

Effect of near-fault earthquakes on North American nuclear design spectra

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Abstract

Ground motion records from recent earthquakes show that near-fault ground motions are different from far-field ground motions in that they often contain strong coherent dynamic long period pulses and permanent ground displacements. The objective of the current study is to assess the safety implications of near-fault earthquakes (NFE) on nuclear power plant structures designed according to North American codes. Fifty-four fault-normal near-fault records in the forward directivity were selected for this investigation. Spectral comparison of the selected earthquake records with the US and Canadian design spectra was conducted. From the investigation it was concluded that the current nuclear design spectra may need to be adjusted to better reflect the effect of near-fault earthquake ground motions.

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1. Introduction

Ground motion records from recent earthquakes show that near-fault earthquakes (NFE) are different from far-field ground motions in that they often contain strong long period pulses and possible permanent ground displacements. The dynamic response is often dominated by a high magnitude velocity pulse of long duration that occurs in the horizontal component direction normal to the strike of the fault.

In near-fault zones, the propagation of rupture towards a site at a velocity close to the shear wave velocity causes most of the seismic energy from the rupture process to arrive in a single large pulse of motion. These pulses occur at the beginning of the record and represent the cumulative effect of the seismic radiation from the fault (Somerville et al., 1997). The ground motion in the forward rupture sites are characterized by the large pulses of long duration in the fault-normal direction. Sites in the opposite direction of fault rupture, or backward sites, have lower amplitude pulses of longer duration than the fault-normal component of the ground motion in the rupture propagation direction.

Although the special characteristics of NFE were known for some time, their importance in earthquake design of civil engi-

neering structures was not fully realized until several failures occurred during the 1992 Landers, 1994 Northridge, and 1995 Kobe earthquake events. The limited number of structures and near-fault records used in the published research emphasize the need for a study of near-fault ground motions and their effect on a wide range of structures designed according to current codes. The effect of NFE may not have been rigorously included in the development of available seismic design codes.

The objective of the current study is to evaluate the safety implications of near-fault earthquake ground motion on the design of nuclear facilities in North America considering the US Nuclear Regulatory Commission NUREG/CR 6728 (2001), “Revisions of Regulatory Guidance on Design Ground Motions”, and the current Canadian code CSA-N289.3 (1992), “Design Procedures for Seismic Qualifications of CANDU Nuclear Power Plants”.

2. Characteristics of NFE records

Ground motion recorded in the near-fault region during recent earthquakes showed significant variation between records even between those recorded by instruments located in the same general area. Some of these records contain high peak ground acceleration (PGA) with short-duration pulses that are known as acceleration spikes. In other cases, the pulses are of longer dura-

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tion but with lower PGA (Anderson and Bertero, 1987). Most of the variability of the ground motion in the far-field region is attributed to distance to fault, the path, and the local site effects. However, in the near-fault zone, the variability in the acceleration time history records is mainly due to rupture directivity effect, the direction of the component measured as to whether it is in the fault-normal or fault parallel directions, type of faulting, and hanging wall effects for thrust faults.

Chopra and Chintanapakdee (2001) conducted an analytical investigation on the response of elastic and inelastic single-degree-of-freedom (SDOF) systems to near-fault and far-field earthquake motions. It was concluded that the velocity-sensitive spectral region for the fault-normal component of NFE is much narrower, and their acceleration-sensitive and displacement-sensitive regions are much wider as compared to far-field motions. The narrower velocity-sensitive region of near-fault records is shifted towards longer periods.

Ghobarah and Elgohary (2002) studied the characteristics of NFE records in terms of their response spectra. A set of 30 near-fault records from ten major earthquake events were selected for the study. The selection of the earthquakes was based on major events with moment magnitude >6 . The records were from stations located at horizontal distance to the surface projection of the rupture not more than 15 km. The high demands of the mean and the mean plus standard deviation of the studied NFE records in the long period range was identified. It was concluded that the separation of the low frequency component of near-fault record from the high frequency content by applying digital signal filters was a realistic method for identifying the near-fault pulse parameters. That procedure provides rational basis to justify and clarify when idealized pulses can substitute for the complete near-fault record in structural analysis.

Kitada et al. (2004) examined 62 NFE ground motions recorded recently in Japan in order to provide records for the use in the Coordinated Research Program (CPR) sponsored by the International Atomic Energy Agency (IAEA) on the safety significance of NFE. The ground motions were recorded on stiff soil sites or rock sites. Sixteen of the examined records were recommended for use in the structural seismic analysis. The main selection criteria for the recommended records were to have short duration and strong directivity, and to contain low frequency impulsive motion in the velocity time history. The maximum acceleration and velocity of the recommended NFE ground motions are plotted on the PGA versus peak ground velocity (PGV) plane as shown in Fig. 1. From the figure, it can be seen that the relationship of the records – recommended by Kitada et al. for NFE analysis – is almost linear, where most of the records are bounded between PGA/PGV ratios of $7\text{--}12\text{ s}^{-1}$, regardless of the earthquake magnitudes and focal distance.

