BROADBAND GROUND MOTION SIMULATION WITHIN THE CITY OF DUZCE (TURKEY) AND BUILDING RESPONSE SIMULATION

S. KARIMZADEH[1], E. OZLU[2], A. ASKAN[3]

[1]Dept. of Civil Engineering, Middle East Technical University, Turkey, Ankara, 06800

[2]Dept. of Earthquake Studies, Middle East Technical University, Turkey, Ankara, 06800

[3]Dept. of Civil Engineering and Dept. of Earthquake Studies, Middle East Technical University, Turkey, Ankara, 06800

E-mail contact of main author: shaghkh@metu.edu.tr

Abstract. Simulated ground motions have been used for both hazard and engineering analyses recently, particularly in areas with significant seismic activity and insufficient seismic networks. From an engineering point of view, one important task is to evaluate the efficiency of the simulated records in building response estimation. In this study, a hybrid ground motion simulation framework is presented to obtain broadband ground motion time histories of potential events in Duzce (Turkey). The objective is to evaluate the efficiency of broadband ground motions for structural response simulation. The hybrid ground motion simulation framework presented herein is a combination of a discrete wavenumber finite element method for simulating low frequencies and stochastic finite fault method for the higher frequencies. The proposed technique is first validated by simulation of the 12 November 1999 Duzce earthquake (M_w= 7.1) which occurred on North Anatolian Fault Zone, Turkey. Then, spatial distribution of simulated peak ground motion intensities in terms of PGA and PGV values are obtained for the 1999 Duzce (M_w= 7.1) earthquake. In addition, ground motion intensities of the simulated records are compared against Ground Motion Prediction Equations (GMPE) derived with global and local datasets. Comparison of the results demonstrates that there is a good match between the simulated and real records. Next, to evaluate the simulated records in building response estimation, nonlinear time history analysis of a typical reinforced-concrete multi-degree-of-freedom structure is performed with both real and simulated records of the 1999 Duzce earthquake in the OpenSees platform. The results reveal that reasonable predictions can be made regarding the dynamic response of structures using the records simulated with the approach presented.

Key Words: Hybrid Ground Motion Simulation, Non-Linear Time History Analysis, Dynamic Structural Response, Multi-Degree-Of-Freedom Structures, Duzce (Turkey)

1. INTRODUCTION

Earthquakes affect urban areas with dense populations significantly. Study of ground motion records is necessary not only for understanding the earthquake mechanisms but also for damage reduction and risk mitigation. In such areas, physically-simulated ground motions are vital for both seismological and earthquake engineering purposes. Strong ground motion simulations are performed with the help of advanced mathematical and computational tools along with detailed regional seismological properties such as source and velocity models (e.g.: [1-5]).

Real earthquake records consist of broadband ground motions. In the literature, low frequency ground motions are mostly simulated with deterministic methods (e.g.: [2]; [6]) while higher frequencies are treated with stochastic approaches to account for the intrinsic stochastic character of motions at those frequency bands (e.g.: [7-9]). The entire frequency band has been accurately simulated using hybrid methods which combine deterministic and stochastic approaches for simulation of low and high frequency components, respectively (e.g.: [10-12]). Alternative ground motion simulation techniques require different computing costs and provide different levels of accuracy (e.g.: [13-16]). The main objective so far has been to investigate the efficiency of simulated motions through comparisons with the observed records from the past earthquakes. However, recently, efforts are made to evaluate simulated motions from an earthquake engineering point of view (e.g.: [14-15]; [17-18]).

In this study, first the 1999 Duzce earthquake (M_w=7.1) is simulated using a broadband ground motion simulation approach. The discrete wavenumber finite element method (e.g.: [19-20]) and stochastic finite–fault methodology with dynamic corner frequency approach [9] is used for simulating the low and high frequency parts of the ground motions, respectively. The broadband frequency is obtained by combining the low and high frequencies following the hybridization approach of Mai and Beroza [21] as implemented in Moratto et al. [22]. The simulated results at various stations are compared against the corresponding observed records in terms of ground motion time histories, Fourier Amplitude Spectra (FAS) and Response Spectra (RS) with 5% damping ratio. The broadband synthetics are also compared against the simulated motions of the same event using an only-stochastic approach [14]. Then, the spatial distribution of the simulated Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) values are obtained at nodes located around the fault plane using the hybrid simulation approach. Next, to examine the efficiency of the simulated records in earthquake engineering, building response is assessed using real and simulated motions of the 1999 Duzce event. The numerical model corresponds to a typical reinforced concrete mid-rise building in the study region. The simulation results are compared in terms of the maximum story displacement due to each horizontal component of the ground motions.

