables (e.g. stress or displacement) at discrete points in space [20].

The typical stages for numerical modeling and analysis involve establishment of a finite difference grid, representing the geometry of the problem under study, choice of the materials models, and definition of the initial and boundary conditions. The model should be in static equilibrium before the dynamic excitation is applied [21].

The selected problem is a simplified representation of typical earth dams with different heights and foundation lengths. Material properties of dam body and foundation are presented in Table (1).

These dams have the same main cross section and material property with Marun earth dam as shown in Figure (3).

The size of each grid depends on the wave propagation velocity, i.e., shear wave velocity (*CS*) in the material and the frequency content of the input motion and the size of the grid (Δl) should be such that the wave transmission is accurate.

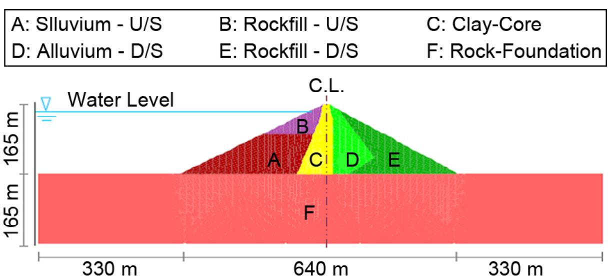

Figure 3. Dam model and material regions.

Table 1. Material properties of dam body and foundation.

Region	Material	ρ (kN/m³)	$E_0 \times 10^6$ (kN/m²)	Cohesion (kN/m²)	Friction Angle (°)	Poisson's Ratio
A	Alluvium-U/S	20.5	1.06-4.21	-	30	0.42
B	Rockfill-U/S	21.0	1.00-2.50	-	39	0.38
C	Clay-Core	21.3	0.20-1.04	38	25	0.40
D	Alluvium-D/S	20.5	1.48-3.57	-	30	0.42
E	Rockfill-D/S	21.0	0.87-2.61	-	35	0.38
A	Rock-Foundation	24.0	12.00	-	-	0.31

The boundary conditions used for the static analysis stage are fixed in the x and y directions along the base of foundation and fixed in the x direction only along the sides of the model to allow for vertical movement in the model due to loading. For the dynamic analysis stage, the sides of the model are considered as free-field boundaries and a compliant boundary are assigned to the base using a quiet boundary in FLAC.

Dynamic finite difference analyses are carried out with the aim of comparing the effect of uniform and SVEGM excitations on earth dams. Different cases considered for dynamic analyses are shown in Table (2). Conditional and unconditional simulation techniques are used to generate SVEGM. Conditional and unconditional seismic ground motions are simulated using two software SIMQKE-II and MATLAB, respectively. Number of sections for non-uniform loading area is equal to number of support motions. The distance between centers of base sections is considered as separation distance and used to generate SVEGM.

Table 2. Cases considered for dynamic analyses.

	Unconditional (MATLAB)	Conditional (SIMQKE-II)	Foundation Length (m)	Number of Sections
H=50 m	Case 1	Case 2	406	2
H=100 m	Case 3	Case 4	807.5	4
H=150 m	Case 5	Case 6	1209	6
H=200 m	Case 7	Case 8	1609	8

The simulated seismic input motions of the cases 3 and 4 can be shown in Figures (4) and (5).

The peak ground acceleration (PGA) and peak ground velocity (PGV) of simulated strong ground motions for all cases are presented in Tables (3) and (4), respectively. The highest PGA and PGV values are 6.36 m/s² and 0.49 m/s. Totally, seismic motions produced using unconditional method (MATLAB software) have larger PGA values.

