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Article

Application of Conditional Mean Spectrum in Nonlinear Response History Analysis of Tall Buildings on Soft Soil

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Abstract. The uniform hazard spectrum (UHS) and conditional mean spectrum (CMS) are commonly used as target spectra in selecting and scaling of records to be used in nonlinear response history analysis (NLRHA). When using CMS with tall buildings, CMS ground motions conditioned at multiple natural periods of the buildings should be considered. The application of CMS ground motions in NLRHA to estimate seismic demands for design of tall buildings located on soft-soil layers in Bangkok is investigated in this study. The seismic demands computed using multiple sets of CMS ground motions are compared with those computed using a single set of UHS spectral matching ground motions. Four existing tall buildings subjected to earthquake excitations in Bangkok were considered. The NLRHA was conducted using multiple sets of CMS ground motions, where periods of interest T^* were considered at the periods closest to the periods of the first-three translational modes of the building in the direction of excitation. It was found that CMS ground motions conditioned at the higher-mode periods result in larger force demands than CMS ground motions conditioned at the fundamental period for some locations along the height of the building. The envelope of demands obtained by using multiple sets of CMS ground motions conditioned at different periods should be used in design but requires significant computational effort. Using UHS spectral matching ground motions can provide results close to such an envelope and reduce the computational effort significantly.

Keywords: Tall building, conditional mean spectrum, uniform hazard spectrum, nonlinear response history analysis.

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1. Introduction

Nonlinear response history analysis (NLRHA) has become more popular analysis method in recent years for the design of new buildings, evaluation of existing buildings, and seismic performance assessment of buildings [1]. For design of new tall buildings, NLRHA is used in the performance based-design method for verification in a final stage of a design project [2, 3]. For existing buildings, NLRHA is used to evaluate performance, design seismic upgrades, and retrofit of existing buildings [4]. NLRHA is also used to determine probability of collapse by explicitly assessing overall seismic performance of buildings [5]. NLRHA is the most accurate but complicated method among seismic analysis methods. Difficulties in NLRHA involve limited understanding of inelastic behavior of a structure, creation of a realistic nonlinear structural model, selection of appropriate earthquake ground motions for the site of interest, significant computational effort, data processing, and result interpretation [6-9]. For practical application of NLRHA, several guidelines, technical reports, and standards [2-4, 10, 11] provide guidance information on nonlinear structural modeling and acceptance criteria of a structural system. In this paper, those guidelines were adopted, and the methods to select and scale earthquake ground motions to be used in NLRHA to estimate seismic demands for design purposes were discussed.

NLRHA is generally performed by using ground motion records that are selected and scaled to match a defined target spectrum. Katsanos et al. [12] provided a comprehensive review on selection of ground motions. The most commonly used target spectra are the uniform hazard spectrum (UHS) and conditional mean spectrum (CMS) [13]. UHS has the same probability of exceedance at all periods from consideration of many scenarios of earthquakes. The spectral shape of the UHS may not resemble the spectral shape of a real ground motion. It is unlikely for one ground motion from the earthquake scenario contributing to the UHS at a period of interest to have as large spectral values as the UHS at all other periods [14]. Using the UHS as the target spectrum would be overly conservative to estimate responses to an earthquake scenario or develop a fragility function [15-18]. On the other hand, the CMS approach proposed by Baker [16] is attractive as it can yield a more realistic spectral shape of earthquakes. The CMS will match the ordinate of the UHS only at the period of interest, T^*. However, the choice of the period of interest when using CMS with tall buildings is not definite as higher modes could be as important as the fundamental mode. Higher modes could be more significant for some response parameters such as base shear force and mid-height overturning moment [8, 19].

The main concerns when using CMS are that results from an analysis using a single CMS vary with the choice of the conditioning period, and that it may underestimate response parameters significantly influenced by multiple vibration modes of the building [20]. To address these concerns, several methods have been proposed. The first method uses multiple sets of CMS conditioned at different vibration periods [16, 20], and the design demand values are obtained by enveloping the mean values of peak demands from analysis using CMS conditioned at different periods. The second method uses two sets of CMS whose shapes are broadened symmetrically about each conditioning period such that the difference of spectral accelerations between the UHS and the CMS is less than 10% [21]. The range of conditioning periods to determine how much to broaden the shape of CMS is based on engineering judgment. The third method uses a single target spectrum which is conditioned at two conditioning periods having spectral accelerations the same as spectral ordinates of the UHS [22]. The shape of the target spectrum in this method can be controlled through the choice of two conditioning periods. The fourth method is the composite spectrum which combines the characteristics of UHS and CMS [23], such that at the periods of $T < T_3$ and $T > 2T_1$ (where T_i is the natural period of mode i in the direction of analysis), the composite spectrum has the same spectral acceleration values as the CMS conditioned at T_3 and $2T_1$, respectively, and in the period range of $T_3 \le T \le 2T_1$, the composite spectrum is taken equal to the UHS. Although, the three previously mentioned methods can reduce the numbers of CMS necessary for performing the analysis, the level of complexity involving the calculation of the target spectrum is significantly increased compared to the CMS conditioned at a single period.

The first method using multiple sets of CMS has been adopted by several design guidelines and codes [24-26]. ASCE 7-16 [24] (Method 2 in Chapter 16) suggests using two or more conditioning periods of vibration contributing significantly to the inelastic dynamic response of the building. According to the commentary of ASCE 7-16, the selected periods might include lengthened first-mode period, e.g., $1.5T_1$, period close to elastic first-mode period, and translational second-mode period of the building in the direction of analysis. More specifically for tall buildings, CTBUH [25] recommends using three CMSs which in aggregate can envelop the UHS over the period range from 0 to 1.5 times the fundamental period of the

building, and the long-period CMS spectral ordinates shall not fall below the UHS in the period range from 1 to 1.5 times the fundamental period of the building. Similarly, PEER [26] recommends using a minimum of three CMSs conditioned at the periods of the first-three translational modes of the building in each direction of analysis. When using CMS as the target spectrum for tall buildings, the numbers of analysis increase with a factor equal to the numbers of conditioning periods considered; hence, significant computational effort will be required. When using spectral matching ground motions and UHS as the target spectrum, only one set of analysis is required. The comparison of seismic demands of tall buildings situated on soft soil computed from NLRHA using CMS ground motions and UHS spectral matching ground motions has not yet been available.