2. STUDY AREA

The study area is Duzce region which is located on North Anatolian Fault Zone (NAFZ), one of the most active fault zones in the world. The faulting mechanism is mostly right-lateral strike-slip in this region (Fig. 1). In the last century, within 3 months two major earthquakes occurred in the area. The 17 August 1999 Kocaeli (M_w=7.4) and the 12 November 1999 (M_w=7.1) Duzce earthquakes caused major structural loss leading to a large number of fatalities. In a previous study by Karimzadeh et al. [14], an only-stochastic approach is used to simulate the ground motions of this event at 5 stations. Even though there are 5 stations within 50 km Joyner and Boore distance (RJB) distance that recorded the mainshock, due to lack of detailed velocity models, in this study only 4 of these stations are studied in detail with the broadband simulation approach. Table 1 presents information on the strong ground motion stations and the corresponding observed records. The raw acceleration-time histories of the selected three stations are taken from strong ground motion database of Turkey [23]. In this study, the velocity models presented in Asten et al. [24] are used in simulations at all stations.

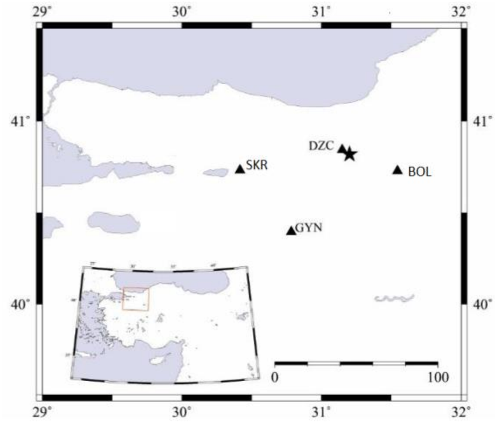

FIG. 1 Map showing the epicenter of the 1999 Duzce Earthquake with the locations of the stations

TABLE 1: RECORDED STRONG GROUND MOTION STATION INFORMATION CORRESPONDING TO THE 1999 DUZCE EARTHQUAKE

Station Name	Code	Latitude °N	Longitude °E	Site Class	R_{EPI} (km)	R_{JB} (km)	PGA EW (cm/s²)	PGA NS (cm/s²)	PGV EW (cm/s)	PGV NS (cm/s)
Bolu	BOL	40.7457	31.6073	D	39.026	46.009	805.88	739.51	66.61	57.78
Düzce	DZC	40.8436	31.1489	D	9.314	6.309	513.78	407.69	90.78	66.47
Göynük	GYN	40.3966	30.7831	D	55.163	66.031	24.82	27.89	8.68	9.84
Sakarya	SKR	40.7371	30.3801	C	64.518	91.505	24.72	17.33	5.17	4.81

3. GROUND MOTION SIMULATION METHODOLOGY

For low frequency simulations, the Discrete Wavenumber Finite Element (DWFE) method as introduced by Olson [6] is used to evaluate the representation theorem integrals on a fault surface. This method employs finite element method to solve the elastic equations for horizontal seismic wavefield while it uses finite differences to obtain numerical solutions for vertical wavefield and time dependence. In this study for simulating the low frequencies, COMPSYN program is used: This approach involves the numerical algorithms by Spudich and Archuleta [25] and it is able to simulate the complete response of the Earth including P and S waves as well as surface waves. The Earth is defined within a three-dimensional Cartesian space where the structure is a function of one dimension (along the depth). As the main input, COMPSYN employs detailed source parameters including the hypocenter, fault mechanism, seismic moment, and slip model on the fault plane. The parameters for the velocity model include the layer thicknesses, corresponding P and S wave velocities and density.

