Spatially Varying Ground Motion Effects on Seismic Response of Adjacent Structures Considering Soil-Structure Interaction

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Abstract: Spatial variation of seismic ground motions is caused by incoherence effect, wave passage, and local site conditions. This study focuses on the effects of spatial variation of earthquake ground motion on the responses of adjacent reinforced concrete (RC) frame structures. The adjacent buildings are modeled considering soil-structure interaction (SSI) so that the buildings can be interacted with each other under uniform and non-uniform ground motions. Three different site classes are used to model the soil layers of SSI system. Based on fast Fourier transformation (FFT), spatially correlated non-uniform ground motions are generated compatible with known power spectrum density function (PSDF) at different locations. Numerical analyses are carried out to investigate the displacement responses and the absolute maximum base shear forces of adjacent structures subjected to spatially varying ground motions. The results are presented in terms of related parameters affecting the structural response using three different types of soil site classes. The responses of adjacent structures have changed remarkably due to spatial variation of ground motions. The effect can be significant on rock site rather than clay site.

Key words: adjacent buildings, spatial ground motions, seismic response, soil-structure interaction, power spectrum density function.

1. INTRODUCTION

The seismic ground motion excitations at supports of the structures are assumed to be uniform in current earthquake-resistant design of structures. However, the implementation of uniform motions at the supports of extended lifeline systems can yield inaccurate responses. Thus, spatially variable seismic ground motions should be considered in seismic response analysis and design of structures (Liao 2006). The seismic response of structures under spatially varying ground motions is the combination of a dynamic component and a pseudostatic component (Konakli and Der Kiureghain 2011). The dynamic response is obtained from the dynamic inertia forces of the ground acceleration at supports. Beside this, the static component of the structures is induced at each time interval to the different support displacements by spatially varying ground motions. The static component of structure is zero under uniform ground motion. Three main causes of spatial variation of ground motions are: wave passage effect (seismic waves arrive at different times at different stations); incoherence effect (differences in the manner of superposition of waves); site effect (local soil conditions) (Harichandran 1999; Hao *et al*. 1989). The results of past analyses reported in the literature indicate that the effect of the spatial variation of earthquake ground motions on the response of bridges cannot be neglected (Saxena *et al*. 2000; Chouw and Hao 2005, 2008). The seismic response of extended structures subjected to spatially varying ground motions were studied extensively by a number of researchers using various

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methods (e.g. random vibration method, response spectrum methods, time- history analyses) (Saxena *et al.* 2000; Lou and Zerva 2005; Hao 1998).

From last few decades, seismic pounding damage has been noticed of adjacent structures in all the severe earthquakes. Damage statistic analysis results have shown that pounding occurred in over 40 percent of the 330 collapsed or severely damaged buildings during the 1985 Mexico (Rosenblueth and Meli 1986). Adjacent structures can be experienced with out-of-phase response during any strong earthquake event because of differences in the dynamic properties of spatially varying earthquake. Several past researches focused on the ground motion spatial variation effects on extended structures like bridges (Hao *et al.* 1989; Nakamura *et al.* 1993; Harichandran *et al.* 1996; Chouw and Hao 2005 2008; Bi *et al.* 2011). But a very few studies have been conducted in case of adjacent structures. Hao and Liu (1998) investigated the influence of spatially varying ground motions on the separation distance of adjacent frame structures. The study concluded that the spatial variation of ground motion effects needs to be considered for low-rise adjacent buildings. A parametric study was conducted by Hao and Zhang (1999) to examine the ground motion spatial variation effects on the relative displacement of adjacent structures. Another study conducted by Behnamfar and Sugimura (1999) have shown the comparison between two numerical methods (deterministic approach and random approach) on the dynamic response of adjacent structures subjected to spatially varying ground motions.

The before works related to seismic response of adjacent structures under spatially varying ground motions neglected the effects of different soil sites and interaction between the adjacent structures. In this work, parametric studies are carried out to evaluate the influence of spatially varying ground motions on the seismic response of the adjacent structures. The recorded known ground motion and artificially generated spatially varying ground motions are used as uniform and non-uniform earthquake inputs. The local soil site conditions effect has been taken into account to evaluate the SSI influence on the seismic analysis results. Furthermore, the interaction between adjacent structures is analyzed to investigate its effect on the structural responses. The conclusions are made based on the structural displacement responses and base shear forces of adjacent structures under three different site classes.

2. GROUND MOTIONS SIMULATION

In this study, spatially correlated non-uniform ground motions are generated compatible with known power spectrum density function at different locations based on the FFT. Computer program Simqke-II (Vanmarcke *et al.* 1999) has been used to perform conditional simulation of earthquake ground motion. The known ground motion, the PSDF of known recorded motions, frequency dependent spatial correlation function and location of the generated motions are the basic input to generate artificial ground motions at selected different points. Figure 1 shows the conditional ground motion simulation technique with Simqke-II software.

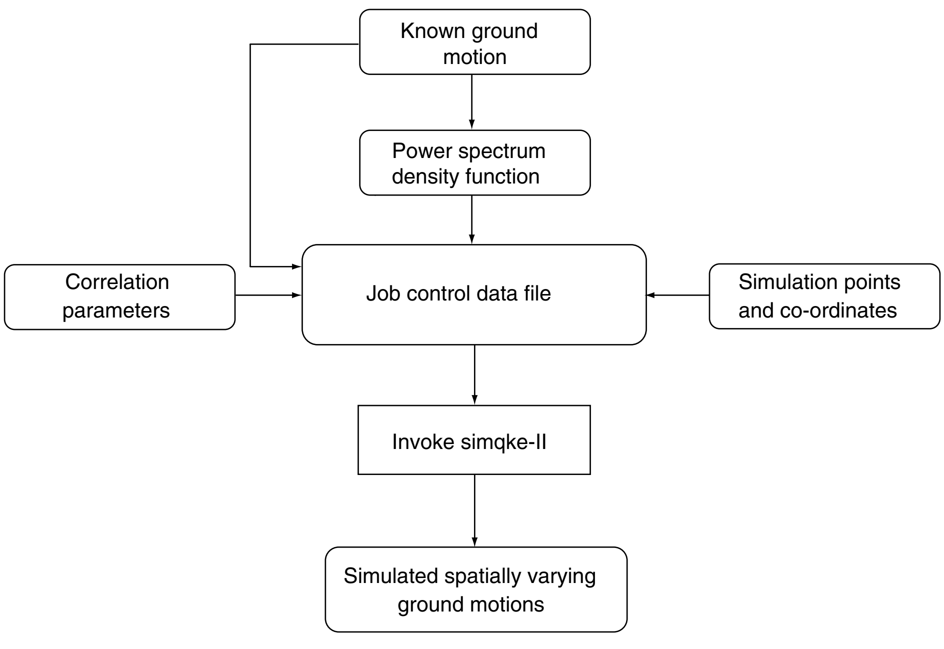


Figure 1. Ground motion simulation process by Simqke-II

2.1. Coherency Model

The model for frequency-dependent spatial correlation function of ground motions was proposed by Harichandran and Vanmarcke (1986). The spatial correlation function used in this work is as follows:

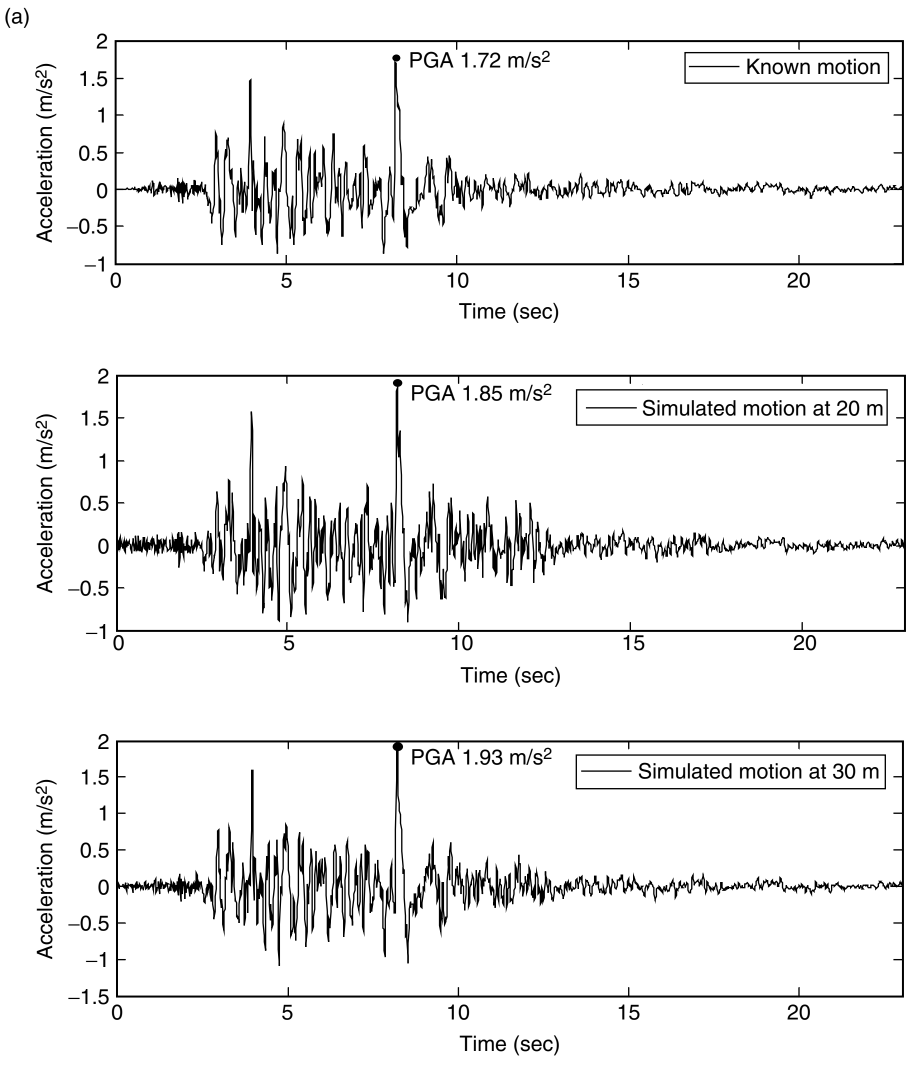
$$\rho_{\omega k}(r_{ij}) = \exp\{\frac{-\omega k\left|r_{ij}\right|}{2\pi cs}\} \tag{1}$$

where, ω is frequency, k is empirical constant, r_{ij} is the relative position vector between two points i and j, c is the shear wave velocity of the medium, and s is the distance-scale parameter. Here, we have assumed distance scale $s = 5$ based on previous study (Vanmarcke *et al*. 1993).

2.2. Artificial Generation of Ground Motions

The 1994 Northridge earthquake from PEER strong motion database record is considered as a recorded known ground acceleration time history and used to generate non-uniform ground motions. The instrumental array was installed on rock site at station 90017 LA - Wonderland Ave. The known and simulated ground motion time histories at target points and corresponding response spectrum plots are shown in Figures 2 and 3 for rock site. Spatially correlated ground motions are also generated for different site classification according to ASCE /SEI 7-10 code. It is assumed that the earthquake wave propagated from left end of soil layers to right end in longitudinal direction. Figure 4 shows the power spectra comparison of simulated motions at different classes of soil site. The peak estimated power spectra for rock site is maximum comparing to others.

The known and generated acceleration time histories are double integrated to get the displacement time histories [as shown in Figure 2(b)]. Then these displacement time histories are used as input of multi-support input motions



(Figure 2 Continued)