This study aimed at investigating the application of CMS ground motions in NLRHA to estimate seismic demands for design of tall buildings located on soft soil. Seismic demands of tall buildings computed from NLRHA using CMS ground motions at multiple conditioning periods were compared to those computed from NLRHA using ground motions selected, scaled, and modified to match UHS at all periods. This study tried to confirm the acceptability of using only a single set of UHS spectral matching ground motions to compute design force and displacement demands, instead of multiple sets of CMS ground motions corresponding to multiple conditioning periods.

2. Description of Buildings

Four existing tall RC shear wall buildings located on soft-soil layers in Bangkok, Thailand, were employed. The buildings were modeled using the as-built building drawing plans. These 15-, 20-, 31-, and 39-story buildings are denoted as B1, B2, B3, and B4, respectively. Buildings B2, B3, and B4 have one tower continuing up to the top floor and podium at the first few stories, which is a typical style of tall buildings in many countries around the world. For all buildings, the RC walls in each story resist more than 75% of the total lateral force. The primary lateral force resisting system of buildings B1-B4 consists of RC core walls and shear walls. The gravity load carrying system for buildings B1, B3, and B4 is RC columns with post-tensioned flat slabs and for building B2 is RC shear walls with post-tensioned flat slabs. Typical floor plans and three-dimensional models of buildings B1-B4 are shown in Fig. 1. The basic characteristics of buildings B1-B4 are summarized in Table 1.

3. Earthquake Ground Motions

The maximum considered earthquake (MCE) ground motions having 2% probability of exceedance in 50 years were employed. The UHS at a hypothetical rock outcrop site in Bangkok was obtained from probabilistic seismic hazard analysis (PSHA) which was carried out by Ornthammarath et al. [27]. The CMSs at the rock outcrop site for six periods of interest (T^*): 0.2, 0.5, 1, 1.5, 2, and 3 seconds were determined using the procedure proposed by Baker [16]. It should be noted that for rock outcrop sites, a CMS matches the UHS only at its conditioning period and is lower than the UHS at other periods as shown in Fig. 2. These rock outcrop CMSs were used as the target spectra to select appropriate rock outcrop ground motions to be used as inputs for site response analysis. Six sets of ground motions having similar seismic mechanisms as in Bangkok were selected from the PEER ground motion database [28] as listed in Table 2. Each set comprises three pairs of ground motions. The first-three sets correspond to short conditioning period (0.2, 0.5, and 1 sec) ground motions from earthquakes having moderate magnitudes of 6.7 to 7.6 with epicentral distances of 80-186 km. The other three sets correspond to long conditioning period (1.5, 2, and 3 sec) ground motions from earthquakes of large magnitudes of 8.3 to 9, recorded at large epicentral distances of 550-1625 km. Since Bangkok is located on soft-soil layers, the selected ground motions for each of the six periods of interest were first scaled by amplitude scaling method to match the target CMS for rock outcrop site and then, simulated to propagate through soft-soil layers underlying downtown area of Bangkok by using SHAKE2000 software [29]. Detailed information of the development of design spectrum, ground motion selections, site response analysis, and soil properties used in this study can be found in [30, 31]. The average spectra of input ground motions scaled to match each of the CMS at rock outcrop are shown in Fig. 3 and an example of output ground motions at soft-soil surface from the site response analysis of input ground motions matching rock outcrop CMS conditioned at 2 sec is presented in Fig. 4. The six sets of output ground motions were considered as CMS soft-soil ground motions. The average spectral acceleration of the six output ground motions in each set of period of interest represents UHS spectral ordinate at that period of interest, as CMS

usually matches UHS at the period of interest. The UHS and six CMSs of soft-soil ground motions for 5% damping ratio are shown in Fig. 5. It should be noted that the soft-soil CMSs defined by the average spectra of soft-soil ground motions could be larger than the soft-soil UHS at periods other than the conditioning period (Fig. 5), which is different from the rock outcrop CMSs determined according to Baker [16] that are always lower than the rock outcrop UHS (Fig. 2). The UHS for soft-soil site in this study came from the envelope of CMSs at only six periods, not all periods and the UHS was taken from CMSs at shortest and longest conditioning periods when period is shorter than 0.2 sec or longer than 3.0 sec. The input ground motions were limited to the conditioning period of 3.0 sec due to limitation of parameters in ground motion prediction equations (GMPE) used in the probabilistic seismic hazard analysis [31]. Longer conditioning periods should be considered for tall buildings when spectral values from GMPE at longer periods become available in a future study.

In the present study, the UHS and CMS at soft-soil site were obtained from response spectra of output ground motions from SHAKE2000 [29, 31]. The shear wave velocity (V_s) profile of the study area is shown in Fig. 6. The dynamic soil properties for the equivalent linear site response analysis are summarized in Table 3. It should be noted that SHAKE2000 uses a one-dimensional equivalent linear site response analysis, in which the nonlinearity of soil deposits is taken into account by equivalent linear soil properties represented by stiffness and damping values adjusted through an iteration procedure until they are compatible with the effective strains induced by the earthquake loading in each soil layer. Due to assumptions in SHAKE2000, its accuracy is not perfect, and the accuracy of site response analysis could be improved by using nonlinear seismic response analysis of soil deposits [32-35].

When using CMS in NLRHA, CMSs at conditioning periods closest to the periods of the first-three translational modes of the building in the direction of seismic excitation were employed. For instance, CMS ground motions conditioned at the periods of 3, 1, and 0.5 sec were used for the 39-story building whose periods of the first-three translational modes in the X-direction are 4.63, 1.06, and 0.48 sec as shown in Fig. 7.

When using UHS as target spectrum, ground motions were scaled and modified to match UHS at all periods; hereafter referred to as UHS spectral matching ground motions. To obtain the UHS spectral matching ground motions, CMS ground motions in the set for conditioning period of 3 sec (Fig. 8) were modified by SeismoMatch [36] to have spectral shape fitted to the UHS. The individual matching spectra, the mean value of matching spectra, and the target spectrum (UHS) of soft-soil ground motions for 2.5% damping ratio are shown in Fig. 9. For tall buildings, damping ratio of 2.5% recommended by PEER [26] was used in this study.