For simulating the high frequency portion of ground motions, stochastic finite-fault method based on a dynamic corner frequency approach is used as implemented in EXSIM program [9]. In this technique, the rectangular fault plane is divided into smaller subfaults. Each subfault is considered as a stochastic point source. In this model, it is assumed that the rupture starts to spread radially from the hypocenter. The ground acceleration is obtained by summing the contributions of all subfault accelerations with kinematic time delays. As input, regional source, path and site parameters are employed.

In this study, the broadband ground motions are obtained by combining the low and high frequencies following the hybridization approach of Mai and Beroza [21] as implemented in Moratto et al. [22]. The Fourier amplitude spectra of low and high frequency seismograms are combined in the frequency domain as follows:

$$A(f) = A^{LF}(f) \cdot W^{LF}(f) + A^{HF}(f) \cdot W^{HF}(f) \quad (1)$$

where $\mathrm{A(f)}$ is the broadband spectrum, $\mathrm{A^{LF}(f)}$ is the low frequency spectrum and $\mathrm{A^{HF}(f)}$ is the high frequency spectrum. $\mathrm{W^{LF}(f)}$ and $\mathrm{W^{HF}(f)}$ are the smoothed frequency-dependent weighing functions for the low and high frequencies, respectively.

3.1 Results of Ground Motion Simulation in the Study Area

The broadband simulations of the 1999 Duzce earthquake are performed at 4 selected stations (DZC, BOL, SKR and GYN) within a Joyner and Boore distances (R_{JB}) less than 50 km. Detailed information on the earthquake and the corresponding simulation parameters are given in Table 2. For simulating the high frequencies, the validated parameters by Ugurhan and Askan [26] are used with the modifications of Karimzadeh et al. [14]. The deterministic calculations are done up to frequencies that could be resolved with 8 finite elements per minimum wavelength. Beyond those frequencies, results of stochastic simulations are employed.

Fig. 2 demonstrates the horizontal components of the observed and simulated acceleration time histories at selected stations. Fig. 3 shows the corresponding FAS and 5% damped elastic Pseudo-Response Spectra (PSA) at each station. It is observed that the estimated PGA at BOL Station from broadband simulation is almost equal to NS direction, while it is ½ times of the real result in EW direction (Fig. 2). In Fig. 2, the real and simulated FAS match in NS direction is better than EW direction at BOL Station. Observed and simulated amplitudes match closely at higher frequencies. At Station DZC, the results of only stochastic method are used, since the station is very close to hypocenter of the earthquake which causes unrealistic results by the deterministic approach as expressed in Spudich and Xu [27]. At DZC, the results reveal that estimated PGA from stochastic method is close to observed PGA in NS direction (Fig. 2). At GYN station, the simulated results match the observed values with slight discrepancies which may be attributed to source or site effects that could not be modeled accurately (Fig. 3). At the SKR station, both EW and NS components are simulated effectively in the high frequency range. However, simulated amplitudes in lower frequencies are observed to have major discrepancies from the corresponding observed values. This could be explained with the long period surface waves in the basin that could not be modeled accurately.

TABLE 2: SIMULATION PARAMETERS OF THE 1999 DUZCE (TURKEY) EARTHQUAKE

Moment Magnitude		7.1	
Fault Orientation		Strike: 264° Dip: 64°	
Fault Dimensions		North Anatolian Fault (NAF) - 65 km × 25 km	
East end Coordinate of the Fault		40.93°N - 31.49°E	
West end Coordinate of the Fault		40.71°N - 30.91°E	
Epicenter		40.82°N - 31.20°E	
Specific Parameters of Deterministic Ground Motion Simulations		**Specific Parameters of Stochastic Ground Motion Simulations**	
Soil Profiles at 4 Stations BOL, DZC, GYN and SKR	Asten et. al. [24]	Stress Drop	100 bars
		Pulsing Area Percentage	30%
Subfault Dimensions	5 km × 5 km	Duration Model	$T = T_0 + 0.05$
Crustal Shear Wave Velocity (β)	3700 m/s	Quality Factor	$Q = 88f^{0.9}$
Rupture Velocity	0.8 β	Geometrical Spreading	R^{-1} $R \leq 30$km $R^{-0.4}$ $30 < R \leq 60$km $R^{-0.6}$ $60 < R \leq 90$km $R^{-0.8}$ $90 < R \leq 100$km $R^{-0.5}$ $R > 30$km
Crustal Density	2800 kg/m³	Windowing Function	Saragoni - Hart
		Kappa Factor	Regional Kappa Model (0.047)
Slip Distribution	Yagi and Kikuchi [28]	Site Amplification Factors	H/V ratios and NEHRP D Amp. F. [29]