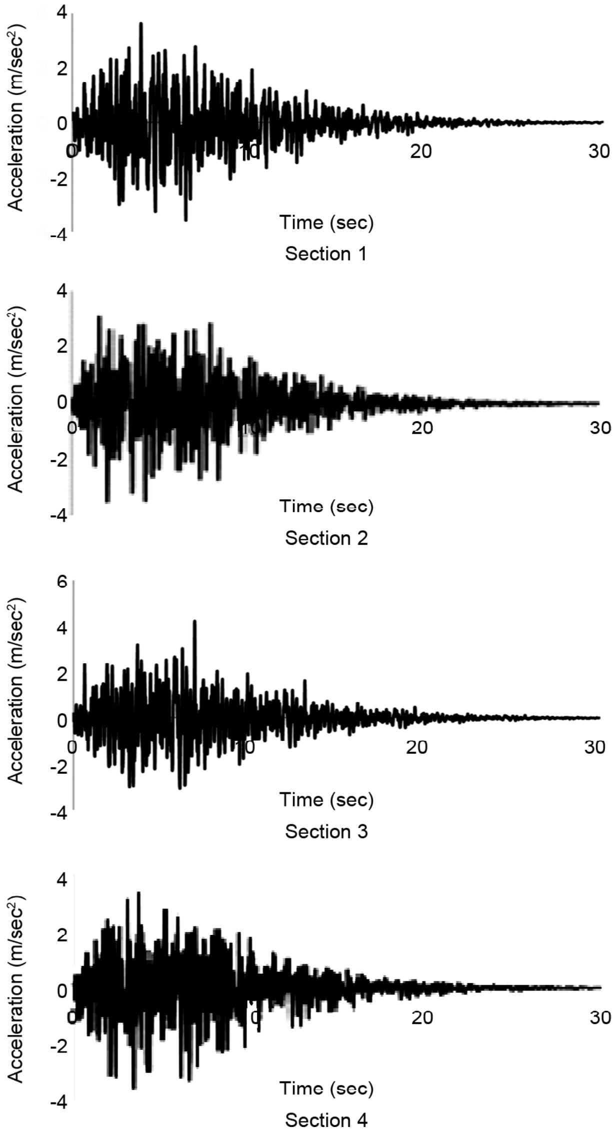

Figure 4. Simulated seismic input motions of the case 3.

6. Dynamic Analysis Results

The eight numerical models were analyzed and the obtained results were processed. The analysis results for the case 1 and case 2 for both uniform and SVEGM excitation are presented in Figure (6). These results show the variation of dam crest horizontal acceleration, horizontal and vertical displacement for crest point and finally, the variation

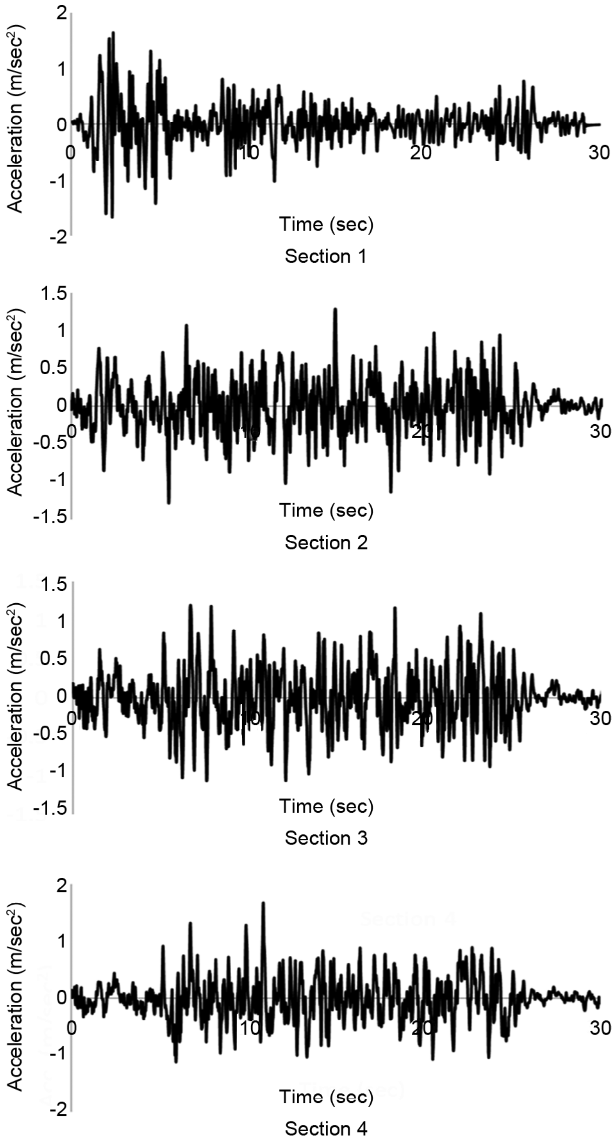

Figure 5. Simulated seismic input motions of the case 4.