4. Numerical Models of Structures

Nonlinear structural models were developed in PERFORM-3D [40]. The RC walls were modeled using inelastic fiber shear wall elements. Nonlinear fiber modeling was used over the entire height because flexural cracking or yielding may occur at any location due to higher-mode effects. The material stress-strain relationship for concrete proposed by Mander et at. [41] was adopted and a bilinear inelastic model proposed by Menegotto and Pinto [42] was used for steel. The expected material strength was used to account for the fact that the actual material strengths are generally greater than the nominal material strengths specified by designers. The material cyclic degradation parameters used in PERFORM-3D were taken from Kolozvari et al. [43]. The RC columns were modeled by linear elastic elements with nonlinear plastic hinge zone at both ends. The plastic zones were modeled by inelastic fiber elements similar to those used for the RC walls. The RC beams and coupling beams were modeled by a middle elastic portion and rotational plastic hinge elements at both ends with modeling parameters given by ASCE 41-13 [4]. Plastic hinge properties were defined by a tri-linear moment-hinge rotation relationship whose cyclic degradation parameters in PERFORM-3D were taken from Naish et al. [44]. The joint between members was considered to be rigid connection. Coupling beams were connected to the walls by using embedded rigid beams to ensure the rigid connection between the coupled walls and the coupling beams. The slabs were assumed to be elastic and were modeled by elastic shell elements. A rigid floor diaphragm was assigned to each floor level.

The damping model recommended by Chopra and McKenna [45] was used. In this damping model, the damping matrix is determined based on mode shapes and natural periods of the initial elastic structure. A damping ratio of 2.5% was assigned to all significant vibration modes as recommended by PEER [26].

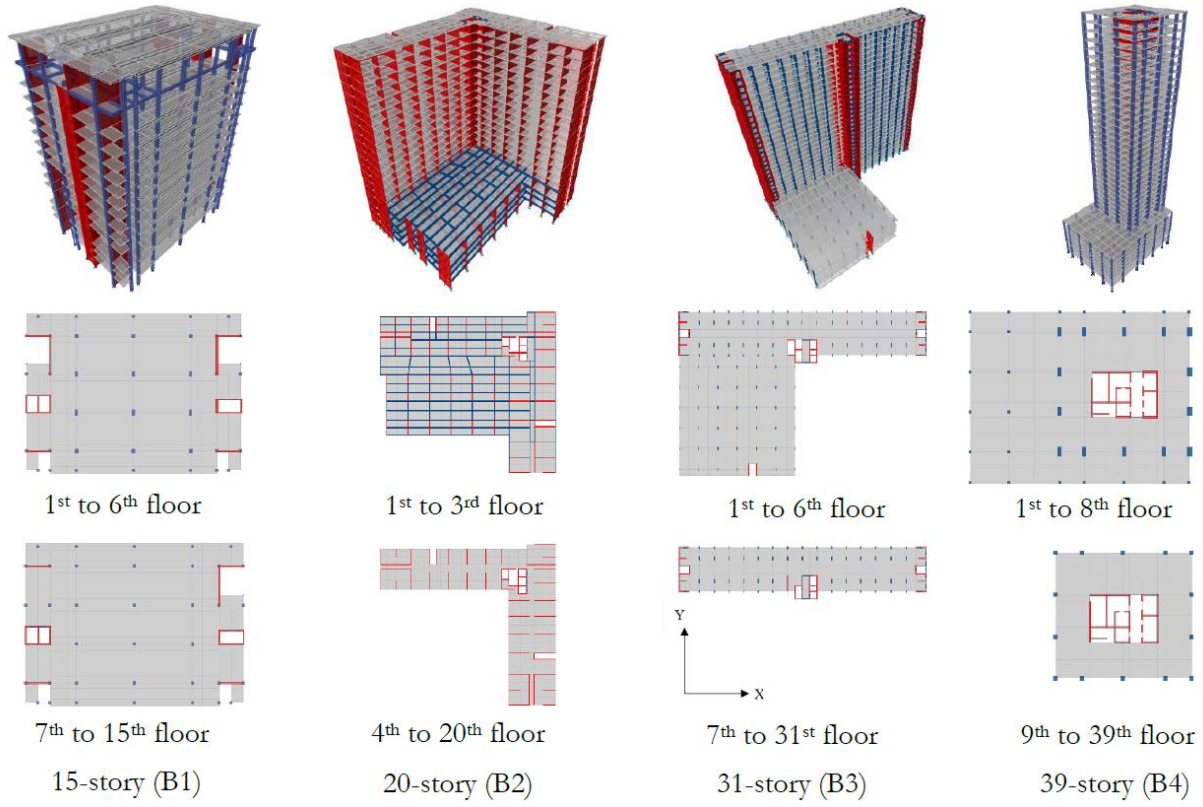

Fig. 1. Floor plans and three-dimensional models of tall RC shear wall buildings B1-B4.

Table 1. Basic characteristics of tall RC shear wall buildings B1-B4.

Building			B1	B2	B3	B4
No. of stories			15	20	31	39
Total height (m)			55.40	54.50	89.95	125.55
Podium height (m)			-	10.05	15.3	26.50
Typical story height (m)			3.2	2.75	2.85	3.2
RC wall section area/floor area at the base			0.012	0.022	0.012	0.015
RC column section area/floor area at the base			0.012	-	0.013	0.013
Maximum wall thickness (m)			0.25	0.20	0.30	0.35
Maximum column size (m x m)			1.2 x 0.6	-	1.8 x 0.5	1.8 x 0.8
Maximum longitudinal reinforcement ratio in wall (%)			1.23	0.85	1.31	1.94
Maximum axial load ratio in wall $P/A_g f_c'$ (%) *			9.8	13.8	14.6	21.0
Natural periods of translational modes (sec)	X-direction	T_1	2.76	1.38	4.29	4.63
		T_2	0.53	0.32	1.12	1.06
		T_3	0.21	0.14	0.51	0.48
	Y-direction	T_1	2.24	1.58	2.86	4.84
		T_2	0.44	0.36	0.71	0.96
		T_3	0.18	0.16	0.35	0.37

* P is the axial load, A_g is the gross section area of wall, f_c' is the compressive strength of concrete.

Table 2. List of ground motions for the six periods of interest: 0.2, 0.5, 1, 1.5, 2, and 3 sec.