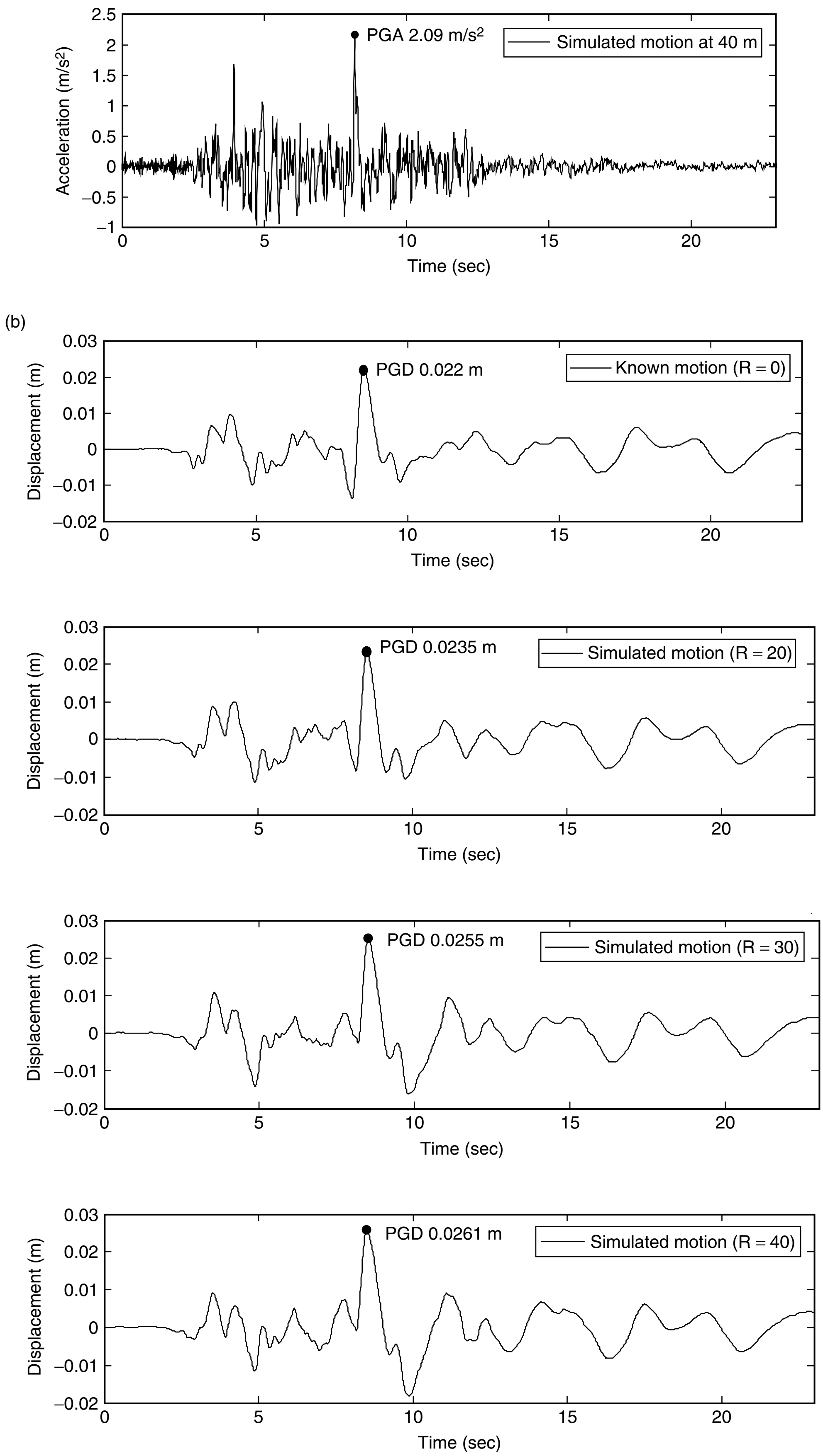


Figure 2. Known and generated ground motion time histories: (a) acceleration; (b) displacement

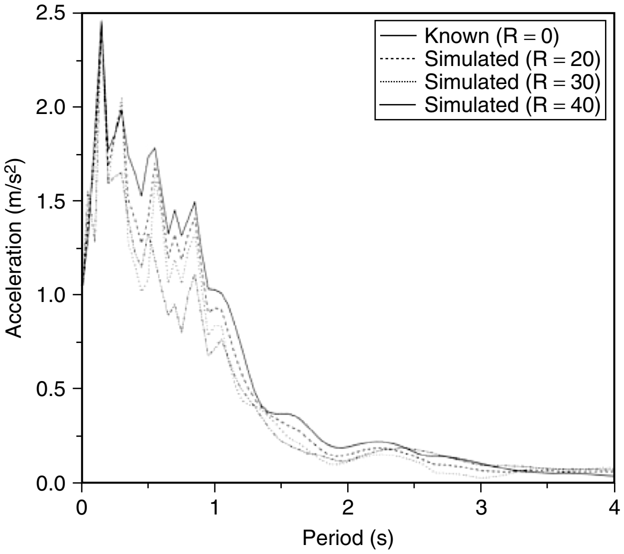


Figure 3. Response spectrum of known and simulated motions

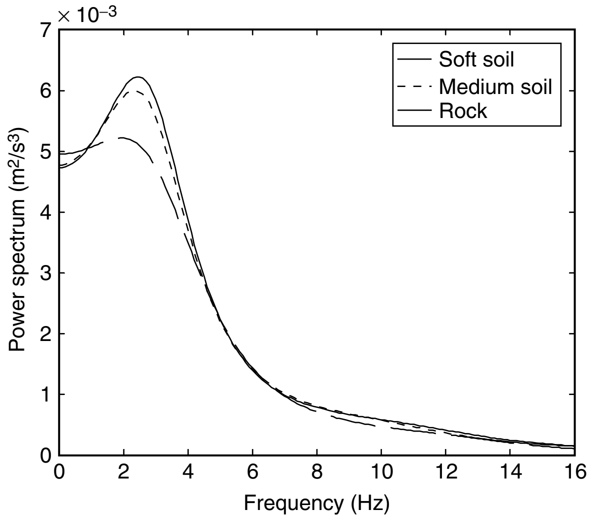


Figure 4. Estimated PSDF of simulated motions at different soil site

(non-uniform ground motions). The Riuz and Penzien high pass filter is used to eliminate drifting of ground velocity and displacement.

3. FE STRUCTURAL MODEL CONSIDERING SSI

Since the current study focuses on the spatially varying ground motion effect on adjacent structures, therefore two closely spaced two-dimensional reinforced concrete frame structures are modeled along with two-dimensional soil layers using finite-element analysis software OpenSees (Mazzoni *et al.* 2005).

3.1. FE Model of Adjacent Structures with SSI

The frame structures are modeled using the displacement-based, Euler-Bernoulli frame element with the distributed plasticity. In each element five integration points are provided and section stress results are computed by discretizing the frame sections into layers. The material properties, beam, and column sections of each frame are same, thus the stiffness of adjacent structures are also same. The service and the total dead loads are applied in the frame using lumped masses at the nodal points. The input parametric values being used are listed in Table 1. The descriptions of symbols used can be found in Appendix I.

The soil layers and foundation are modeled with four-node plane-strain element using a bilinear isoperimetric formulation (Yang *et al.* 2008). The footing materials are modeled as linear elastic with young's modulus E = 20,000 MPa and Poisson's ratio = 0.20. Pressure-independent multi-yield-surface model (Gu *et al.* 2009) is used for modeling of soil materials. The model of adjacent structures with SSI system is shown in Figure 5. The two dimensional (2D) soil model depicted in Figure 5 is a tiny portion of a very large soil domain. The bottom nodes of soil layers are fully fixed to assume the bedrock below the layers. Equal degree of freedom (DOF) of multi-point constraint (MPC) has been used to tie structural elements and soil elements together. The equal DOF is a command in Opensees to build a multi-point constrain between the nodes (Mazzoni *et al.* 2005). Simple shear deformation pattern of soil layers has been considered to describe the lateral boundary condition (Gu *et al.* 2009). Thus the end nodes of soil

Table 1. Parametric values of concrete and steel materials

Smoothed popovics-saenz concrete			J2 Plasticity steel	
Parameter	Core concrete	Cover concrete	Parameter	Value
f_c (kPa)	34473.8	27579.04	E(kPa)	2.1 × 108
f_u(kPa)	25723.0	1000.0	f_y(kPa)	2.48 × 105
ε_0	0.005	0.002	H_{kin}(kPa)	1.61 × 106
ε_u	0.02	0.012	H_{iso}	0.0
E_c (kPa)	2.7851 × 107	2.4910 × 107		
η	0.2	0.2		