In this study, to evaluate the simulations quantitatively, misfits are calculated between simulated and real records in terms of FAS and RS as given in Eqs. 2 and 3 [14]:

$$Misfit_{FAS} = \frac{1}{n_f}\sum_{f=1}^{n_f}\left|log\frac{FAS_{syn}(f)}{FAS_{real}(f)}\right| \tag{2}$$

$$Misfit_{RS} = \frac{1}{n_T}\sum_{T=1}^{n_T}\left|log\frac{RS_{syn}(T)}{RS_{real}(T)}\right| \tag{3}$$

where n_f and n_T are the total number of discrete frequencies and periods in the selected frequency/period-band. $FAS_{syn}(f)$ and $FAS_{real}(f)$ correspond to the simulated and observed Fourier amplitude at frequency f, respectively. $RS_{syn}(T)$ and $RS_{real}(T)$ correspond to the simulated and observed response spectral amplitude at period T, respectively. The results of misfits in terms of FAS and RS for all stations are provided in Tables 3 and 4, respectively. Broadband simulations provide smaller FAS misfits when compared to only-stochastic method [16]. A similar observation is valid for the RS misfits.

The other types of misfits are in terms of PGA and PGV as given in Eqs. 4 and 5, respectively [14]:

$$Misfit_{PGA} = \left|\frac{PGA_{syn}}{PGA_{real}}\right| - 1 \tag{4}$$

$$Misfit_{PGV} = \left|\frac{PGV_{syn}}{PGV_{real}}\right| - 1 \tag{5}$$

where PGA_{syn} and PGA_{real} are the simulated and real PGA values, while PGV_{syn} and PGV_{real} are the simulated and real PGV values. The misfits in terms of PGA and PGV are given in Table 5.

Table 6 compares the simulated ground motion intensities against the corresponding values estimated by Ground Motion Prediction Equations (GMPEs) of Akkar & Cagnan [30] (AC10) and Boore & Atkinson [31] (BA08). It is observed that the simulated values are mostly consistent with the empirical ones except for BOL station.

TABLE 3: FAS MISFITS OF REAL AND SIMULATED RECORDS FOR EAST-WEST (EW) AND NORTH-SOUTH (NS) COMPONENTS

$\mathrm{MISFIT}_{\mathrm{FAS}}$	**EW COMPONENT**	**NS COMPONENT**
STATIONS	**0 Hz - 10 Hz**	**0 Hz - 10 Hz**
BOL	0.3753	0.4125
DZC	0.4205	0.3844
GYN	0.3923	0.4096
SKR	0.3918	0.4752

TABLE 4: RS MISFITS OF REAL AND SIMULATED RECORDS FOR EAST-WEST (EW) AND NORTH-SOUTH (NS) COMPONENTS

$\mathrm{MISFIT}_{\mathrm{RS}}$	**EW COMPONENT**		**NS COMPONENT**	
STATIONS	**Broadband Simulation Misfit**	**Stochastic Method Misfit**	**Broadband Simulation Misfit**	**Stochastic Method Misfit**
	0 - 4 sec	**0 - 4 sec**	**0 - 4 sec**	**0 - 4 sec**
BOL	0.2719	0.5630	0.1644	0.6251
DZC	0.1768		0.1721	
GYN	0.3852	0.2802	0.3144	0.3096
SKR	0.1640	0.7343	0.3756	0.7623

TABLE 5: PGA AND PGV MISFITS OF REAL AND SIMULATED RECORDS FOR EAST-WEST (EW) AND NORTH-SOUTH (NS) COMPONENTS

Station Name	**Code**	**$\mathrm{Misfit}_{\mathrm{PGA}}$**		**$\mathrm{Misfit}_{\mathrm{PGV}}$**	
		EW	**NS**	**EW**	**NS**
Bolu	BOL	-0.52	-0.16	-0.39	0.05
Düzce	DZC	-0.28		-0.10	
Göynük	GYN	3.04	2.73	0.42	-0.05
Sakarya	SKR	1.31	1.82	-0.17	-0.43