3. Response of structures to NFE

Available research on the response of structures to NFE records is fairly limited. Krawinkler et al. (1999) studied the effect of specific pulses with pulse period T_p on the response of structures with a fundamental period of T at various performance

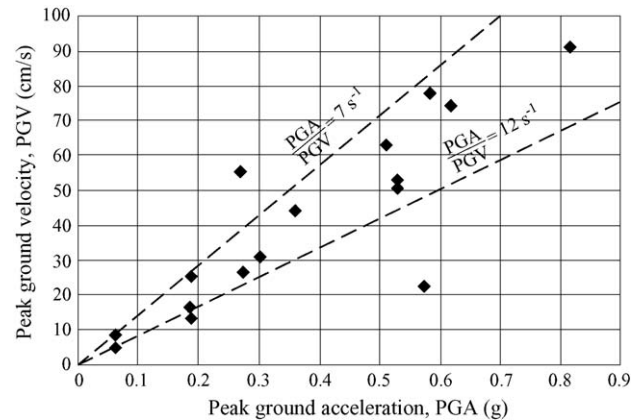


Fig. 1. Relationship of PGA vs. PGV for NFE records on stiff soil (Kitada et al., 2004).

levels. It was found that SDOF spectra are adequate to represent multi-degree-of-freedom (MDOF) system ductility demands for stiff structures with $T/T_p < 1.0$, but are poor in representing the demands for flexible structures with $T/T_p > 1.0$. It was concluded that SDOF spectra alone are inadequate to represent seismic demands for NFE ground motions.

Liao et al. (2001) studied the nonlinear response characteristics of reinforced concrete frames subjected to NFE. Five and twelve-storey moment resisting frames were designed according to the Taiwan building code. Four near-fault records from the 1999 Chi-Chi (Taiwan) earthquake were used as well as another set of earthquake records at the same locations recorded during previous events representing far-field earthquakes. All records were scaled to the same PGA of 3.0 m/s^2 . It was concluded that storey drifts calculated based on near-fault ground motion input for both 5- and 12-storey frames were higher than the storey drifts due to far-field ground motion.

El Sheikh et al. (2003) studied the nonlinear response characteristics of 3-, 6-, 12-, and 20-storey reinforced concrete frames subjected to NFE. Results were obtained in the form of static pushover using modal square root of the sum of the squares (SRSS) pattern and dynamic capacity curves from four selected NFE records. The capacity curve obtained from the nonlinear pushover analysis was found to provide a lower bound when compared to dynamic response of the structure. In other words, for the same base shear, the static pushover analysis gave conservative estimates of the displacement of the structure. It was also concluded that the nonlinear static pushover approach is particularly suited for displacement-based design of structures subjected to NFE.

Alavi and Krawinkler (2004) demonstrated that an equivalent acceleration pulse may be used in the structural analysis instead of the actual time history in a range of structure period to pulse period ratio (T/T_p) of $0.375\text{--}3.0$. The equivalent pulses are defined by three parameters: the pulse type, pulse period T_p , and pulse intensity $a_{g,\max}$ ($=a_{\text{eff}}$). A sensitivity analysis concluded that the structural response is not very sensitive to the choice of T_p . On the basis of a regression analysis, it was concluded that T_p is dependent on the magnitude of the ground motion M , such

that:

$$\log_{10} T_p = -1.76 + 0.31M \quad (1)$$

Due to the square nature of the proposed pulses, the maximum velocity $v_{g,\max}$ ($=v_{\text{eff}}$) is related to the maximum acceleration such that: $v_{\text{eff}} = a_{\text{eff}} T_p / 4$. To estimate the intensity of the equivalent pulse, the differences between the maximum story ductility demands obtained from the near-fault record and the equivalent pulse were minimized. A regression analysis was conducted and the v_{eff} was found to be dependent on the magnitude M and the distance R of the fault, such that:

$$\log_{10} v_{\text{eff}} = -2.03 + 0.65M - 0.47 \log_{10} R \quad (2)$$

Eqs. (1) and (2) when plotted, show that the equivalent near-fault pulse becomes very large for large magnitude and diminishes around a magnitude of approximately 5.5. Eqs. (1) and (2) are based on a relatively small set of near-fault records from earthquakes of magnitude ranging from 6.2 to 7.5 and need to be evaluated in more details, particularly for smaller magnitude earthquakes (higher performance levels).

4. North American nuclear design spectra

4.1. US regulatory guidance on design ground motions NUREG/CR 6728

The US-NUREG/CR 6728 (2001) provides recommendations for seismic design ground motions for nuclear facilities in various regions of the US. The overall approach taken to define response spectral shapes applicable to western US (WUS) and central and eastern US (CEUS) conditions is to rely as much as possible on recorded strong ground motions. These motions are supplemented, where necessary, by ground motion estimates from well-validated theoretical models. A database of recorded time histories forms the foundation of empirical recommendations for spectral shapes. The database of recorded time histories includes motions at WUS and CEUS rock and soil sites, divided into magnitude (M) and distance (fault distance, R) sections. The database also includes motions recorded as recently as the 1999 Kocaeli, Turkey and the 1999 Chi-Chi, Taiwan earthquakes.

The appropriate design spectrum is selected using a probabilistic seismic hazard analysis (PSHA) for rock sites. The spectral shapes are scaled to match the uniform hazard spectrum (UHS) ordinates at 10 and 1 Hz. For design, the UHS is modified by a scale factor to a uniform reliability spectrum (URS). This scale factor achieves a relatively consistent annual frequency of plant component failure across the range of plant locations and structural frequencies. The developed response spectral shapes vary with magnitude of earthquake and distance to fault. To provide relationships for specifying a response spectral shape for a given magnitude and distance within the specified range of the attenuation relationships, a function was fitted to the weighted empirical spectral shapes.