T^* (sec)	Pair no.	Earthquake event	Year	Station	Magnitude M_w	Distance (km)
0.2	1	Kobe, Japan	1995	OKA	6.9	87
	2	Hector Mine	1999	Anza-Tripp Flats Training	7.1	102
	3	Northridge-01	1994	Rancho Cucamonga-Deer Canyon	6.7	80
0.5	1	Kocaeli, Turkey	1999	Tekirdag	7.5	165
	2	Hector Mine	1999	Anza-Tripp Flats Training	7.1	102
	3	Hector Mine	1999	Pacoima Kagel Canyon	7.1	186
1.0	1	Hector Mine	1999	Pacoima Kagel Canyon	7.1	186
	2	Chi-Chi, Taiwan	1999	TAP078	7.6	120
	3	Hector Mine	1999	Anza-Tripp Flats Training	7.1	102
1.5	1	Tokachi-oki	2003	YMT015	8.3	550
	2	Tohoku	2011	SIG007	9.0	689
	3	Tohoku	2011	HKD06	9.0	663
2.0	1	Tohoku	2011	HKD048	9.0	655
	2	Tohoku	2011	SIG007	9.0	689
	3	Tokachi-oki	2003	FKS02	8.3	550
3.0	1	Tohoku	2011	OSK004	9.0	747
	2	Tohoku	2011	HKD06	9.0	663
	3	W. Coast of Northern Sumatra	2004	PYAY	9.0	1625

T^* is the conditioning period.

Table 3. Dynamic soil properties for equivalent linear analysis [31].

No.	Depth (m)	Material type	Dynamic soil properties
1	0-15	Clay (PI=50)	Vucetic and Dobry [37]
2	15-30	Clay (PI=30)	Vucetic and Dobry [37]
3	30-60	Clay (PI=15)	Vucetic and Dobry [37]
4	60-100	Clay (PI=0)	Vucetic and Dobry [37]
5	100-740 (basement rock)	Sand	Seed and Idriss [38]
6	Rock	Rock	Schnabel [39]

PI=Plasticity Index.

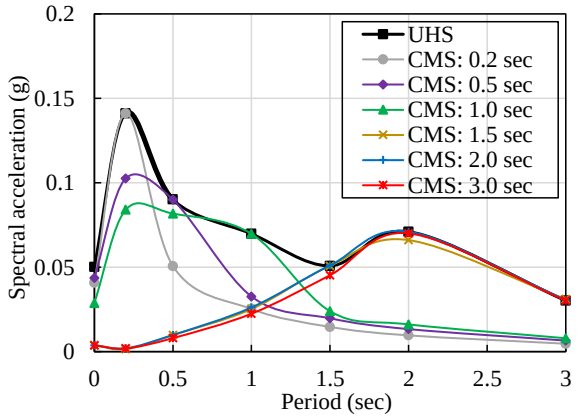

Fig. 2. Uniform hazard spectrum (UHS) and conditional mean spectrum (CMS) conditioned at 0.2, 0.5, 1, 1.5, 2, and 3 sec at rock outcrop for 5% damping ratio.

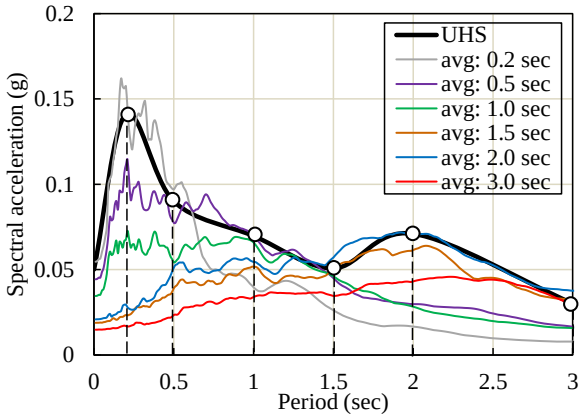

Fig. 3. Uniform hazard spectrum (UHS) and average spectra of rock outcrop ground motions matching conditional mean spectrum (CMS) at rock outcrop for 5% damping ratio.

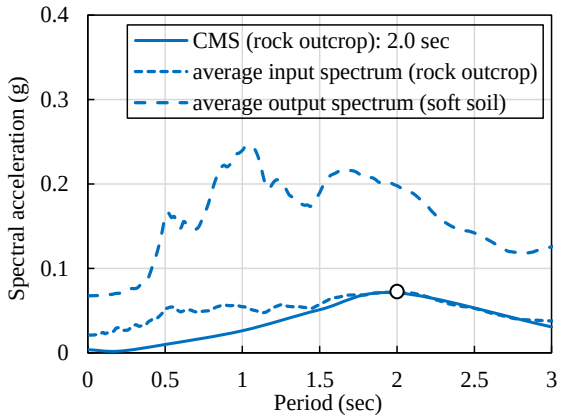

Fig. 4. Conditional mean spectrum (CMS) at rock outcrop, average spectrum of input ground motions at rock outcrop, and average spectrum of output ground motion at soft-soil site for conditioning period of 2 sec.

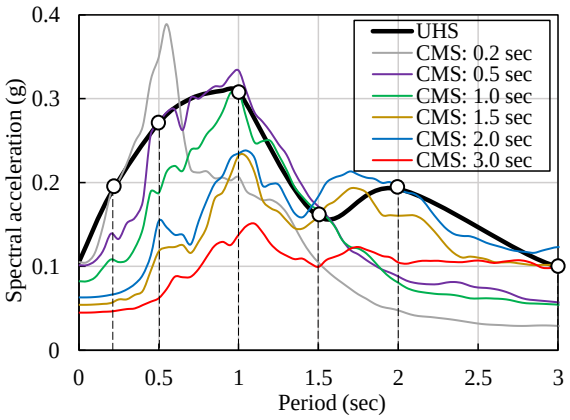

Fig. 5. Uniform hazard spectrum (UHS) and average spectra of soft-soil ground motions considered as conditional mean spectrum (CMS) at soft-soil site for 5% damping ratio.