TABLE 6: COMPARISON OF SIMULATED PEAK AMPLITUDES WITH EMPIRICAL ESTIMATES FROM GMPE'S

Stations	PGA (cm/s^2)				PGV (cm/s)			
	Simulated EW	Simulated NS	Estimated using BA08	Estimated using AC10	Simulated EW	Simulated NS	Estimated using BA08	Estimated using AC10
BOL	384.19	620.59	114.72	51.92	40.71	60.74	10.70	7.69
DZC	332.32		320.72	281.15	70.69		37.47	27.44
GYN	100.19	104.02	81.39	35.01	12.33	9.36	8.08	5.87
SKR	52.44	48.89	54.32	24.22	4.27	2.76	6.08	4.57

Next, ground motion simulations are performed for the 1999 Duzce event (M_w=7.1) at selected nodes located within a region bounded by 40°- 41° latitudes and 30.6°- 32° longitudes with a regular grid spacing of 0.2°. To perform simulations at nodes where velocity profiles are not available, the velocity model from Asten et al. [24] at the closest possible site is used. Spatial distribution of simulated PGA and PGV values in both directions are plotted in Fig. 4. Results reveal that maximum peak ground motion values in both directions are observed at nodes located in close vicinity of the fault plane with softer soil conditions.

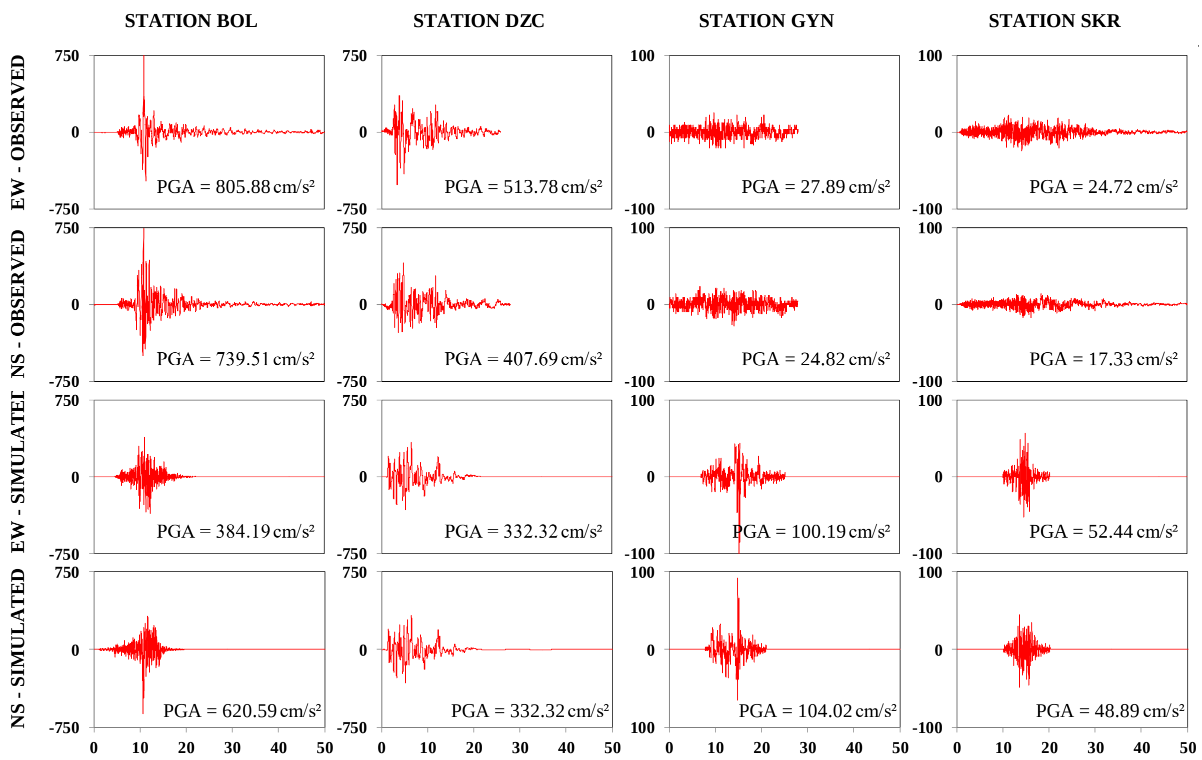

FIG. 2 Observed and simulated accelerograms with EW and NS components for four stations