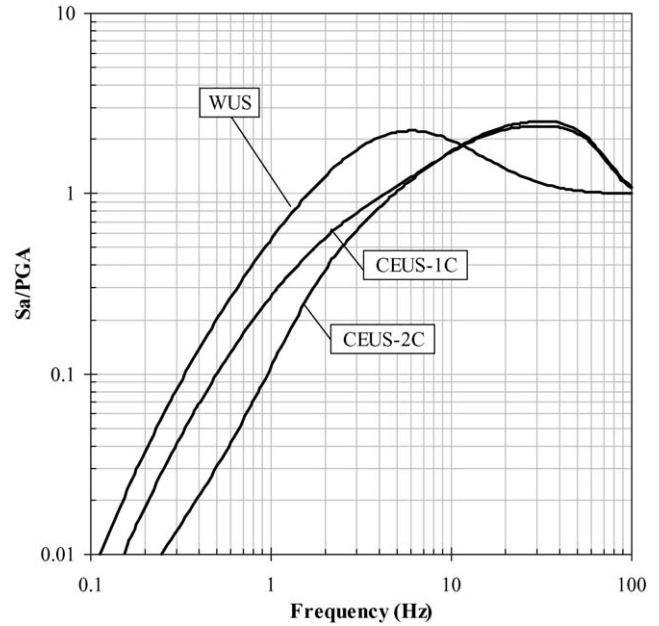


Fig. 2. Comparison of US-NUREG spectra for WUS and CEUS (for 1C and 2C models) for $M=6$ and $R=10$ km at rock sites.

The design spectral shapes for WUS and CEUS on rock sites are given by the following two equations, respectively:

$$\ln \left(\frac{S_a(f)}{\text{PGA}} \right) = \frac{C_1}{\cosh(C_2 f^{C_3})} + C_4 \left[\frac{e^{C_5 f}}{f^{C_6}} \right] \quad (3)$$

$$\ln \left(\frac{S_a(f)}{\text{PGA}} \right) = \frac{C_1}{\cosh(C_2 f^{C_3})} + C_4 \left[\frac{e^{C_5 f}}{f^{C_6}} + \frac{C_7 e^{C_8 f}}{f^{C_9}} \right]^{1/2} \quad (4)$$

where $S_a(f)/\text{PGA}$ is the pseudo acceleration (at frequency f)-to-peak ground acceleration ratio.

The coefficients C_1 to C_9 are functions of the magnitude M and the fault distance R . Functions for the coefficients that correspond to the best fit of the design spectral shapes for WUS and CEUS are given in the US-NUREG (2001) and shown in Appendix A. One set of functions for the nine coefficients is given for WUS, while two sets of functions for the coefficients are given for CEUS, namely, 1C and 2C for single corner and double corner frequency models, respectively. It can be seen that the form of Eqs. (3) and (4) is not based on a physical model, but is rather designed to fit the general characteristics of the spectral shapes. Fig. 2 shows a comparison between the US-NUREG recommended spectra for WUS and CEUS (for 1C and 2C models) for $M=6$ and $R=10$ km at rock sites.

The US-NUREG does not provide spectral shapes for soil conditions giving the reason that this is strongly site-dependent problem. The guidelines include procedures for developing hazard-consistent spectra for specific site soil conditions.

4.2. Canadian nuclear seismic design code CSA-N289.3

CSA-N289.3 (1992) provides guidelines for the seismic design procedures for the Canadian nuclear power plants. The code adopts seismic analysis using standard response spec-

tra. Fig. 3 shows the code response spectra on rock sites for ground motion of 0.1 g PGA, 71 mm/s PGV, and 30.5 mm peak ground displacement (PGD). The same figure shows the standard 5% damping response spectra for rock and soil sites scaled to 0.1 g. The spectra can be scaled according to the peak ground acceleration of a given site. In the development of the [CSA-N289.3 \(1992\)](#) design spectra, NFE effects were not specifically included. However, when sufficient strong motion records representative of the site geological condition are available, the code allows for the development of site-dependent ground response spectra that can be used for design.

5. NFE ground motion data

A set of 54 near-fault records from major earthquake events was selected for the analysis in this study. Most of the records were from a fault-normal mechanism in the forward directivity zone and the recording stations are within 20 km from the fault. The NFE records were divided into two groups according to the magnitude of the earthquake. Categorization of earthquakes was based on their magnitudes. [Table 1](#) shows 29 records with magnitude >6, while [Table 2](#) shows 25 records with magnitude

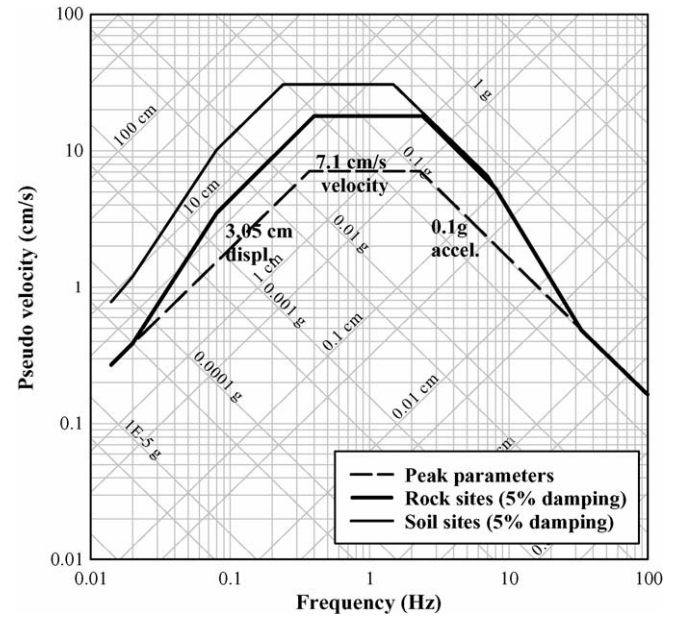


Fig. 3. CSA-N289.3 standard spectra at peak ground motion parameters and calculated for 5% damping ratio for rock and soil sites (normalized to 0.1 g).