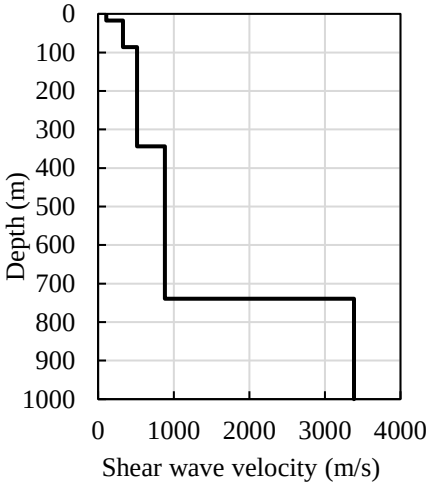

Fig. 6. Shear wave velocity profile of Bangkok site [31].

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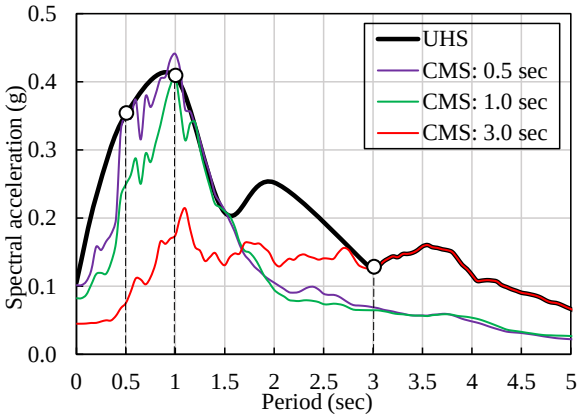

Fig. 7. Conditional mean spectrum (CMS) conditioned at 0.5, 1, and 3 sec of soft-soil ground motions for 2.5% damping ratio used in NLRHA for the 39-story building.

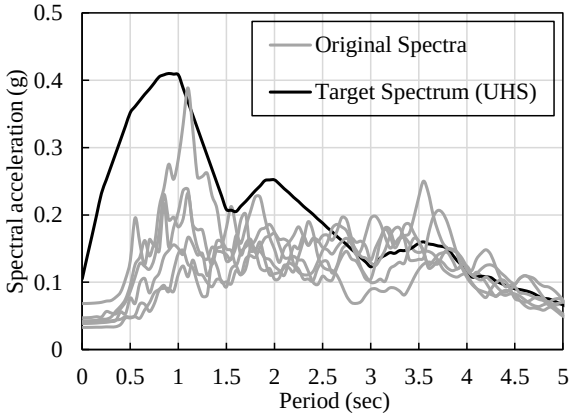

Fig. 8. Original spectra of CMS ground motions conditioned at 3 sec and target spectrum of soft-soil ground motions for 2.5% damping ratio.

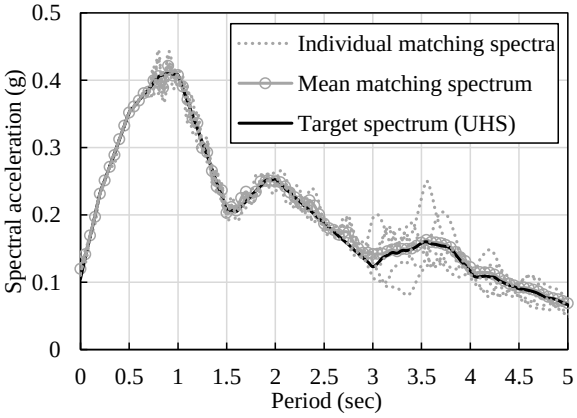

Fig. 9. Individual matching spectra, mean matching spectrum, and target spectrum of soft-soil ground motions for 2.5% damping ratio.

5. Analysis Considerations

PERFORM-3D [40] was used to conduct NLRHA. For each building, two different types of ground motions were used in NLRHA. The first type consists of three sets of CMS ground motions corresponding to conditioning periods closest to periods of the first-three translational modes of the building in the direction of excitation considered. The second type is the set of six UHS spectral matching ground motions as shown in Fig. 9. The ground motions were applied in each direction separately for all analyses considered. Gravity load of all dead loads plus 25% of live loads were applied before NLRHA.

6. Results

The results presented are the mean values of peak responses considered: story shear force normalized by seismic weight of the building (V_{story}/W), story overturning moment (M_{story}), floor displacement, and story drift ratio. Responses to excitation in the X- and Y-directions of the building are presented.

6.1. Comparison of Results from Analysis Using Three Sets of CMS Ground Motions

The comparison of seismic demands computed from NLRHA using three sets of CMS ground motions conditioned at three different periods closest to the periods of the first-three translational modes of the

building in X- and Y-directions is shown in Fig. 10 and Fig. 11, respectively. It was found that the CMSs conditioned at short periods (higher-mode periods) result in larger force demands than the CMS conditioned at long period (first-mode period) for some locations along the height of the building. For instance, the CMSs conditioned at short periods cause significantly larger shear forces at the base region of the 15-story (B1) and 20-story (B2) buildings, and throughout the height of the 31-story (B3) and 39-story (B4) buildings as shown in Fig. 10(a) and Fig. 11(a), and they cause larger overturning moments at the upper stories of the 31-story and 39-story buildings as shown in Fig. 10(b) and Fig. 11(b), compared to the CMS conditioned at long period. This is because the base shear forces and mid-height overturning moments in a tall building are significantly contributed from higher-mode response as reported by previous studies [8, 19]. Therefore, the design demand values should conservatively consider the envelope of force demands from NLRHA using CMS ground motions conditioned at multiple periods. This finding is consistent with the recommendations of the recent guidelines and standards [24-26]. For story drift ratios (Fig 10(c) and Fig. 11(c)) and floor displacements (Fig. 10(d) and Fig. 11(d)), the CMS conditioned at the fundamental period is sufficient for conducting the evaluation as it provides larger results than the CMSs conditioned at higher-mode periods throughout the height of the building because floor displacements and story drift ratios are dominantly contributed from the first-mode response.