Table 3. PGAs (m/sec^2) of simulated motions.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Section 1	3.09	1.68	3.65	1.68	4.16	1.68	5.68	1.68
Section 2	3.05	1.1	3.44	1.29	3.89	1.32	4.55	1.45
Section 3			4.22	1.19	4.54	1.76	6.02	1.62
Section 4			3.5	1.68	4.09	1.4	4.86	1.72
Section 5					3.94	1.61	5.07	1.58
Section 6					4.46	1.51	5.44	1.67
Section 7							5.92	1.63
Section 8							6.36	1.99

Table 4. PGVs (m/sec) of simulated motions.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Section 1	0.21	0.19	0.22	0.19	0.24	0.19	0.22	0.19
Section 2	0.19	0.19	0.19	0.27	0.2	0.33	0.23	0.33
Section 3			0.2	0.28	0.21	0.31	0.25	0.36
Section 4			0.18	0.37	0.19	0.33	0.21	0.43
Section 5					0.21	0.32	0.23	0.49
Section 6					0.23	0.31	0.23	0.47
Section 7							0.27	0.39
Section 8							0.25	0.41

of peak acceleration along the dam height.

As can be seen from Figure (6c), the dam crest horizontal displacement values in uniform and SVEGM excitations are close to each other. In case 2, uniform excitation produces almost higher horizontal displacement values compared to those obtained under SVEGM excitation (Figure 6d).

As shown in Figure (6e), it is evident that SVEGM can change drastically the vertical displacement at dam crest. Also, SVEGM results in higher vertical displacement values at dam crest than those produced by uniform excitation (Figure 6f). As can be seen from Figures (6g) and (6h), almost similar distribution of peak acceleration values is obtained along the dam height due to both types of excitations.

The results of cases 3 and 4 are shown in Figure (7). In the cases 3 and 4, uniform excitation produces higher horizontal displacement values of dam crest compared to those obtained under SVEGM excitation, as can be seen in Figures (7c) and (7d). The similar conclusion can be made for vertical displacement values at dam crest (Figure 7e). Also, from Figure (7f), SVEGM input motion results in higher vertical displacement value at dam crest at the end of excitation than that produced by uniform excitation. It can be seen from Figure (7g), that almost similar distribution of peak acceleration values are obtained along the dam height due to both types of excitations. In addition, uniform excitation produces larger values of peak acceleration along the dam height than those due to SVEGM excitation (Figure 7h).

The results of dynamic analyses for cases 5 and 6 are shown in Figure (8).

From Figure (8d), uniform input analysis produces higher values of horizontal displacement at dam crest. Also, according to Figure (8f), it can be found that, SVEGM produces larger vertical displacement values at dam crest at the end of excitation (case 6). As can be seen from Figure (8h), uniform input motion produces higher peak acceleration values than those obtained under SVEGM case (case 6).

Totally, in case 5, uniform input motion produces larger horizontal and vertical dam crest displacements and also larger peak accelerations along the dam height.

The results of dynamic analyses for cases 7 and 8 are shown in the Figure (9).