Table 1
NFE records in forward directivity with magnitude >6

Earthquake	Date	Site	Station and component	<i>M</i>	<i>R</i> (km)	PGA (g)	PGV (cm/s)	PGA/PGV (s ⁻¹)
Gazli, USSR ^a	17/05/1976	Rock	Karakyr, GZ090	7.3	3.0	0.718	71.7	9.8
Morgan Hill, CA	24/04/1984	Rock	Gilroy array #6, G06-UP	6.2	11.8	0.405	14.1	28.2
Morgan Hill, CA	24/04/1984	Rock	Coyote Lake Dam, CYC285	6.2	0.1	1.298	80.8	15.8
Morgan Hill, CA	24/04/1984	Rock	Gilroy Gavilan Coll., GIL067	6.2	14.0	0.114	3.6	31.1
Cape Mendocino, CA ^a	25/04/1992	Rock	Cape Mendocino, CPM000	7.1	8.5	1.497	127.6	11.5
Landers, CA	28/06/1992	Rock	Lucerne, LCN345	7.3	1.1	0.785	32.0	24.1
Northridge, CA ^a	17/01/1994	Rock	Pacomia Kagel Canyon, PKC360	6.6	8.2	0.433	51.5	8.2
Northridge, CA	17/01/1994	Rock	Pacomia Dam, PUL104	6.6	8.0	1.585	55.8	27.9
Izumi, Japan	26/03/1997	Rock	0832 – KGS002,0	6.3	13.2	0.727	15.3	46.7
Miyanojoh, Japan	26/03/1997	Rock	0832 – KGS005,90	6.3	14.8	0.493	20.9	23.1
Akune, Japan	13/05/1997	Rock	0538 – KGS004,0	6.2	12.8	0.156	9.6	15.9
Ikumonaka, Japan	25/06/1997	Rock	0950 – YMG003,90	6.1	20.0	0.136	3.7	35.7
Susa, Japan	25/06/1997	Rock	0950 – YMG001,90	6.1	19.5	0.140	2.4	57.7
Tsuwano, Japan	25/06/1997	Rock	0950 – SMN014,0	6.1	14.5	0.421	7.7	53.8
Kocaeli, Turkey ^a	17/08/1999	Rock	Arcelick, 000	7.4	17.0	0.298	23.8	12.0
Kocaeli, Turkey ^a	17/08/1999	Rock	Gebze, 000	7.4	17.0	0.401	49.1	8.0
Chi-Chi, Taiwan	20/09/1999	Rock	TCU045, N	7.3	20.0	0.512	39.0	12.9
Chi-Chi, Taiwan	20/09/1999	Rock	TCU095, N	7.3	17.0	0.712	49.1	14.2
Chi-Chi, Taiwan ^a	20/09/1999	Rock	CHY080-W	7.3	14.9	0.968	107.5	8.8
Average (19 records)				6.7	11.7			
Average (6 records) ^a				7.2	11.4			
Nigata Prefecture, JP	16/06/1964	Soil	Kawagishi-cho, EW	7.5	0.0	0.171	56.5	3.0
San Fernando, CA ^a	02/09/1971	Soil	Pacoima Dam, PCD164	6.6	2.8	1.226	112.6	10.7
Imperial Valley, CA	15/10/1979	Soil	El Centro array #6, VL	6.6	1.3	1.665	57.5	28.4
Imperial Valley, CA	15/10/1979	Soil	El Centro array #7, VL	6.6	0.6	0.544	26.4	20.2
Loma Prieta, CA ^a	18/10/1989	Soil	Gilroy Array #6, GO6000	7.0	19.9	0.126	12.8	9.7
Loma Prieta, CA	18/10/1989	Soil	Corralitos, CLS000	7.0	5.1	0.644	55.2	11.4
Cape Mendocino, CA ^a	25/04/1992	Soil	Petrolia, PET090	7.1	9.5	0.662	89.8	7.2
Kobe, Japan	16/01/1995	Soil	Takarazuka, TAZ090	7.0	1.2	0.694	120.8	5.6
Erzican, Turkey ^a	18/08/1999	Soil	Erzican, ERZ-EW	6.9	17.0	0.619	59.4	10.2
Duzce, Turkey	11/12/1999	Soil	Bolu, BOL090	7.2	17.6	0.822	62.1	13.0
Average (10 records)				7.0	7.5			
Average (5 records) ^a				6.9	10.9			

^a NFE records with PGA/PGV ratio ranging from 7 to 12 Hz.