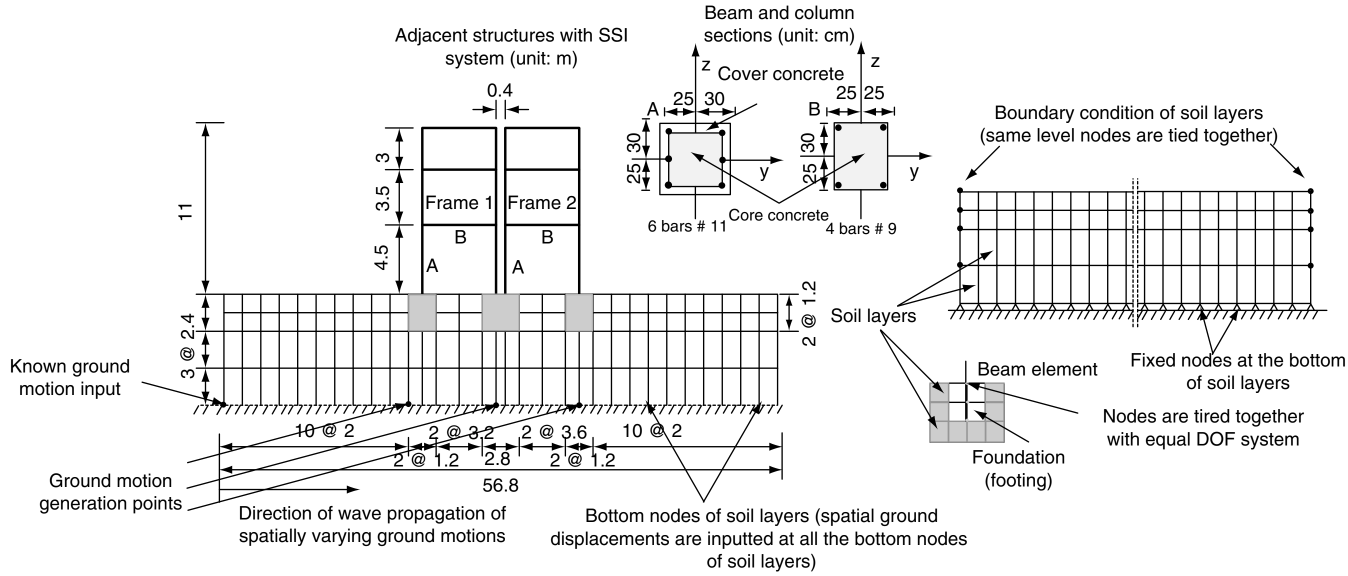


Figure 5. Model of adjacent structures and constraints used in SSI system

layers at the same elevation are also tied together using the equal DOF constraints to fulfill the above condition (See Figure 5). Numerical analysis of the SSI system has been conducted for both uniform and multi-support (non-uniform) base excitation. In case of uniform excitation, recorded acceleration time history is used, on the other hand spatial ground displacements are used for multi-support excitation.

3.2. Local Soil Site Classification

In this case study three cases are considered where three different types of site classes are used according to ASCE /SEI 7-10 code (Table 2) to investigate the influence of non-uniform input motion considering SSI.

3.3. Dynamic Analysis of Adjacent Structures

The dynamic time history analyses of adjacent frame structures are conducted using OpenSees. Newmark-β method is used for the integration operations with parameters $\beta = 0.2756$ and $\gamma = 0.55$ with a constant time interval $\Delta t = 0.01$[s].

Table 2. Local soil site classes

Site class	Shear wave velocity (m/s)	Selected value for this Study
B. Rock	760-1520	1000
C. Very dense soil	360-760	430
D. Stiff soil	180-360	220

3.4. Uniform Ground Motion Input

For dynamic analysis, acceleration time-history should be applied for uniform ground motion in OpenSees software framework (Figure 6). The plain constraint handler is used in OpenSees with all the support condition fixed. The recorded acceleration time history is used for uniform excitation.

3.5. Multi-Support Ground Motion Input

In case of non-uniform ground motion (multi-support excitation) displacement time histories are the inputs for dynamic analysis as shown in Figure 7. Artificially generated spatially varying ground acceleration time histories are first converted to spatial ground displacements by double integration. Then, spatial ground displacements are used as input time histories of multi-support excitation. Spatial ground displacement time

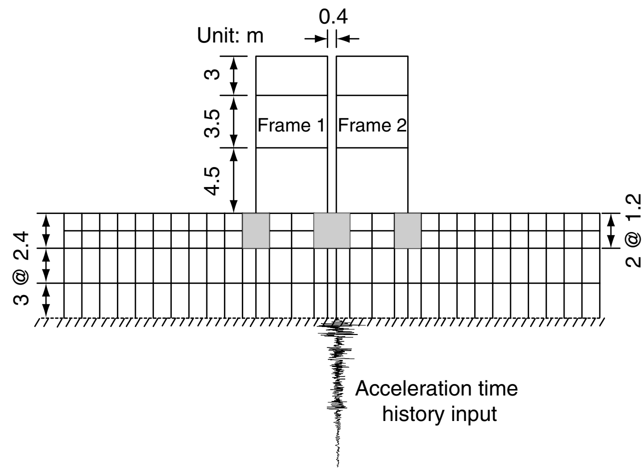


Figure 6. Uniform ground motion input

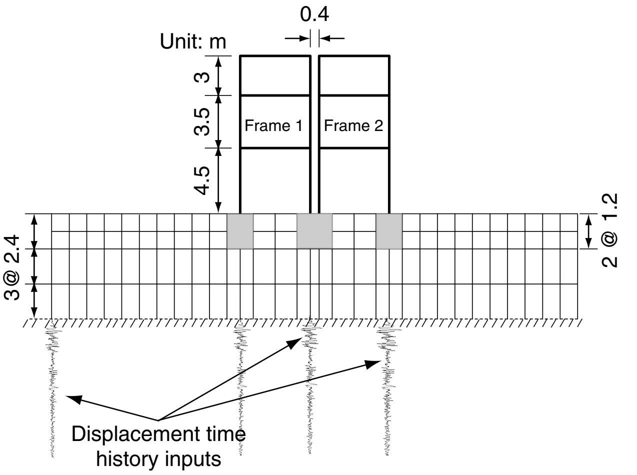


Figure 7. Multi-support ground motion inputs

histories are inputted at all the bottom nodes of soil layers. The transformation constraint handler is used in OpenSees with all supports are free in the direction that multi-support excitation is applied. For multi-support excitation analysis the displacement response of each structural node is stored as absolute displacement. Therefore, relative displacement can be calculated by subtracting the input displacement from the absolute displacement.

