EFFECT OF GROUND MOTION PARAMETERS ON THE SEISMIC VERTICAL-TO-HORIZONTAL ACCELERATION RATIOS

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Abstract: *Recent studies clearly show the necessity of including the vertical component of earthquake ground motions in the seismic analysis and design of structures. This study investigates the effects of earthquake magnitude (M_w), epicentral distance (R_{epi}), and soil condition according to the average shear wave velocity (V_{s30}) on both the vertical-to-horizontal (V/H) spectral accelerations (SA) and peak ground accelerations (PGA) in the Eastern Canada region. To this end, 248 sets of records were selected from 67 earthquakes that occurred in the studied seismic region, with a magnitude (M_w) of 3.0 and above, an epicentral distance (R_{epi}) of less than 150 km, and different site soil conditions. In all cases, the computed average trendlines of PGA and SA ratios were found to be higher than the empirical ratio of 2/3 recommended in the current NBC edition. Moreover, a significant increase in the PGA ratios was observed with larger earthquake magnitude (M_w), reduced distance from the epicentre (R_{epi}), and smaller shear wave velocity (V_{s30}). Likewise, notable impacts of earthquake magnitude and soil condition on the V/H SA ratios were observed. In this regard, the average V/H SA ratio increased for periods up to 2.0 sec for larger earthquake magnitudes, and the ratio increased at soil conditions with smaller shear wave velocity (V_{s30}) for periods less than 0.5 sec. Finally, no correlation between the epicentral distance and the SA ratios was concluded.*

Keywords: Eastern Canada seismic region, the vertical component of ground motion, peak ground acceleration (PGA), spectral acceleration (SA), vertical-to-horizontal (V/H) ratio.

1. Introduction

The effects of vertical ground motion are usually disregarded in the seismic design and analysis of structures since deemed to be less important than horizontal motion effects (Beresnev et al., 2002). This assumption is based on the perception that buildings are mostly sufficiently rigid in the vertical direction. However, structural damage to the buildings, bridges, and subsequently non-structural components (NSCs) has been reported due to the destructive effect of the vertical ground motion following severe earthquakes, such as the 1994 M_w 6.7 Northridge earthquake (Bozorgnia et al., 1995; Papazoglou & Elnashai, 1996) and the 2012 M_w 5.8 Mirandola earthquake (Breccolotti & Materazzi, 2016). Hence, it is imperative to incorporate the vertical seismic component into the design of significant structures like long-span bridges, flooring systems with large bay spans, nuclear power facilities, and NSCs (Elgamal & He, 2004; Shirai et al., 2004; Nayak, 2021; Wang et al., 2023).

The vertical component of an earthquake is characterized by a higher frequency content when compared to horizontal components and tends to have a higher ratio of acceleration to velocity (a/v), particularly in the near-fault zone (Tso et al., 1992). In seismic events where P-waves are predominant, the peak vertical acceleration fluctuates based on parameters like earthquake magnitude, soil condition, and proximity to the fault (Bozorgnia et al., 2000). Most research findings on vertical ground motions indicate that the earthquake magnitude (M_w), epicentral distance (R_{epi}) and soil type notably impact the intensification of vertical ground acceleration, especially at shorter period ranges (Almahdi et al., 2020). In contrast, no significant effect of the fault mechanism was concluded (Campbell & Bozorgnia, 2000; Ambraseys & Douglas, 2003). Essentially, the vertical ground acceleration on firm soil sites, with the average shear wave velocity between 250 and 700 m/s ($250 < V_{s30} < 700$ m/s), is comparatively higher than the other soil types due to reduced inelastic attenuation and the absence of non-linear site effects (Campbell & Bozorgnia, 2003; Ambraseys et al., 2005).

Since the characteristics of the earthquake source and propagation path are identical and shared between the vertical and horizontal components of an earthquake, a strong correlation and relationship between them is anticipated. Consequently, the vertical seismic motion used as input spectra for seismic design should be harmonious with the horizontal motion and spectra outlined in seismic codes (Shirai et al., 2004). Therefore, the vertical component of ground motion in the form of the vertical-to-horizontal (V/H) spectral acceleration (SA) and peak ground acceleration (PGA) ratios was examined in several studies such as Pekcan et al. (2003), Bozorgnia and Campbell (2004), Gülerce and Abrahamson (2011), Wieser et al. (2012) and Mazloom and Assi (2022).