Table 2
NFE records in forward directivity with magnitude <6

Earthquake	Date	Site	Station and component	<i>M</i>	<i>R</i> (km)	PGA (g)	PGV (cm/s)	PGA PGV (s ⁻¹)
Iwate Prefecture, Japan ^a	01/04/1970	Rock	Miyako Harbor, NS	5.8	17.0	0.189	4.4	42.1
New Madrid, Missouri	31/12/1988	Rock	Ridgely, Tennessee	2.2	10.0	0.009	0.2	44.1
Knoxville, Tennessee	12/02/1989	Rock	Corryton, HL (N0)	2.4	9.8	0.005	0.2	24.5
Miramichi, Canada ^a	31/03/1982	Rock	Mitchell Lake Rd., N28	5.0	3.9	0.193	1.9	99.7
Whitter Narrows, Calif. ^a	10/01/1987	Rock	Transmitter Hill, GRV330	5.9	12.1	0.457	19.0	23.6
Whitter Narrows, Calif. ^a	10/01/1987	Rock	SanGabriel–EGrand, GRV180	5.9	9.0	0.304	23.0	13.0
Helena, Montana ^a	31/10/1987	Rock	Carroll College HMC270	5.5	8.0	0.173	16.5	10.3
Massena, New York ^a	08/09/1988	Rock	MSNA_NCEER, N335	2.3	10.0	0.009	0.2	44.1
Massena, New York	19/07/1989	Rock	MSNA_NCEER, N335	2.7	7.5	0.003	0.1	29.4
Hinoemata, Japan ^a	02/06/1996	Rock	FKS029, 90	4.3	13.7	0.350	4.6	74.6
Naruko, Japan ^a	13/08/1996	Rock	MYG005,90	5.0	11.0	0.708	5.7	122.0
Atami, Japan ^a	03/03/1997	Rock	SZO001, 90	5.0	18.9	0.127	1.3	95.8
Itohi, Japan ^a	26/04/1998	Rock	SZO002, 90	4.7	10.7	0.356	8.4	41.6
Atami, Japan ^a	26/04/1998	Rock	SZO001, 90	4.7	19.4	0.070	0.8	85.8
Average (14 records)				4.4	11.5			
Average (10 records) ^a				5.6	13.5			
Ibaraki Prefecture, Japan	14/11/1964	Soil	Atomic Energy Research, NS	5.1	8.0	0.202	39.6	5.0
Japanese Eq.	28/05/1966	Soil	Matsushiro-C, NS	5.3	4.0	0.380	34.0	11.0
Japanese Eq.	30/03/1968	Soil	Wakayama Harbor, EW	5.0	5.0	0.442	13.7	31.6
Lytle Creek, CA	09/12/1970	Soil	Wrightwood, WTW205	5.4	15.4	0.200	10.5	18.7
Livermore, CA	27/01/1980	Soil	Eastman Kodak, KOD180	5.8	17.6	0.301	19.1	15.5
Chalfant Valley	21/07/1986	Soil	Zack Brothers Ranch ZAK270	5.9	11.0	0.143	7.0	20.0
Chiba Prefecture, Japan	11/10/1997	Soil	Kashima Harbor Works, EW	5.2	12.0	0.128	8.2	15.3
Duzce, Turkey aftershock	12/11/1999	Soil	496, EW	5.4	17.9	0.590	26.5	21.8
Duzce, Turkey aftershock	12/11/1999	Soil	492, NS	5.4	17.7	0.620	17.1	35.6
Duzce, Turkey aftershock	12/11/1999	Soil	487, EW	5.4	16.9	0.155	14.0	10.9
Duzce, Turkey aftershock	12/11/1999	Soil	498, EW	5.4	17.5	0.212	8.0	26.0
Average (11 records)				5.4	13.0			

^a NFE records on rock sites with magnitude <6 and >4.

<6. The records were divided into two groups with respect to magnitude of 6 since it is likely that a siting study of a near-fault site would identify the design magnitude >6. For each record, the earthquake recording station, site soil type, magnitude, distance to fault, PGA and PGV data is provided. The records include motions recorded in East and West North America as well as other countries. Each group is divided into two subgroups according to the site condition, either rock or soil. In the two tables, the records in the soil sites' subgroups include records on shallow and deep stiff soil and do not contain records measured on soft soil. It is not likely that near-fault records on soft soil be of interest for nuclear power plants, except in special cases.

6. Elastic response spectra

A comparison between the spectra of the NFE ground motions and the design spectra of the US-NUREG and CSA-N289.3 was conducted. Fig. 4 shows a comparison between the mean and mean plus one standard deviation (Mean + std) of spectra of the NFE records on rock sites with magnitude >6 (19 records, Table 1) and the US-NUREG recommended spectra at WUS and CEUS. The figure also includes the CSA-N289.3 design spectrum. The US-NUREG design spectra were calculated using Eqs. (3) and (4) for WUS and CEUS regions, respectively. In order to determine the coefficients C_1 to C_9 in the

equations, the values of the magnitude M and the distance to fault R were taken as the average of the used records, i.e. $M = 6.7$ and $R = 11.7$ km. Fig. 4 shows that the CSA-N289.3 design spectrum is higher than the WUS design spectrum for the whole frequency range. The CSA-N289.3 design spectrum is also higher than the CEUS spectra for frequencies up to 10 Hz. The mean plus one standard deviation spectrum of the used records is higher than that of WUS and CEUS regions but less than the CSA-N289.3 spectrum in the frequency range of 2–10 Hz where major nuclear structures are normally within. For frequencies above 10 Hz, the mean plus one standard deviation spectrum of the used records is higher than both US-NUREG and CSA-N289.3 design spectra.

Fig. 5 shows a comparison between the mean and mean plus one standard deviation of spectra of the NFE records on rock sites with magnitude <6 and >4 (10 records, Table 2) and the US-NUREG design spectra (WUS and CEUS) as well as the CSA-N289.3 design spectra. Observations made from the comparison for rock sites with magnitudes >6 (Fig. 4) are also largely valid for magnitudes <6 as well.

Fig. 6 shows a comparison between the mean and mean plus one standard deviation of the spectra of the NFE records of magnitude >6 listed in Table 1 on both rock (19 records) and soil sites (10 records) and the CSA-N289.3 design spectrum. The 5% damping spectra of the NFE ground motions were scaled to PGA of 0.1 g for comparison. Fig. 6 shows that the spectra of the near-fault records on rock of magnitude >6 are higher