The study further extended to investigate the effects of separation distance and interaction between two adjacent structures under uniform and multi-support ground motion excitation. For this purpose separated adjacent frames (separation distance 4.4 m) and single frame numerical models are developed as shown in Figures 8(a) and 8(b) with the same dimensions and

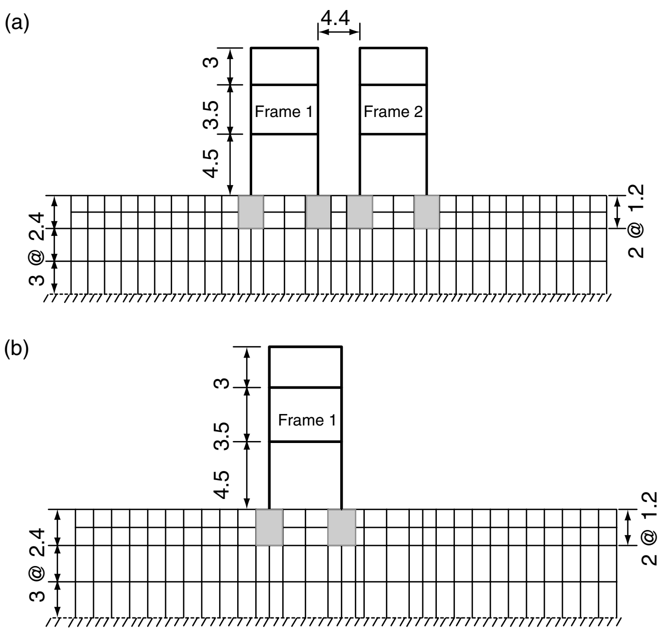


Figure 8. (a) Separate adjacent frames; (b) Single frame

material properties of adjacent structures with interaction at foundation level (Figure 5). Two frames are separated by soil column without any interaction in foundation. The soil properties are selected as rock site. The dynamic analyses of both models are conducted under uniform and spatially varying ground motions.

4. RESULT AND DISCUSSION

Before investigating spatially varying ground motions analysis results, roof drift responses of frame 1 and frame 2 under uniform (acceleration input) and multi-support (displacement inputs) of 1994 Northridge earthquake excitation are compared. The results show good agreements between uniform and multi-support analysis approach (Figure 9).

The dynamic analyses of SSI system are carried out for three different soil sites listed in Table 2. The results are displayed in terms of absolute maximum inter-story drift

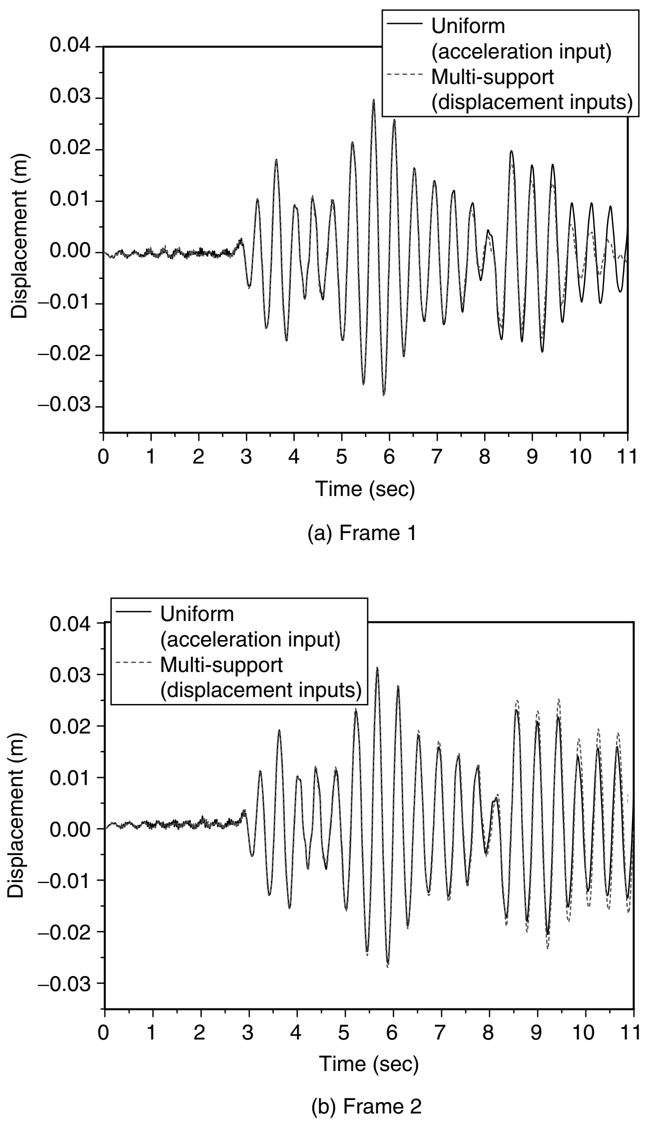


Figure 9. Verification of multi-support input analysis

(relative displacement between each floor level) and absolute maximum story displacement (relative displacement between the ground surface and floor level). From the obtained analysis results, it shows that the inter-story drifts and story displacements of adjacent structures are different for uniform and multi-support (non-uniform) input motions. In Figure 10 maximum inter-story drift and maximum story displacement responses of adjacent structures under uniform excitation are fairly similar for clay site. However, responses of frame 1 and frame 2 are quite different due to non-uniform input motions at the base of soil layers. In case of very dense soil site frame 2 of non-uniform input exhibits the maximum responses (Figure 11). It has been noticed that, story drift response has increased 22% at 0-1 story level when the SSI system is subjected to spatially varying ground motions than the response obtained from uniform input motion [Figure 11(a)]. Furthermore, the maximum story displacement of frame 2 at top floor level under multi-support input is 21% larger than that of the uniform input motion [Figure 11(b)].