6.2. Comparison of Results from Analysis Using CMS and UHS as Target Spectrum

The comparison of seismic demands computed from NLRHA using CMS and UHS as target spectrum is shown in Fig. 12 and Fig. 13 for seismic excitation in X- and Y-directions, respectively. The results from analysis using CMS as target spectrum refer to the envelope of results (Envelope CMS in Fig. 12 and Fig. 13) from NLRHA using three sets of CMS ground motions as discussed in the preceding section. When using UHS as target spectrum, the computed results (UHS in Fig. 12 and Fig. 13) are the mean values of peak response computed from NLRHA using six UHS spectral matching ground motions. It was found that using UHS spectral matching ground motions provides very similar seismic demands for most cases and slightly larger floor displacements and story drift ratios for Y-direction of the 20-story (B2) building (Fig. 13(c) and Fig. 13(d)), compared to the envelope of results from NLRHA using CMS conditioned at multiple periods. Therefore, using UHS as target spectrum to select and scale ground motions together with spectral-matching modification can take care of the enveloping task required when using CMS; hence, it can significantly reduce the computational effort because only one set of analysis is required as opposed to three sets of analysis required when using CMS as target spectrum. This finding is different from the results of Kwong and Chopra [22] who conducted a study on a 20-story RC frame building located on stiff soil, and reported that using UHS as the target spectrum to select and scale earthquake records to be used in intensity-based assessment of a building provides over-conservative estimates for computing seismic design demands. This difference could be due to many reasons as many parameters in the present study and [22] are not the same. For instance, (1) the UHS in [22] is generally larger than CMS at most periods, except at the conditioning periods where UHS and CMS values are equal; (2) when using UHS, ground motions in [22] were scaled to match UHS at the fundamental period, whereas ground motions in the present study were scaled and modified to match UHS at all periods; and (3) the lateral force resisting system and site class are different. A future study using the same conditions and parameters is recommended to clarify inconsistency between the two studies.

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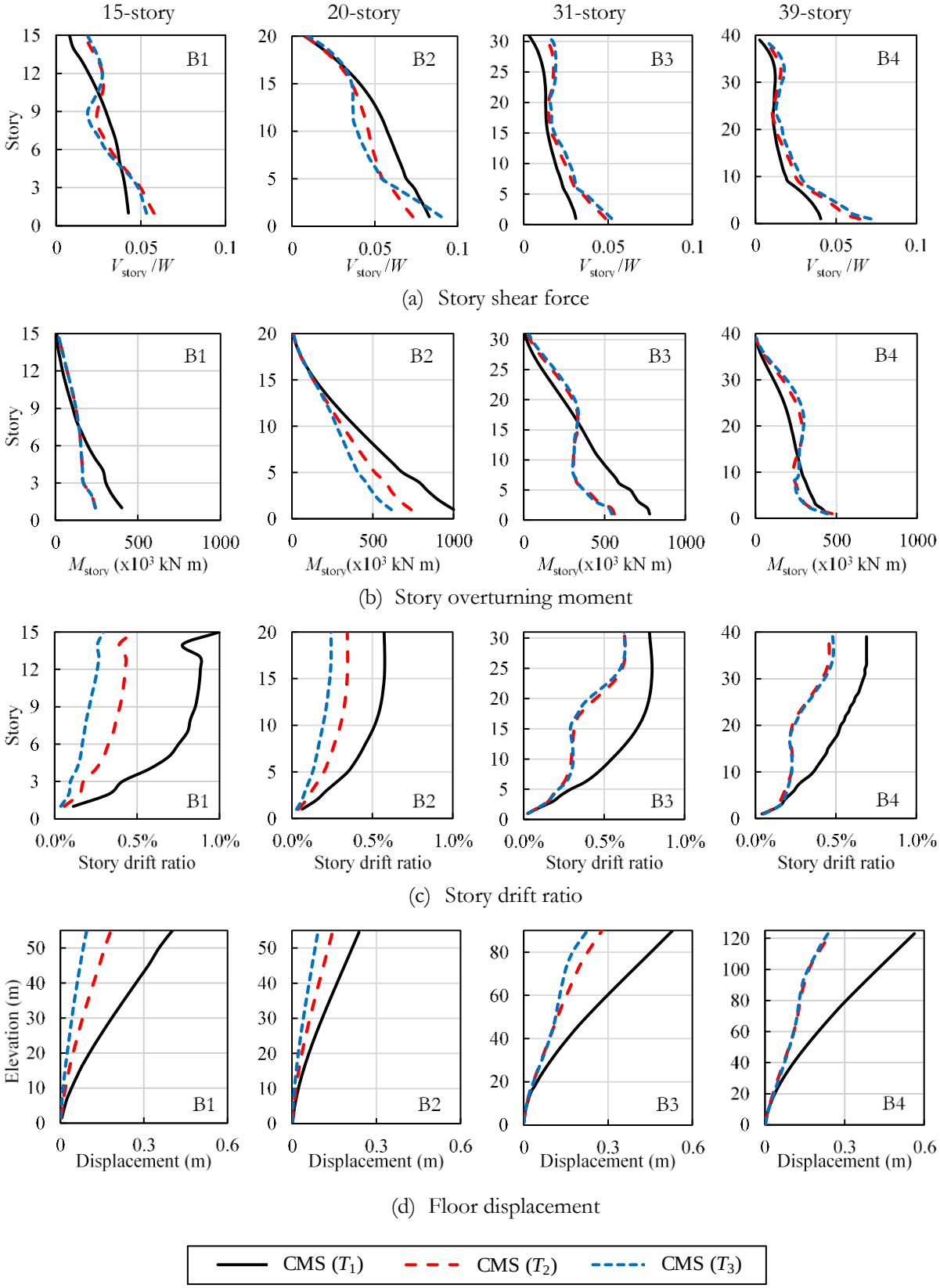

Fig. 10. (a) Story shear force; (b) story overturning moment; (c) story drift ratio; and (d) floor displacement computed from NLRHA for X-direction seismic excitation using three sets of CMS ground motions. CMS (T_1), CMS (T_2), and CMS (T_3) refer to the computed results using CMS conditioned at periods closest to the periods of the 1st, 2nd, and 3rd translational modes of the building in the direction of seismic excitation, respectively.