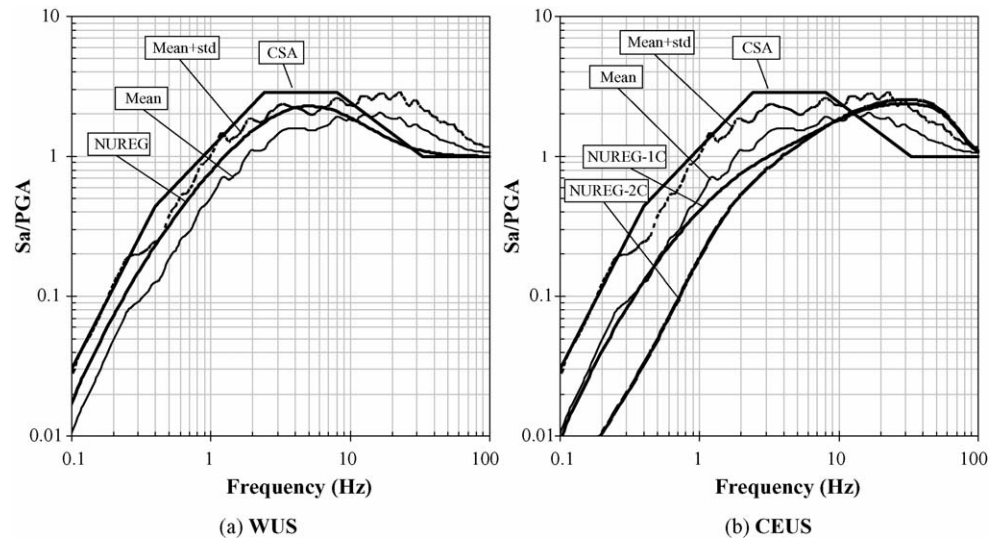


Fig. 4. Comparison between the spectra of NFE records with magnitude >6 on rock sites (19 records, Table 1), the CSA-N289.3 and the US-NUREG 2001 recommended design spectral shapes at (a) WUS; and (b) CEUS (1C and 2C) for $M=6.7$ and $R=11.7$ km.

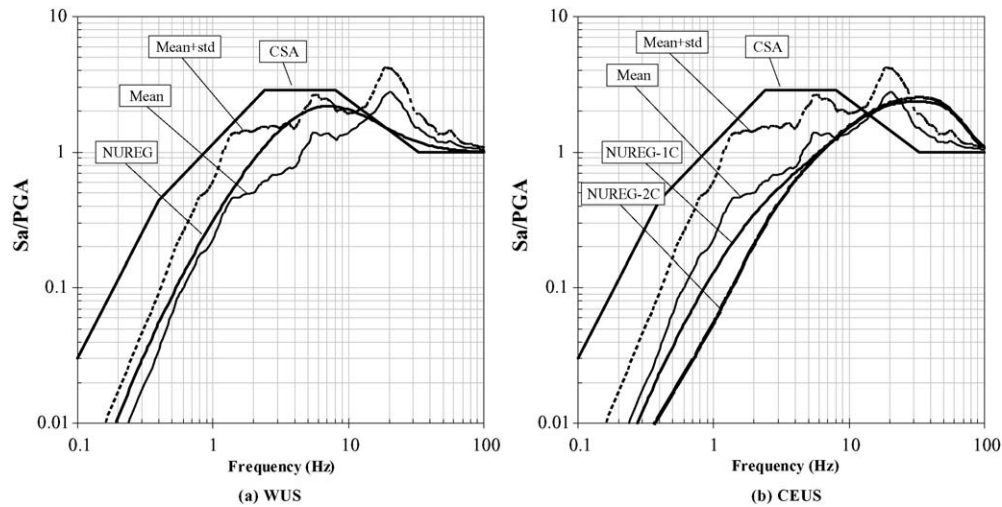


Fig. 5. Comparison between the spectra of NFE records with magnitude <6 and >4 on rock sites (10 records, Table 2), the CSA-N289.3 and the US-NUREG 2001 recommended design spectral shapes at (a) WUS; and (b) CEUS (1C and 2C) for $M=5.6$ and $R=13.5$ km.

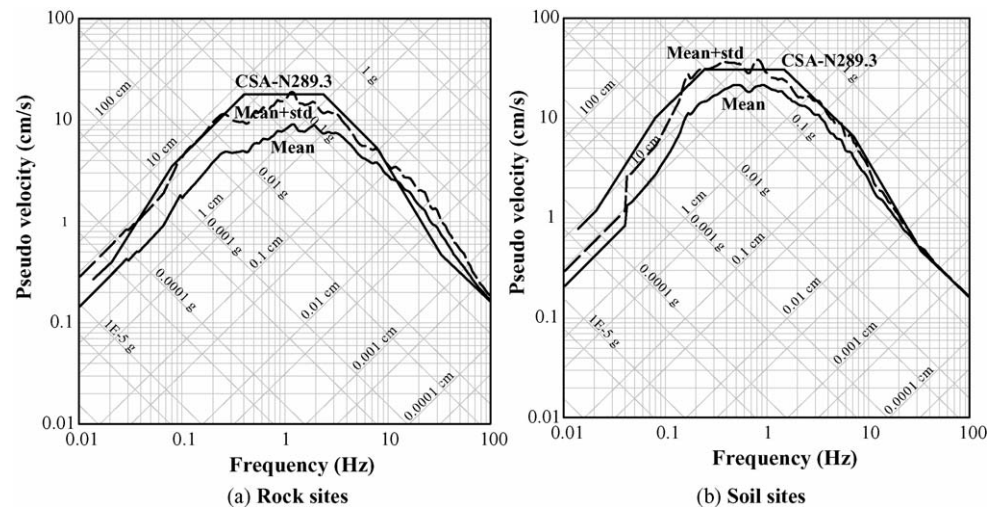


Fig. 6. Comparison between the spectra of NFE records (Table 1) of magnitude >6 on (a) rock sites (19 records); and (b) soil sites (10 records) scaled to PGA of 0.1 g and the CSA-N289.3 design spectrum.