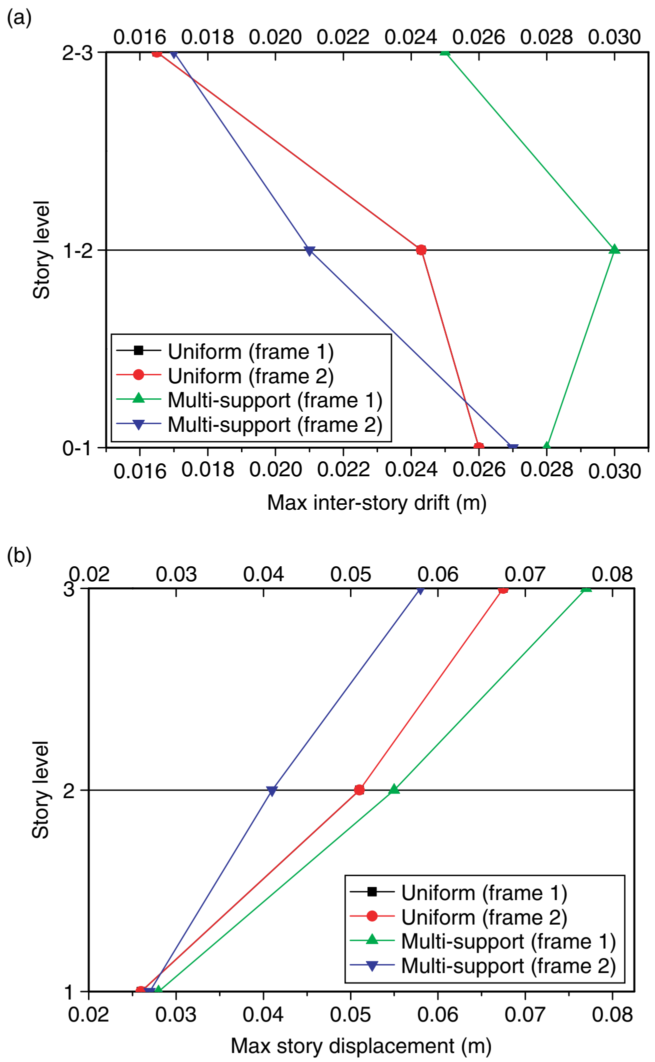


Figure 10. (a) Maximum inter-story drift responses of adjacent structures (c = 220 m/s); (b) Maximum story displacement responses of adjacent structures (c = 220 m/s)

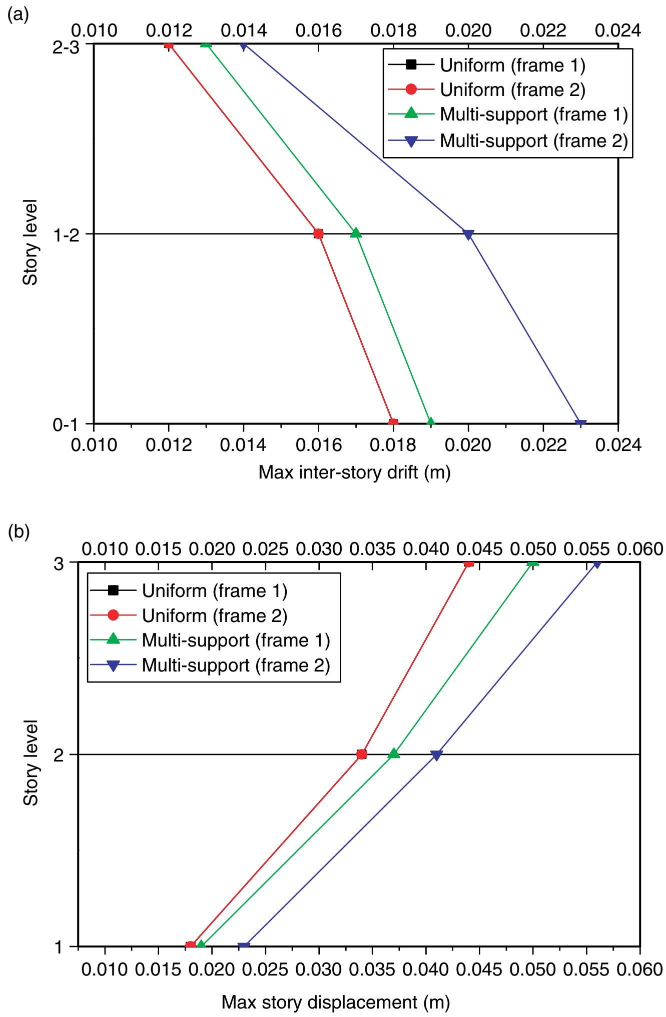


Figure 11. (a) Maximum inter-story drift responses of adjacent structures (c = 430 m/s); (b) Maximum story displacement responses of adjacent structures (c = 430 m/s)

For rock site the structural response phenomena are quite similar with very dense soil and the percentage of story drift response has increased to almost 50% of the uniform motion [Figure 12(a)]. A noticeable change in maximum story displacement response of frame 2 at top floor level is also observed due to spatial variation of ground motion. Compare to the uniform motion response 33% larger response is obtained under non-uniform motion at rock site [Figure 12(b)]. Thus the above observations indicate that with the increase of stiffness of soil site the spatial ground motion effect also getting significant accordingly. Figure 13 shows that under multi-support excitation, roof drift response is maximum

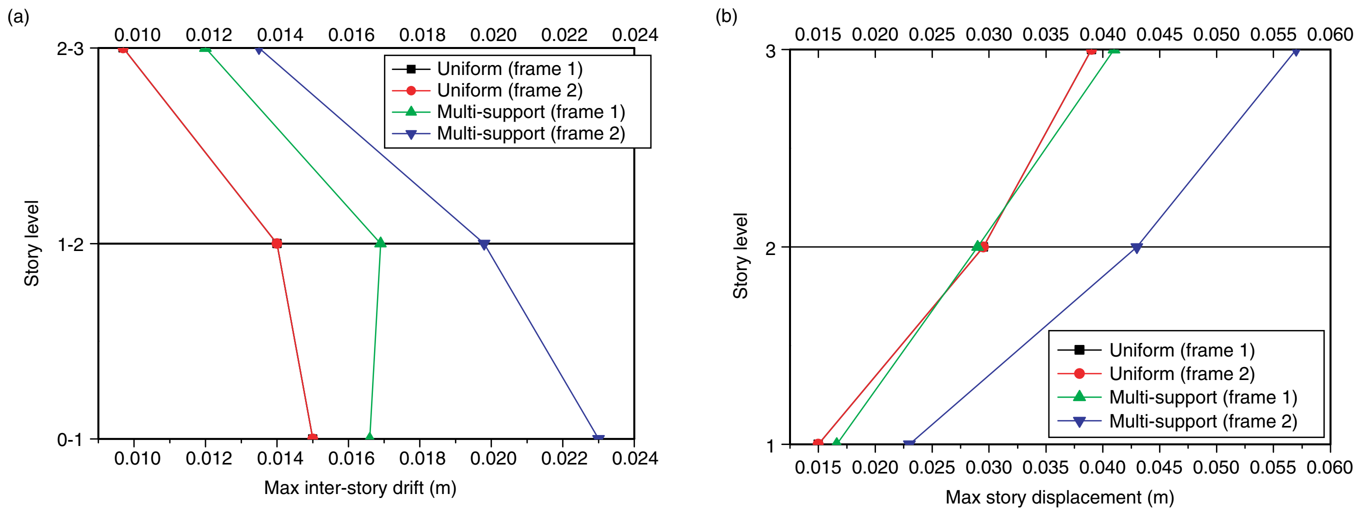


Figure 12. (a) Maximum inter-story drift responses of adjacent structures (c = 1000 m/s); (b) Maximum story displacement responses of adjacent structures (c = 1000 m/s)