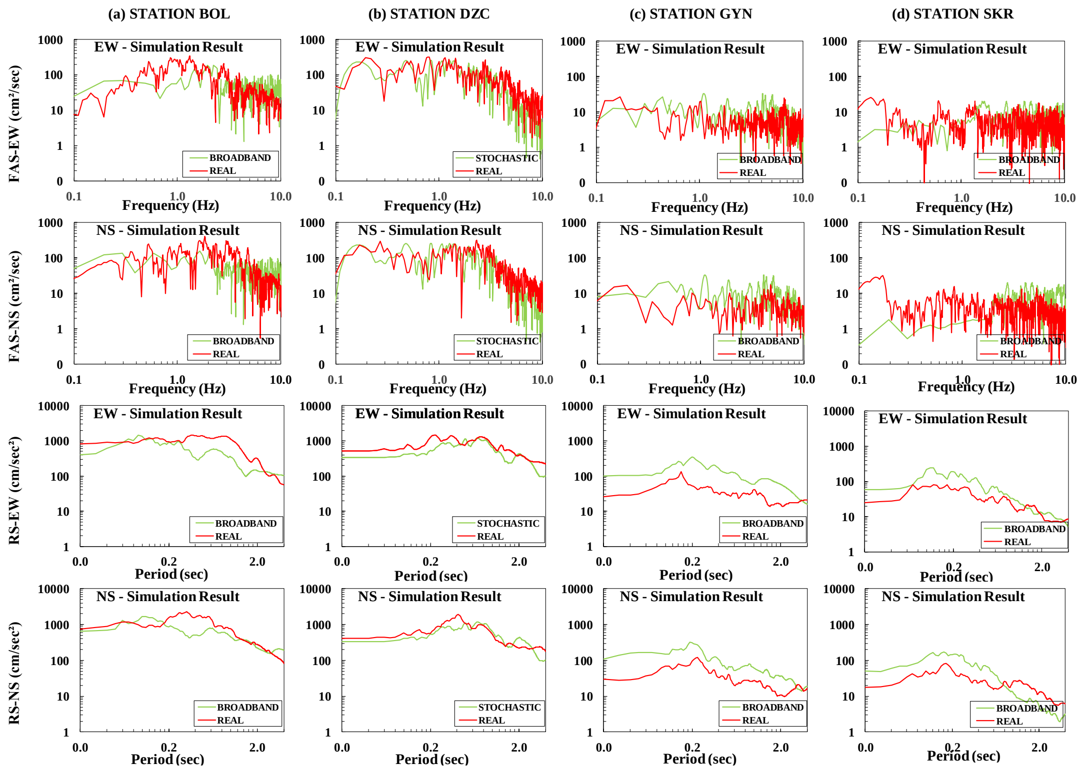

FIG. 3 Comparison of real and simulated FAS and RS with 5% damping at stations (a) BOL, (b) DZC, (c) GYN and (d) SKR for EW and NS components