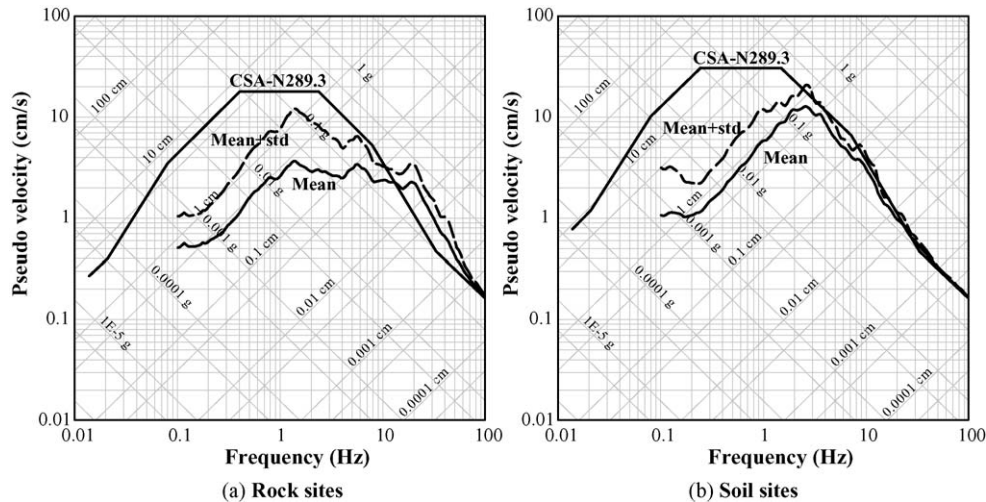


Fig. 7. Comparison between the spectra of NFE records (Table 2) of magnitude <6 on (a) rock sites (14 records); and (b) soil sites (11 records) scaled to PGA of 0.1 g and the CSA-N289.3 design spectrum.

than the nuclear design spectrum for the frequency range of <0.04 Hz (25.0 s period) and over 10 Hz (0.1 s period). The fundamental frequencies of major nuclear structures are normally in the range of 2–10 Hz where the design spectrum is higher than the spectra of the near-fault records. However, the fundamental frequencies of equipments may be higher than 10 Hz where the design spectrum is less than the spectra of the near-fault records. For the case of the near-fault records on soil of magnitude >6 , the CSA-N289.3 spectrum is less than the mean plus one standard deviation of the NFE spectrum in the frequency range of 0.1–2 Hz (0.5–10 s period). Even though it has been the practice not to build nuclear power plants on soil sites in near-fault zones, the design spectrum in the constant velocity range may need to be increased by almost 30%.

Fig. 7 shows a comparison between the mean and mean plus one standard deviation of the spectra of the NFE records of magnitude <6 listed in Table 2 on both rock (14 records) and soil sites

(11 records) and the CSA-N289.3 design spectrum. From the figure, it can be concluded that the spectra of the near-fault records on rock of magnitude <6 are higher than the nuclear design spectrum for the frequency range over 10 Hz (0.1 s period).

The implication of NFE records of magnitude >6 with PGA/PGV ratio ranging from $7\text{--}12\text{ s}^{-1}$ is studied. These records are denoted with an asterisk superscripted in Table 1. The selected PGA/PGV ratio and PGV value criteria are chosen to conform to the recommendations of Kitada et al. (2004) for records to be used in the seismic analysis of nuclear power plant structures. Fig. 8 shows comparison between the spectra of the selected records on rock sites (6 records) and the US-NUREG design spectra at WUS and CEUS as well as the CSA-N289.3 design spectrum. Fig. 9 shows the comparison between the spectra of the selected records on rock (6 records) and soil sites (4 records) and the CSA-N289.3 design spectrum. From the two figures it is observed that the mean plus standard deviation spec-

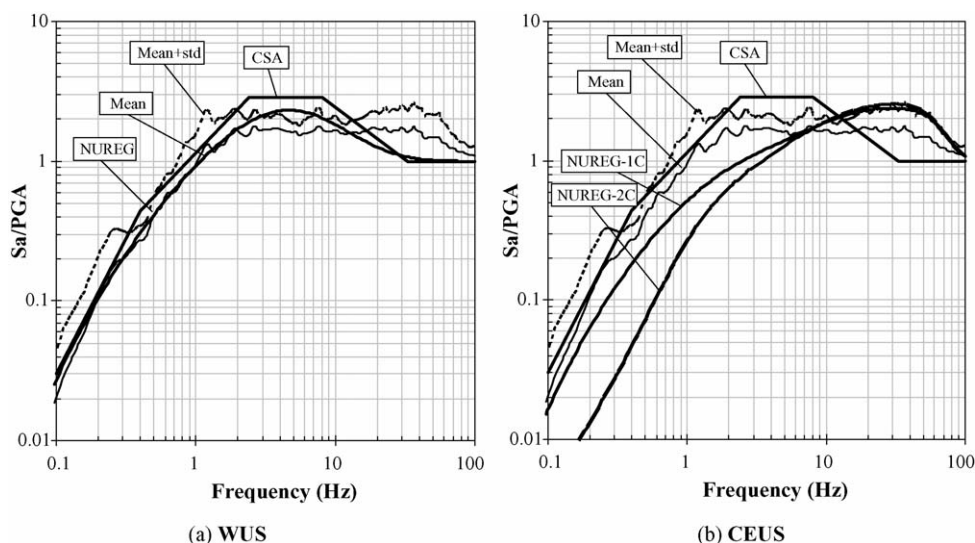


Fig. 8. Comparison between the spectra of NFE records with magnitude >6 and PGA/PGV ratio of $7\text{--}12\text{ s}^{-1}$ on rock sites (6 records, Table 1), the CSA-N289.3 and the US-NUREG 2001 recommended design spectral shapes at (a) WUS; and (b) CEUS for $M=7.2$ and $R=11.4$ km.