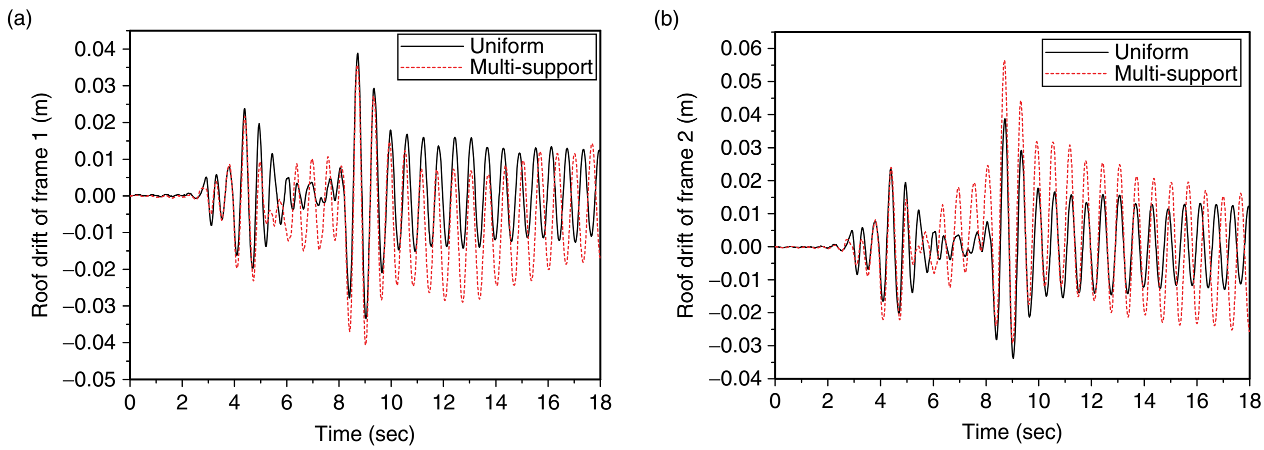


Figure 13. Roof drift response of adjacent frames subjected to uniform and multi-support motions at rock site

Table 3. Base shear forces of adjacent structures

	Base shear force (kN)			
	Uniform		Multi-support	
Soil site properties	Frame 1	Frame 2	Frame 1	Frame 2
c = 220 m/s	407.35	407.16	512.87	384.14
c = 430 m/s	327.00	327.40	348.20	377.60
c = 1000 m/s	295.17	295.25	369.42	416.52

for frame 2 at rock site. It is also noticed that drift response of frame 2 is more than frame 1 due to spatial variation of ground motions. Table 3 displays the absolute maximum base shear forces of adjacent structures for three different soil sites used in this study. For all the cases maximum base shear forces of adjacent structures are fairly similar under uniform input ground motion. Maximum shear force has induced at the base of the frame 1 subjected to multi-support input motion for clay site. Maximum based share forces of frame 1 and frame 2 have been increased 6.08% and 13% respectively due to ground motion spatial variations. The percentage increments of base shear forces are maximum (20% and 29.08% respectively) for both frame 1 and frame 2 at rock site under multi-support excitation. Shear forces of adjacent structures are different subjected to multi support excitation due to spatially varying ground motion and for the rock site the effect is remarkable.

The maximum drift and displacement responses of adjacent separate frames are plotted in Figure 14. The results show that the displacement responses of separate frames are fairly similar to the responses of closely spaced frames (interaction between frames at footing) subjected to uniform seismic loading. However, inter-story drifts and story displacements of frame 1 and frame 2 have changed largely under multi-support inputs caused by the spatially varying ground motions. The Maximum inter-story drift responses resulted from the analysis of separate adjacent structures are calculated in Table 5 under spatially varying motions. The percentage error for frame 1 varies from 2.4 to 7.8%, on the other hand 4.2% is the maximum error calculated for frame 2. The errors noticed in the drift responses of frame 1 may occur due to the interaction effect between frame 1 and 2. The interaction effect and the location change of frame 2 are the causes of the errors in the frame 2. Figure 15 depicts the maximum inter-story drift and story displacement responses of a single frame subjected to

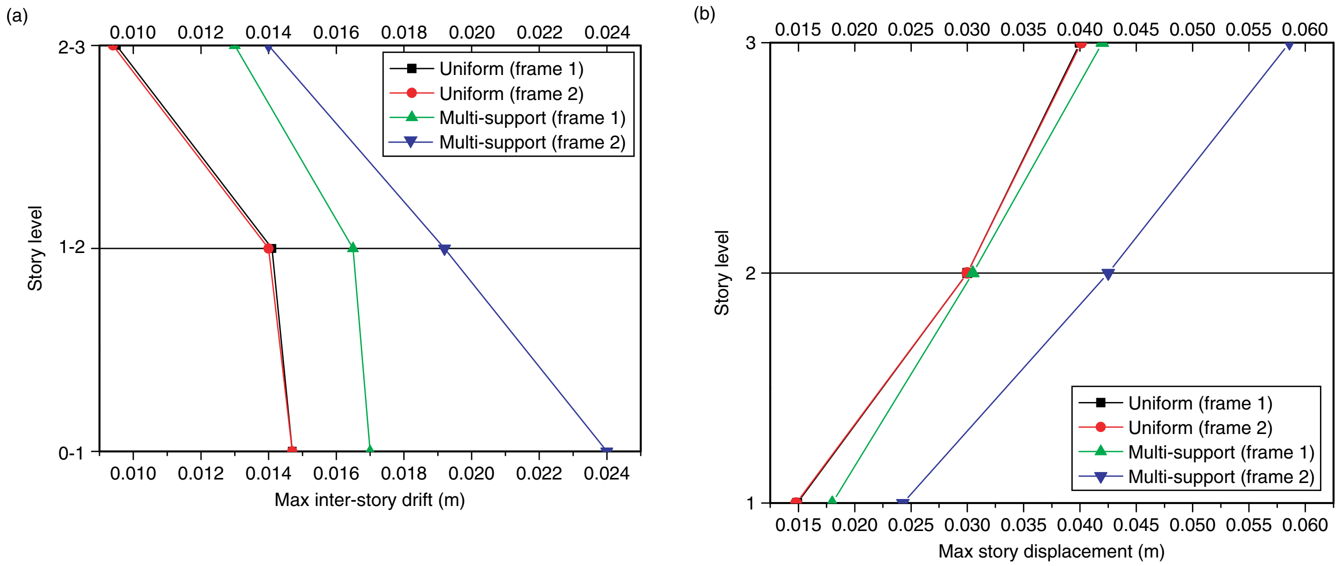


Figure 14. (a) Maximum inter-story drift responses of adjacent separate structures (c = 1000 m/s); (b) Maximum story displacement responses of adjacent separate structures (c = 1000 m/s)