An analytical study to investigate the effects of earthquake magnitude, distance from the fault and the site conditions on V/H SA and PGA acceleration ratios was carried out by Bozorgnia and Campbell (2004) on a dataset comprising 443 near-source accelerograms. Data were collected from 36 earthquakes around the world in tectonically active regions, with magnitudes ranging from 4.7 to 7.7, recorded within a 60 km radius at the seismogenic rupture zone, specifically in shallow crustal areas on firm soil and very firm soil, soft rock, and firm rock. The notable effects of earthquake magnitude, distance from the fault and the site conditions, especially for firm soil sites, as well as the insignificant effect of the fault mechanism on the V/H spectral acceleration (SA) ratio, were determined. For all aforementioned parameters, the V/H SA ratio was notably large (near 1.8) in the shorter period range, precisely at periods less than 0.25 sec. Furthermore, the assessment of the soil conditions effect revealed that the average V/H ratio exceeds unity. This ratio reached 1.8 in the short period range of the near-field earthquakes with a large magnitude and at sites with firm soil.

Research conducted by McGuire et al. (2001) for the seismic regions of the Western United States (WUS) and Central-Eastern United States (CEUS) evidenced that the V/H ratio computed from recorded data is not influenced by fault distance for sites located at distances ranging from 20 km to 1000 km. However, in the CEUS seismic zone, a notable dependence of the V/H ratio on earthquake magnitude was noted, particularly in firm soil sites compared to rock sites. Nonetheless, when examining databases in the CEUS region, it was pointed out that hard rock site conditions exhibited high V/H ratios at higher frequencies, particularly at very close distances. Additionally, a decrease in the correlation between earthquake magnitude and distance from the fault was observed for both firm soil and rock sites. In similar studies by Pezeshk et al. (2018) for Central and Eastern North America (CENA) using earthquakes with magnitudes greater than 3.4 and epicentral distances of less than 1000 km, it was demonstrated that the V/H PGA and SA ratios vary as a function of the earthquake magnitude, source to site distance, and the shear-wave velocity of soil.

The National Building Code of Canada (NBC 2015, 2015b) suggests determining the vertical design spectral acceleration by multiplying the provided horizontal values by a single empirical ratio of 2/3 for the different Canadian seismic regions. A study conducted by Mazloom and Assi (2022) found that the computed mean V/H SA ratios reached a value of 0.86 in short periods up to 1.3 sec, which exceeded the recommended ratio of 2/3 by the National Building Code of Canada (NBC 2015, 2015b). Conclusions were based on the study of 248 time-history accelerations of 67 earthquakes recorded on very dense soil and soft rock (categorized as Site Class C by NBC 2015) in the Eastern Canada region, with a magnitude greater than 3.0 and the epicentral distance of less than 150 km. In a comparison study by Mazloom and Assi (2021), it was shown that the obtained V/H SA ratios are almost close for site classes A (hard rock with $V_{s30} > 1500$ m/s) and C (very dense soil and soft rock with $360 < V_{s30} < 760$ m/s) in the short period range up to 0.18 sec, with slightly higher ratios obtained for Site Class C. However, these two studies did not investigate the effects of earthquake magnitude and epicentral distance.

This paper assesses the importance of parameters which could affect the vertical acceleration spectra in the Eastern Canada seismic region, such as earthquake magnitude, epicentral distance, and soil type. For this purpose, the computed V/H PGA and SA ratios of the historical records described in the study by Mazloom and Assi (2022) were used in order to determine the impact level of the above-mentioned parameters on the vertical acceleration of earthquakes for this seismic region.