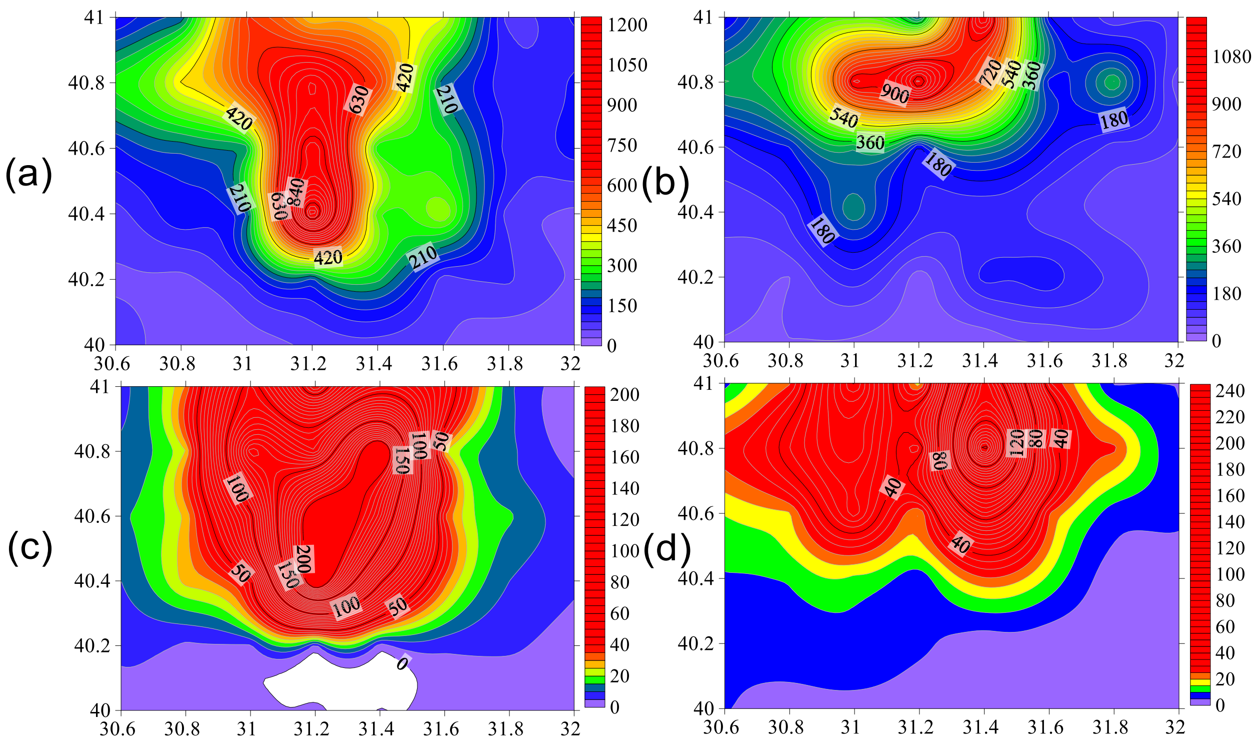

FIG. 4 Spatial distribution of simulated (a) PGA (cm/s2) in EW direction, (b) PGA (cm/s2) in NS direction, (c) PGV (cm/s) in EW direction and (d) PGV (cm/s) in NS direction for the 1999 Duzce event (M_w=7.1)

3.2 Building Response Simulations

In this part, efficiency of simulations are evaluated in terms of nonlinear responses of a building structure due to the real and the corresponding simulated records of the 1999 Duzce event. For this purpose, Nonlinear Time History Analysis (NLTHA) is carried out using OpenSees platform which employs finite element method. The selected building is a reinforced concrete frame selected from the Duzce damage database with 4 stories (3m storey height), 3 bays (5m bay width) and fundamental period of 0.49 seconds. Further details corresponding to the selected frame can be found in Karimzadeh et al. [14]. The maximum storey displacements computed from both the real and simulated records are presented in Table 7. Results reveal that structural responses estimated from simulated ground motions closely match with those from real ones at most stations. At GYN station however, the real and simulated structural responses are different which is believed to arise from the discrepancies between the real and simulated FAS. At DZC station, the geometric mean of the simulated responses at both directions is in good match with the real responses. Finally, it is observed that when the simulated records are acceptable seismologically (for instance: smaller misfits are obtained in terms of FAS as shown in Table 7, the simulated structural responses are also satisfactory