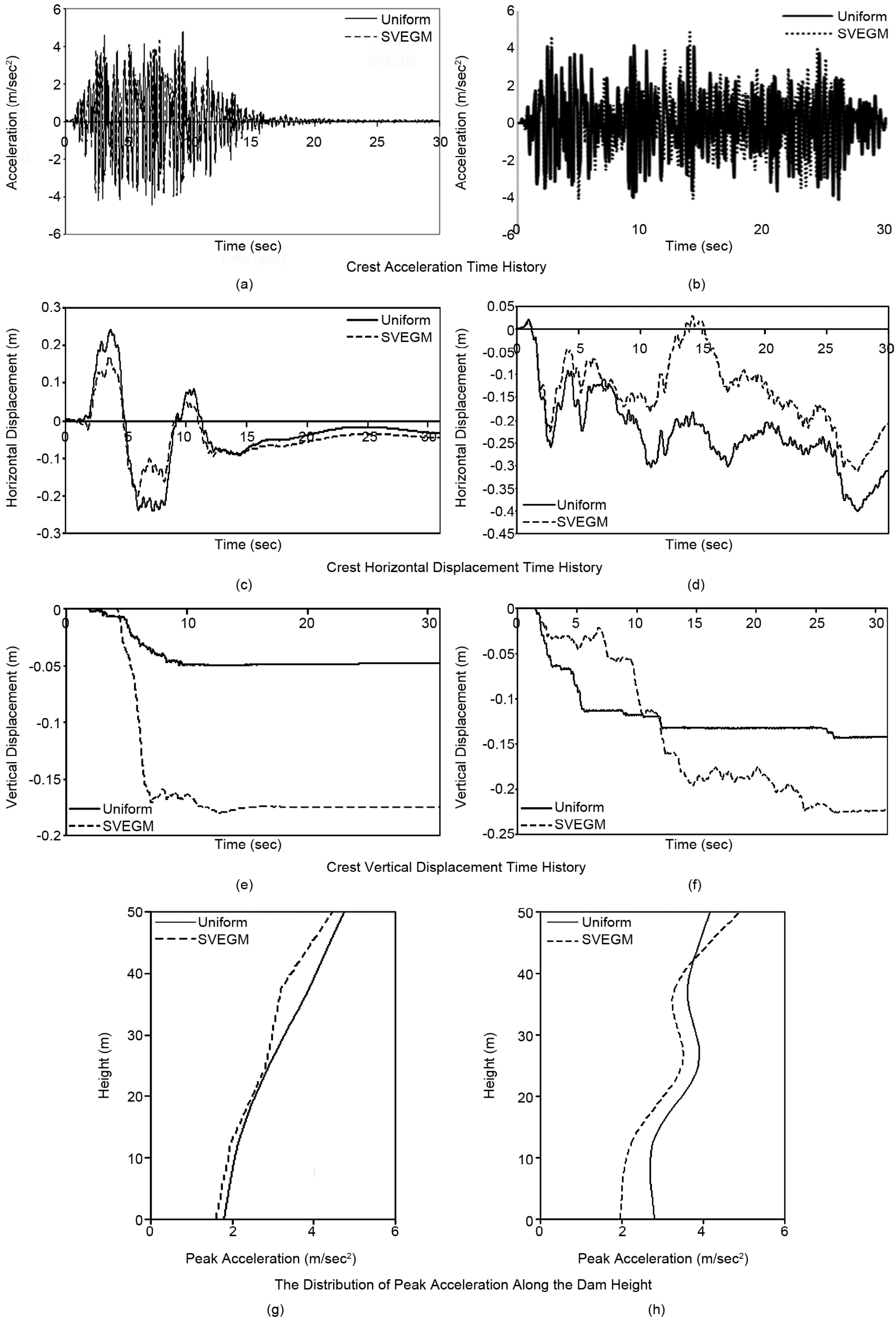

Figure 6. The analysis results of cases 1 (left side) and case 2 (right side) for uniform and SVEGM excitation.