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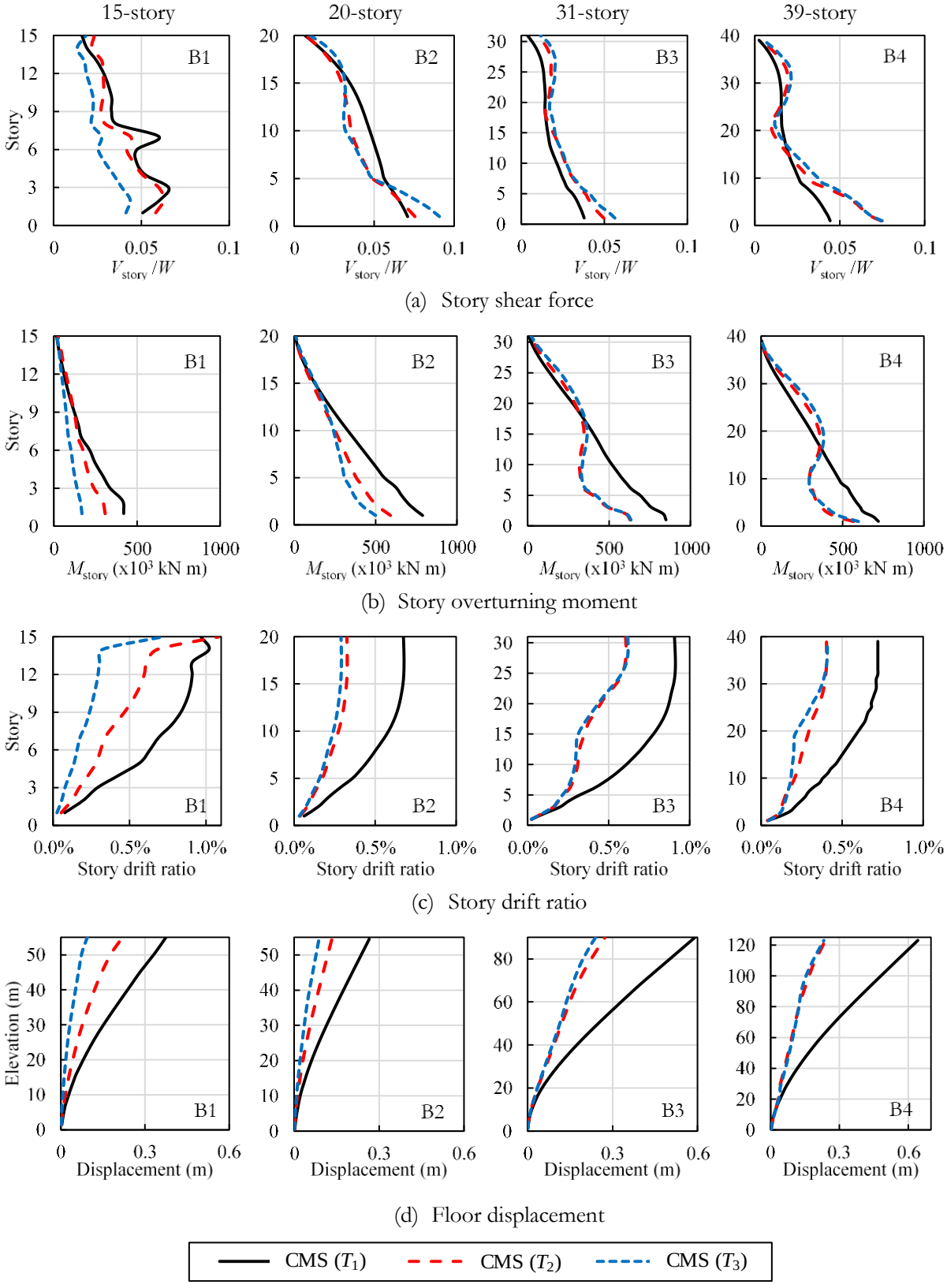

Fig. 11. (a) Story shear force; (b) story overturning moment; (c) story drift ratio; and (d) floor displacement computed from NLRHA for Y-direction seismic excitation using three sets of CMS ground motions. CMS (T_1), CMS (T_2), and CMS (T_3) refer to the computed results using CMS conditioned at periods closest to the periods of the 1st, 2nd, and 3rd translational modes of the building in the direction of seismic excitation, respectively.

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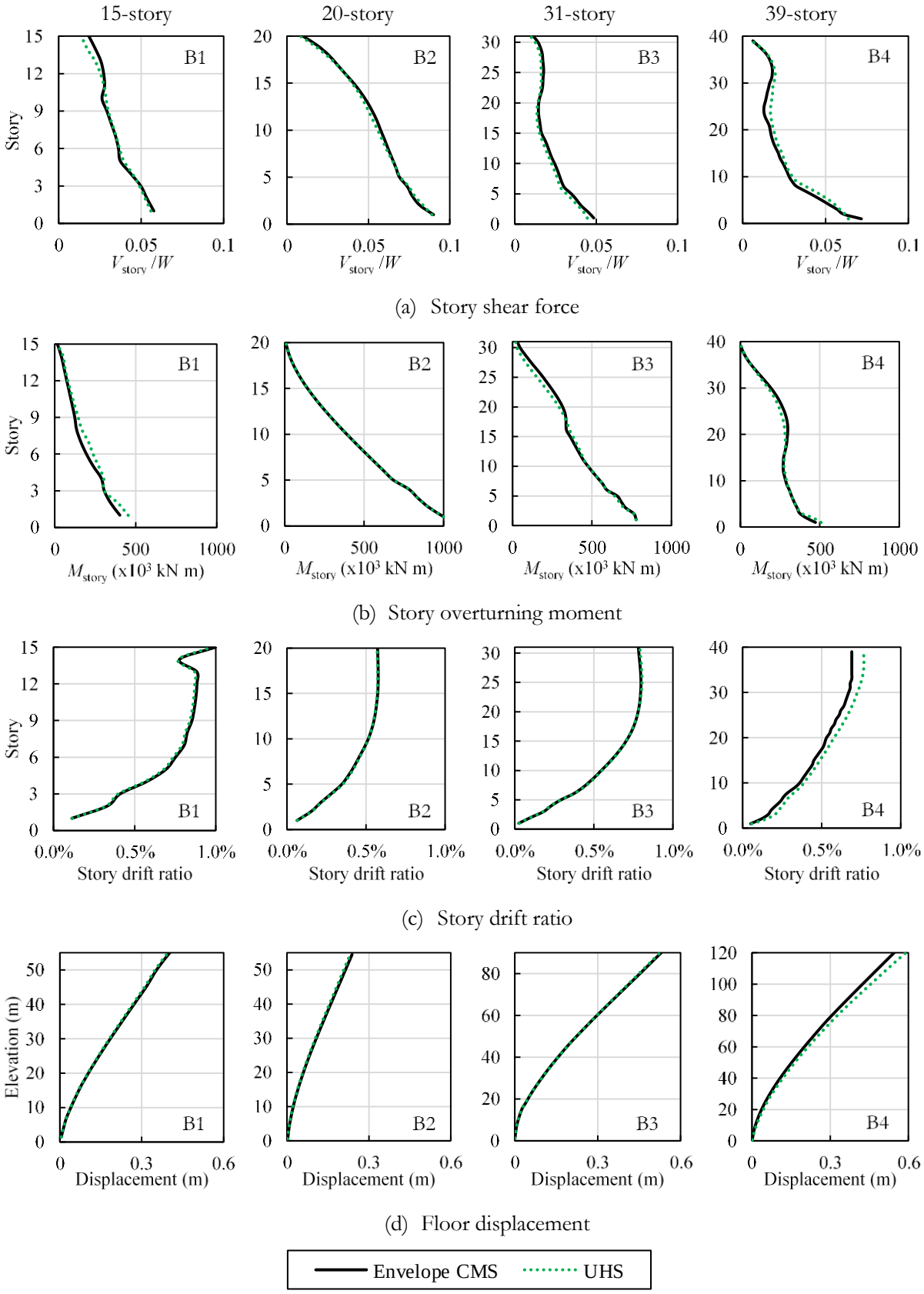