TABLE 7: MAXIMUM STOREY DISPLACEMENTS FROM REAL AND SIMULATED RECORDS AT ALL STATIONS

		EW DIRECTION			NS DIRECTION			GEOMETRIC MEAN		
	Storeys	**Real Storey Displacement (mm)**	**Synthetic Storey Displacement (mm)**	**Synthetic / Real Ratio**	**Real Storey Displacement (mm)**	**Synthetic Storey Displacement (mm)**	**Synthetic / Real Ratio**	**Real Storey Displacement (mm)**	**Synthetic Storey Displacement (mm)**	**Synthetic / Real Ratio**
Station BOL	Storey 1	18.49 mm	17.02 mm	0.92	21.43 mm	64.48 mm	3.01	19.90 mm	33.12 mm	1.66
	Storey 2	39.01 mm	52.67 mm	1.35	39.33 mm	117.53 mm	2.99	39.17 mm	78.68 mm	2.01
	Storey 3	53.06 mm	66.64 mm	1.26	48.15 mm	148.40 mm	3.08	50.55 mm	99.44 mm	1.97
	Storey 4	60.46 mm	73.99 mm	1.22	52.55 mm	161.57 mm	3.07	56.37 mm	109.34 mm	1.94
Station DZC	Storey 1	105.31 mm	59.81 mm	0.57	22.63 mm	59.81 mm	2.64	48.82 mm	59.81 mm	1.23
	Storey 2	190.50 mm	108.57 mm	0.57	42.89 mm	108.57 mm	2.53	90.39 mm	108.57 mm	1.20
	Storey 3	243.44 mm	139.34 mm	0.57	61.06 mm	139.34 mm	2.28	121.92 mm	139.34 mm	1.14
	Storey 4	270.43 mm	153.61 mm	0.57	71.03 mm	153.61 mm	2.16	138.59 mm	153.61 mm	1.11
Station GYN	Storey 1	1.20 mm	4.26 mm	3.55	1.13 mm	2.86 mm	2.53	1.17 mm	3.49 mm	3.00
	Storey 2	2.48 mm	8.87 mm	3.57	2.39 mm	5.94 mm	2.49	2.43 mm	7.26 mm	2.98
	Storey 3	3.53 mm	12.55 mm	3.55	3.48 mm	8.23 mm	2.37	3.50 mm	10.16 mm	2.90
	Storey 4	4.18 mm	14.71 mm	3.52	4.17 mm	9.49 mm	2.27	4.18 mm	11.81 mm	2.83
Station SKR	Storey 1	1.06 mm	2.66 mm	2.50	0.96 mm	1.22 mm	1.28	1.01 mm	1.80 mm	1.79
	Storey 2	2.24 mm	5.54 mm	2.48	2.04 mm	2.67 mm	1.31	2.13 mm	3.85 mm	1.80
	Storey 3	3.22 mm	7.79 mm	2.42	3.01 mm	4.08 mm	1.36	3.11 mm	5.64 mm	1.81
	Storey 4	3.82 mm	9.05 mm	2.37	3.61 mm	5.08 mm	1.41	3.71 mm	6.78 mm	1.83

4. CONCLUSION

The main objective of this study is to simulate the ground motions of the 1999 Duzce (M_w=7.1) earthquake using a broadband simulation approach where discrete wavenumber finite element and the stochastic finite-fault methods are used to simulate the low and high frequencies, respectively. A total of four stations (DZC, BOL, GYN, and SKR) are selected within a Joyner and Boore distance less than 50 km. To evaluate the simulated motions, both seismological and structural measures are used. Real and simulated ground motions are first compared in terms of FAS, RS, PGA and PGV misfits. The results from the broadband approach are then compared to the results from a previous study that employed only the stochastic method for the entire frequency band. The simulated peak ground motion values are also compared against the existing local and global GMPE's for verification purposes. Next, the spatial distribution of the simulated PGA and PGV values are obtained within the selected study area. Finally, the efficiency of the simulated motions is evaluated in terms of nonlinear dynamic structural responses against the real values for a typical RC frame.

The following conclusions can be drawn from the numerical results presented in this study:

- It is observed that the simulated records obtained with the hybrid methodology match the real records more closely compared to the stochastically-generated synthetics for the entire frequency band. Smaller values in terms of all seismological misfits including FAS, RS, PGA, and PGV are obtained with the hybrid methodology.
- For the very near-field stations, deterministic approach cannot effectively simulate the ground motions (e.g.: Station DZC)
- A close match in between the simulated peak values and the corresponding values obtained from the GMPE's reveals the use of a physically reasonable source, propagation and site modelling despite the existing uncertainties.
- For the selected RC building, results of dynamic analyses based on broadband simulated motions closely match the real structural responses. The responses obtained from the broadband approach provide better fits to the real responses than those obtained from only-stochastic approach.
- The numerical results obtained in this study suggest that the use of simulated broadband ground motions for earthquake engineering purposes is promising.

Finally, the approach presented herein should be further evaluated through simulation of different past earthquakes and study of other building types.

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