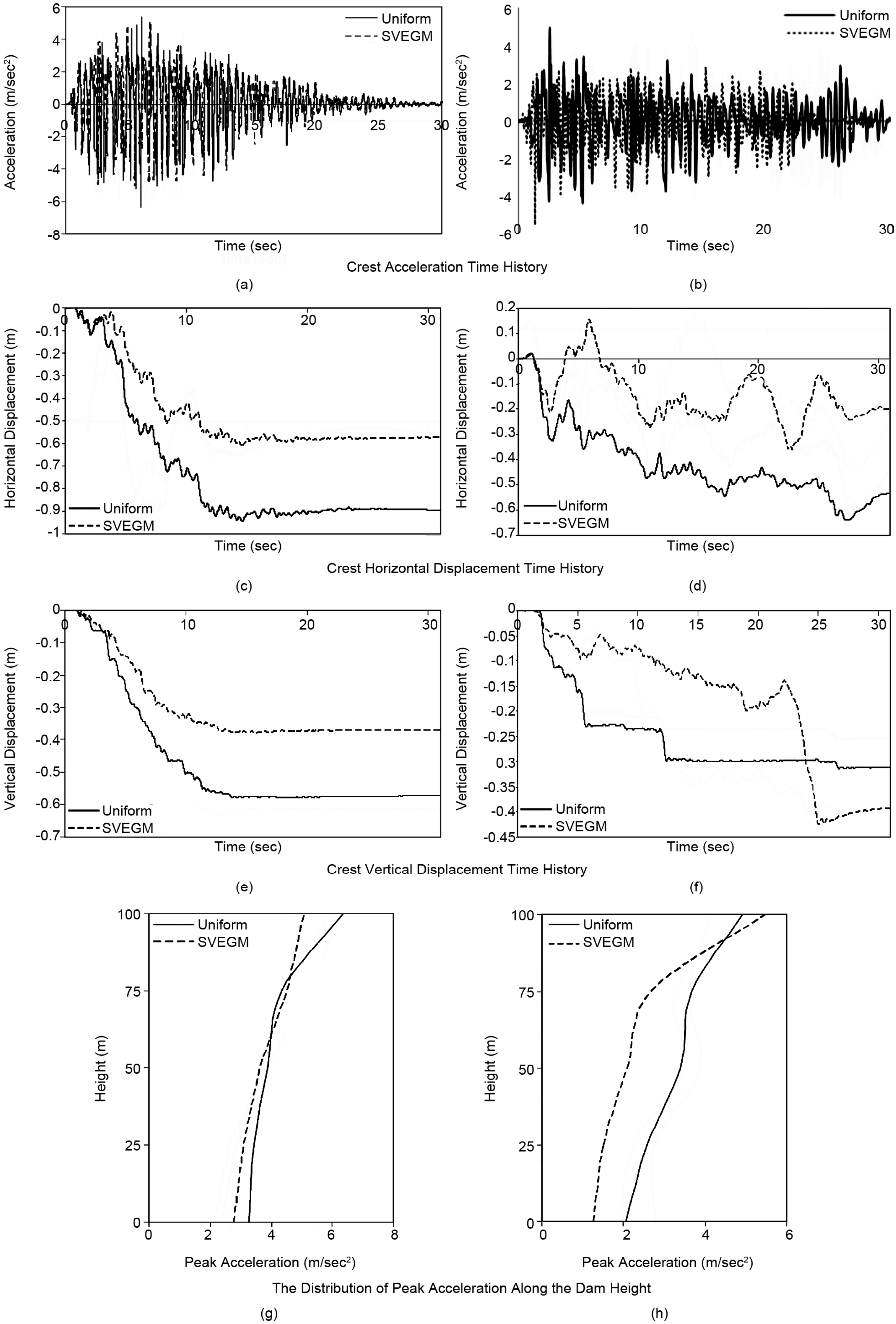

Figure 7. The analysis results of cases 3 (left side) and case 4 (right side) for uniform and SVEGM excitation.