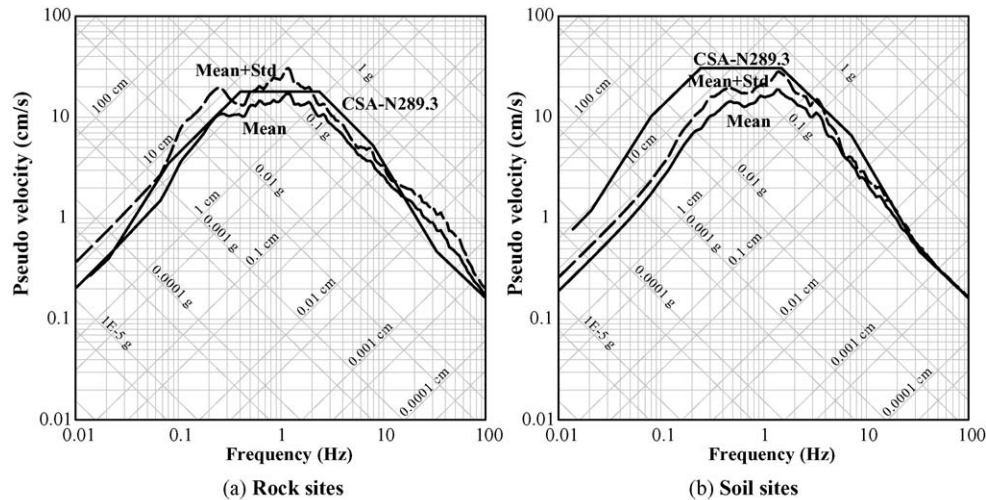


Fig. 9. Comparison between the spectra of NFE records of magnitude >6 with PGA/PGV ratio of $7\text{--}12\text{ s}^{-1}$ (Table 1) on (a) rock sites (6 records); and (b) soil sites (4 records) scaled to PGA of 0.1 g and the CSA-N289.3 design spectrum.

trum of the selected records on rock sites is higher than the CSA-N289.3 design spectrum for frequencies <2 and $>10\text{ Hz}$. This observation is also valid for the WUS region. The mean plus standard deviation spectrum of the selected records on rock sites is higher than the CEUS spectra for frequencies up to 20 Hz .

7. Conclusions and recommendations

The response spectra of 54 near-fault earthquake records are compared to the design spectra of US-NUREG/CR 6728 (2001) and CSA-N289.3 (1992). Most of the records are from a fault-normal mechanism in the forward directivity zone and the recording stations are within 20 km from the fault. The NFE records were divided into two groups according to the magnitude of the earthquake whether it is ≤ 6 . Each group is divided into two subgroups according to the site condition, either rock or soil. Based on the conducted analysis, the following conclusions and recommendations are reached:

1. The mean plus one standard deviation spectrum of NFE records on rock sites is less than the CSA-N289.3 (1992)

design spectrum in the frequency range of $2\text{--}10\text{ Hz}$ where major nuclear structures are normally within. This observation is valid for NFE records with magnitudes ≤ 6 .

2. The mean plus one standard deviation spectrum of NFE records with magnitude ≥ 6 on rock sites is higher than CSA-N289.3 (1992) design spectra for frequencies above 10 Hz where the fundamental frequencies of some nuclear equipment might be. Therefore, it is recommended that the CSA-N289.3 (1992) design spectra for rock sites be adjusted to accommodate the increased response at frequencies above 10 Hz .
3. The CSA-N289.3 (1992) design spectrum sufficiently envelopes the mean plus one standard deviation spectrum of NFE records on soil over the range of practical frequencies. This observation is valid for NFE records with magnitudes ≤ 6 .
4. The mean plus one standard deviation spectrum of the studied NFE records on rock sites is higher than the US-NUREG (2001) recommended spectra (calculated using the average magnitude and distance to fault of the considered records) over a wide frequency range for WUS, and for frequen-

Table A.1

Response spectral shape coefficients for 5% damping (NUREG 2001)

	WUS	CEUS (1C) ^a	CEUS (2C) ^b
C_1	1.8197	0.88657	0.97697
C_2	0.30163	$\exp(-10.411)$	$\exp(-9.4827)$
C_3	$0.47498 + 0.034356M + 0.0057204 \ln(R + 1)$	2.5099	2.3006
C_4	$-12.650 + M[2.4796 - 0.14732M + 0.034605 \ln(0.040762R + 1)]$	$-7.4408 + M[1.5220 - 0.088588M + 0.0073069 \ln(0.12639R + 1)]$	$-12.665 + M[2.4869 - 0.14562M + 0.024477 \ln(0.041807R + 1)]$
C_5	-0.25746	-0.34965	-0.21002
C_6	$0.29784 + 0.010723M - 0.0000133R$	$-0.31162 + 0.0019646R$	$0.74361 + 0.0000671R$
C_7	n.a.	3.7841	$\exp[-13.476 + M(4.4007 - 0.31651M + 0.000235R)]$
C_8	n.a.	-0.89019	$0.95259 + M(-0.58275 + 0.000166R)$
C_9	n.a.	$0.39806 + 0.058832M$	$-3.3534 + 0.44094M$

Note: Eq. (3) is used for the WUS; Eq. (4) is used for the CEUS. M , moment magnitude; R , fault distance.

^a 1C, single corner frequency model.

^b 2C, double corner frequency model.

cies below 30 Hz for CEUS. This observation is valid for NFE records with magnitudes ≤ 6 . Therefore, it is recommended that the US-NUREG (2001) spectra for rock sites be adjusted to accommodate the increased response due to NFE effects.

It should be noted that the above conclusions are based on limited analysis of few cases and specific magnitude and distance combinations. More analysis covering more cases will need to be conducted to refine or generalize the conclusions.

Appendix A

See Table A.1.

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