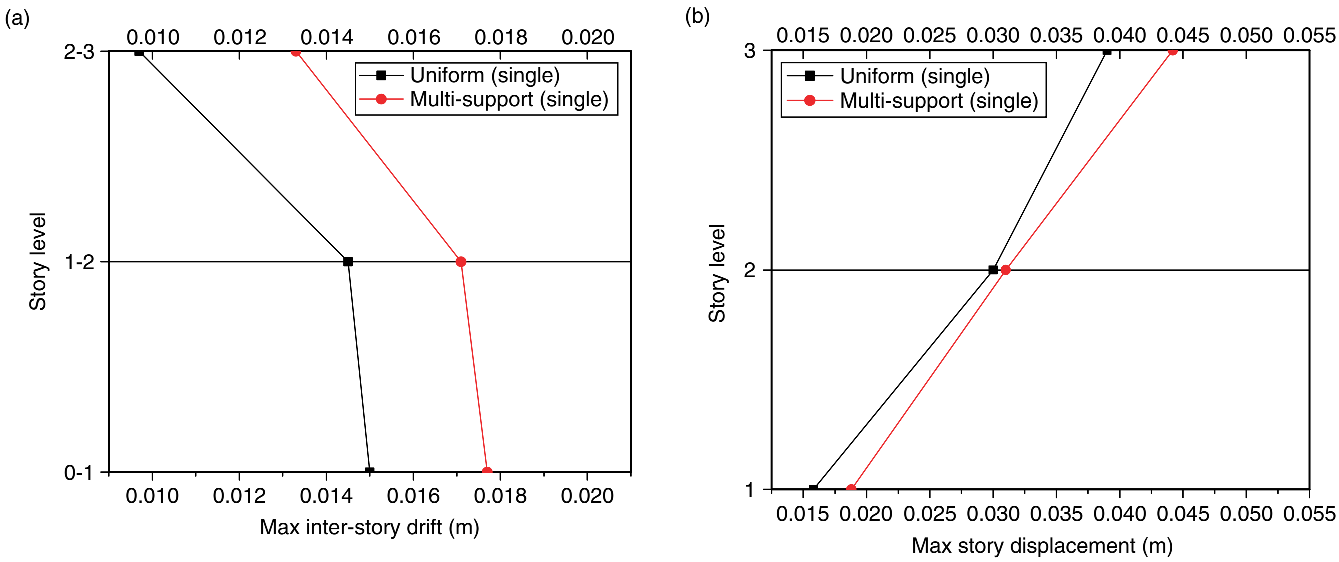


Figure 15. (a) Maximum inter-story drift responses of single frame (c = 1000 m/s); (b) Maximum story displacement responses of single frame (c = 1000 m/s)

Table 4. Inter-story drift response comparison of closely spaced frames, separate adjacent frames and single frame under multi-support excitation

	Maximum inter-story drift responses (m)					Percentage error = $\left\lvert 1 - \dfrac{Frame_{Sep}}{Frame_{Clo}} \right\rvert \times 100\%$	
	Closely spaced frames ($Frame_{Clo}$)		Separate frames ($Frame_{Sep}$)		Single Frame		
Story level	Frame 1	Frame 2	Frame 1	Frame 2	Frame 1	Frame 1	Frame 2
0–1	0.0166	0.0230	0.0170	0.0240	0.0177	2.40	4.20
1–2	0.0169	0.0198	0.0165	0.0192	0.0171	2.42	3.12
2–3	0.0120	0.0135	0.0130	0.0140	0.0133	7.80	3.60

uniform and non-uniform motions. The drift and displacement responses are similar to the closely spaced and separate adjacent frames under uniform motion. However, responses of single frame structural system subjected to spatially varying ground motions are larger compared to the frame 1 of interacted frames (closely spaced and separate frame systems) as shown in Figure 15 and Table 4. The maximum inter-story drift of Frame 1 in closely spaced frame system is 0.0169 m which is less than the maximum inter-story drift of Frame 1 in separate frames and single frame system (0.0170 m and 0.0177 m respectively). Thus, the interaction between frame 1 and 2 has a positive effect on the structural responses of frame 1 in adjacent frame structures.

5. CONCLUSION

The effect of spatial variation of ground motion of adjacent structures considering different soil sites has been investigated in this study. Two low-rise frame structures with same dynamic properties are modeled including soil layers with the foundation of the structures. Spatially varying artificial ground motions are generated compatible with known recorded ground motion at different points of soil base. Then the dynamic analyses of frame structures with SSI system were conducted under both uniform and generated non-uniform ground motions. Three different site classes are used to evaluate the SSI effect on the adjacent structures. The core conclusions of this study can be summarized as follows:

(1) The influence of spatial variation of ground motion has been noticed in all the cases as maximum inter-story drifts, maximum story displacements and maximum base shear forces of adjacent structures are different under multi-support input.

(2) Ground motion spatial variation effects are different for different site classes. The effect is more significant on rock site comparing to other soil sites. Inter-story drift and story displacement responses have increased 50% and 33% respectively for rock site due to spatially varying ground motion.

(3) The effect of non-uniform inputs on the maximum base shear forces of adjacent structures is also noticeable. Maximum shear force increased up to 29.08% because of the spatial variation of ground motions. The maximum base share force (416.52 kN) induced on the frame 2, thus the effect is more prominent on the frame 2 rather than frame 1.

(4) The influence of separation distance and interaction between two adjacent structures are also examined under uniform and non-uniform dynamic loading. The findings show that the displacement responses are nearly similar for separate and closely spaced adjacent structures. The maximum percentage of error in seismic analysis of separate frames is 7.8% under non-uniform ground motion. The errors cause in the drift responses of frame 2 due to the combined effects of large separation distance and the interaction of frames at foundation level. Furthermore the dynamic analysis of single frame system concluded that the interaction between two adjacent structures reduces the maximum drift and displacement responses of frame 1.

The above conclusions are based on the numerical results of two low rise adjacent RC frame structures. The results in this study clearly indicate the necessity of considering spatial variation of ground motions effects on low-rise adjacent structures.

ACKNOWLEDGEMENTS

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NOTATION

$f_c(kPa)$	concrete compressive strength (kPa)
$f_u(kPa)$	concrete crushing strength (kPa)
ε_0	concrete strain at maximum strength
ε_u	concrete strain at crushing strength
$E_c(kPa)$	initial tangent stiffness (kPa)
η	smoothing parameter
$E(kPa)$	Young's modulus (kPa)
$f_y(kPa)$	yield strength (kPa)
$H_{kin}(kPa)$	kinematic hardening modulus (kPa)
H_{iso}	isotropic hardening modulus