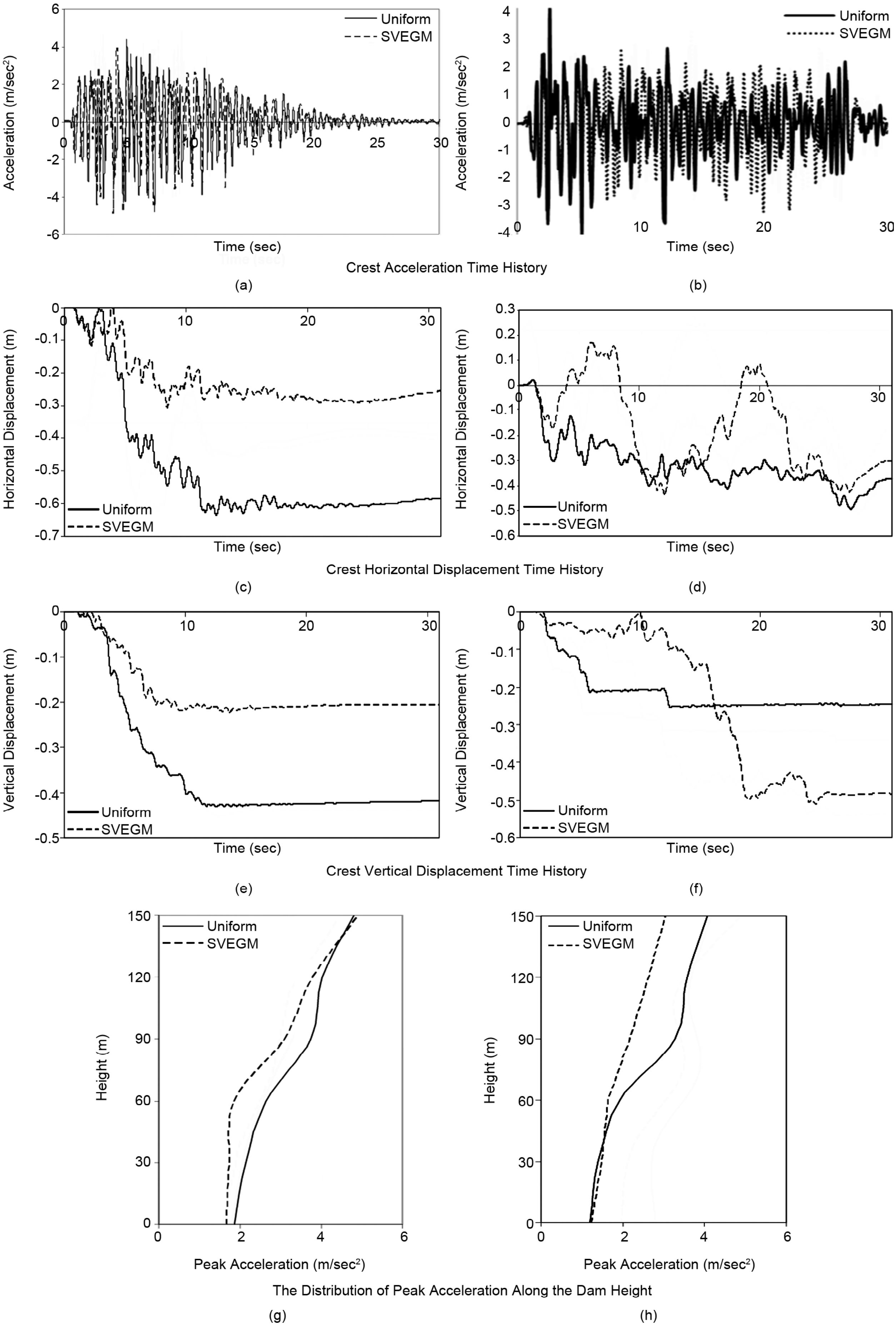

Figure 8. The analysis results of cases 5 (left side) and case 6 (right side) for uniform and SVEGM excitation.