Fig. 12. (a) Story shear force; (b) story overturning moment; (c) story drift ratio; and (d) floor displacement computed from NLRHA for X-direction seismic excitation using CMS and UHS as the target spectrum.

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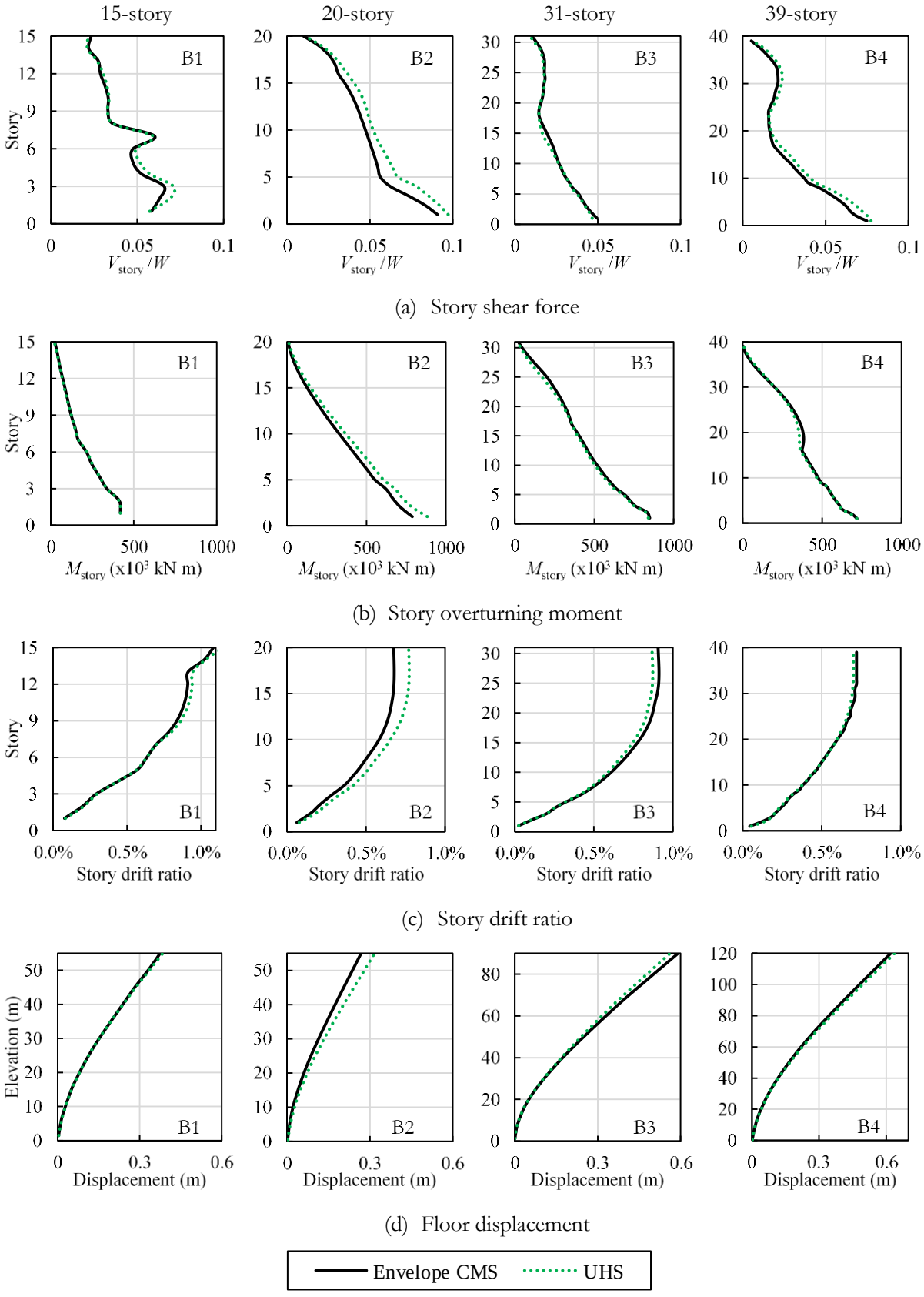

Fig. 13. (a) Story shear force; (b) story overturning moment; (c) story drift ratio; and (d) floor displacement computed from NLRHA for Y-direction seismic excitation using CMS and UHS as the target spectrum.

7. Conclusions

Four existing tall buildings located on soft-soil layers in Bangkok were used in this study to investigate the application of CMS in NLRHA for design purposes and to compare seismic demands computed by NLRHA using CMS and UHS as target spectrum in selecting and scaling of ground motions. When using CMS as target spectrum for tall buildings, higher-mode periods should also be considered for response parameters dominated by higher modes such as base shear forces and mid-height overturning moments. Enveloping of force demands computed from NLRHA using CMS ground motions conditioned at multiple periods should be undertaken before used as design demand values. For response quantities dominated by the fundamental mode such as floor displacements and story drift ratios, CMS ground motions conditioned at the fundamental period are sufficient to be used in the analysis. Using UHS spectral matching ground motions can avoid enveloping of results and significantly reduce the computational effort as required when using multiple sets of CMS ground motions conditioned at multiple periods.

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