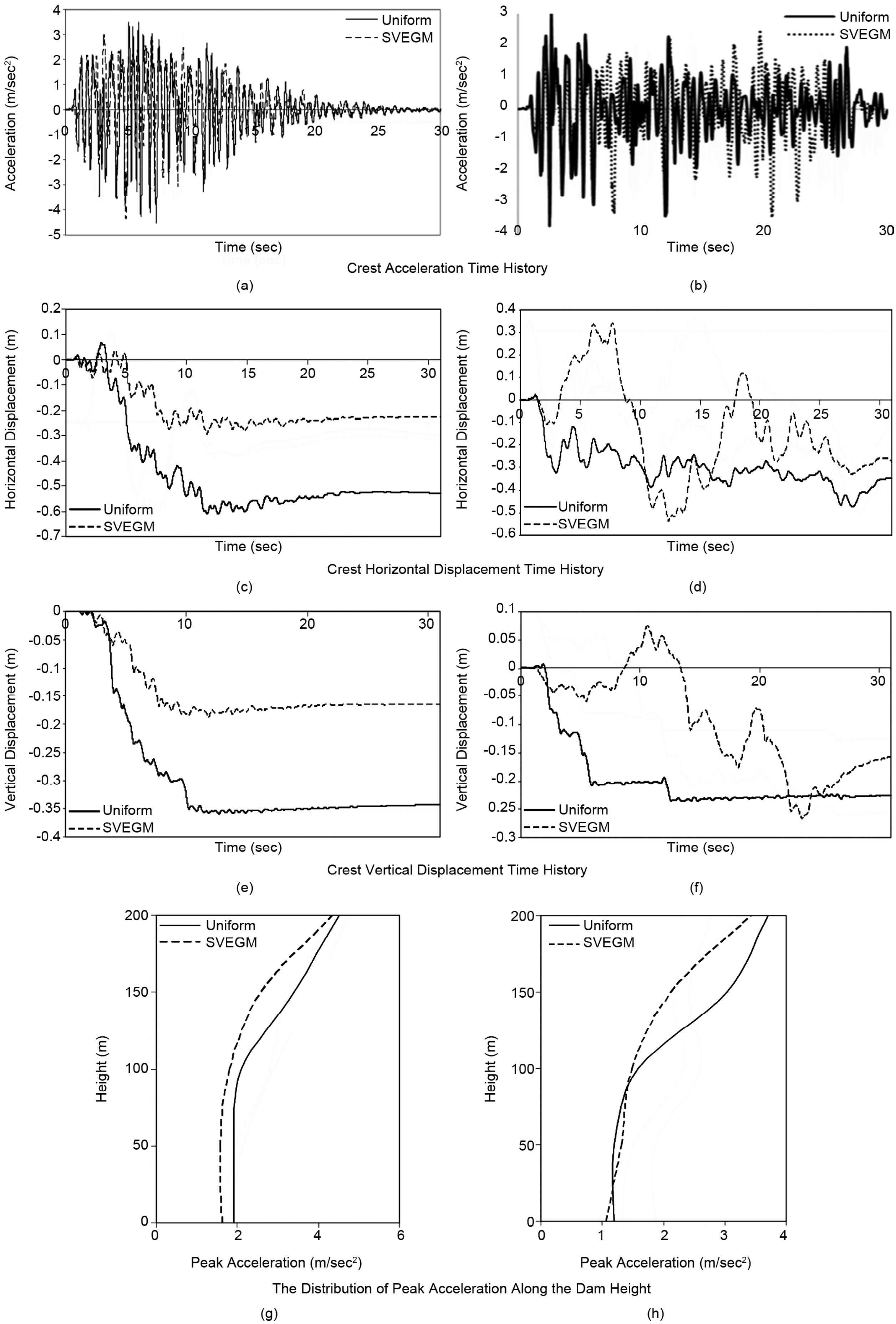

Figure 9. The analysis results of cases 7 (left side) and 8 (right side) for uniform and SVEGM excitation.

According to Figures (9c) and (9d), by applying SVEGM excitation, the dam crest horizontal displacement values of 20 cm at the end of excitation are obtained in both cases 7 and 8. Furthermore, the vertical displacement values of 15 cm due to SVEGM input motion are obtained at the end of excitation in both cases 7 and 8, at the dam crest. Also, the peak accelerations due to uniform excitation have approximately higher values than those obtained due to SVEGM excitations, in both cases 7 and 8.

Considering some delay time between the input excitation and the response of the dam body in crest level, the sudden jump in displacement values observed in Figures (6) to (9), can be attributed to sudden increase in the input motion.

7. Conclusion

The aim of this paper is to investigate the effect of SVEGM on dynamic response of earth dams. Different models of dam bodies in height and foundation length are considered for this purpose. SVEGM is generated using two different methods: conditional an unconditional simulation.

In the case of smallest dam, SVEGM cause larger values of vertical displacement. In the case of tallest dam considered, uniform excitation produces responses higher than SVEGM input motion. The SVEGM generated using conditional scheme tends to produce higher values of dam crest vertical displacement compared to corresponding uniform excitation. In all cases of the analyses, horizontal displacement of dam crest calculated using uniform input motion is higher than that obtained under SVEGM excitation. In the cases of dam with heights 50 m, 100 m and using conditional generated input motions, the values of peak acceleration due to SVEGM excitation are slightly higher than those calculated under uniform input motion.

As a general conclusion, the uniform input motions can produce higher values of dynamic responses. However, SVEGM can be significant effect on the vertical displacement of dam crest for dams with a height equal to 50 m.

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