2. Data Selection

A total of 248 sets of historical records collected in the study by Mazloom and Assi (2022) from 67 earthquake events spanning from 1982 to 2015, in the Eastern Canada seismic region were chosen for this study. The selected earthquakes were then categorized based on their name, date of occurrence, and magnitude (M_w), as outlined in Table 1. The majority of the data was sourced from the Ground Motion Databases within the Engineering Seismology Toolbox (Seismotoolbox, 2019). The records for the 1982 M_w 4.9 Miramichi earthquakes and the 1988 Mw 5.9 Saguenay earthquake were obtained from Natural Resources Canada (NRCAN, 2001). A few ground motion series were also selected from the Strong-Motion Cosmos Virtual Data Center (VDC, 2018) and the Pacific Earthquake Engineering Research Center (PEER-NGA, 2018). In instances where information such as the earthquake name, magnitude, site conditions, and distance from the fault was missing, data were extracted from the Incorporated Research Institutions for Seismology (IRIS, 2018) and the U.S. Geological Survey (USGS, 2018). Since the majority of the earthquake magnitudes from historical events were provided in M_n form, the corresponding moment magnitudes (M_w) were obtained from both the USGS website (2018) and according to the equations proposed in the study by Bent (2009). The selected seismic events and the number of records were documented across four distinct site classes, determined according to the V_{s30} criteria proposed in NBC 2015. Thus, a total of 203, 22, 19 and 4 sets of records were collected from Site Class A (known as the hard rock with V_{s30} > 1500 m/s), Site Class B (rock, 760 < V_{s30} ≤ 1500 m/s), Site Class C (very dense soil and soft rock, 360 < V_{s30} < 760 m/s), and Site Class D (stiff soil, 180 < V_{s30} < 360 m/s), respectively.

Table 1. Chronologically sorted collection of the earthquakes

Earthquake Name	Date	M_W
Miramichi	1982/03/31	4.9
Miramichi	1982/05/06	3.5
Saguenay	1988/11/25	5.9
Crique Rouge	1992/11/17	4.0
Lac-du-Cerf	1993/05/06	3.0
Salaberry-de-Valleyfield	1993/07/30	3.3
Lac-Nominingue	1993/08/30	3.2
La Malbaie	1993/12/01	3.0
Mont-Laurier	1993/12/25	3.6
Saint-Joseph-de-la-Rive	1993/12/30	3.3
Port-au-Saumon	1994/09/25	3.8
Cheneville	1995/02/15	3.0
Saint-Philippe	1995/09/12	3.2
Lac-Aubin	1996/03/14	4.0
Lac-Quinn	1996/12/31	3.0
Lac-Aubin	1997/05/24	3.7
Baie-Saint-Paul	1997/08/20	3.2
La Malbaie	1997/10/28	4.3
Les Grands-Deserts	1997/11/06	4.9
Lac-Ministuk	1998/01/10	3.2
Fort-Coulonge	1998/02/26	3.2
Papineauville	1998/04/18	3.6
La Conception	1998/07/30	4.0
Lac-Saguenay	1999/06/18	3.0
Morin-Heights	1999/10/31	3.7
Ajax, Ontario	1999/11/26	3.3
Saint-Pascal	2000/06/15	3.2
Baie-Saint-Paul	2000/07/12	3.7
Baie-Saint-Paul	2000/07/12	3.0
Charlevoix	2001/05/22	3.1
Cap-Chat	2002/01/20	3.6
Notre-Dame-des-Prairies	2002/02/11	3.3
Au-Sable-Forks	2002/04/20	5.1
Au-Sable-Forks	2002/04/20	3.6

Earthquake Name	Date	M_W
Port-Cartier	2002/07/23	3.5
Baie-Saint-Paul	2002/08/17	3.3
Saint Regis Falls	2003/04/08	3.2
La Malbaie	2003/06/13	3.6
Les-des-Plages	2003/08/20	3.0
La Baie	2004/05/04	3.0
Port Hope	2004/08/04	3.2
Val-David	2005/03/03	3.0
Rivière-du-Loup	2005/03/06	4.7
Notre-Dame-de-Pontmain	2005/05/25	3.2
Fort-Coulonge	2005/07/04	3.1
La Minerve	2005/09/06	3.0
Georgian Bay	2005/10/20	3.8
Franklin	2006/01/09	3.7
Thurso	2006/02/25	4.1
Acadia	2006/10/03	3.9
Baie-Saint-Paul	2006/04/07	3.8
Sainte-Anne-des-Monts	2006/05/28	3.1
Eagle Lake	2006/07/14	3.5
Smooth Rock Falls	2006/12/07	3.7
Lac Saint-Crepin	2007/10/01	3.6
Rivière-du-Loup	2008/11/15	3.7
Brownsburg-Chatham	2010/02/28	3.2
Val-des-Bois	2010/06/23	5.1
Hawkesbury	2011/03/16	3.6
Thurso	2011/09/18	3.5
Verchères	2012/10/10	3.7
Hawkesbury	2012/11/06	3.5
Shawville	2013/05/17	4.5
Shawville	2013/05/17	3.3
Saddlebrook	2013/05/21	3.0
Hawkesbury	2015/07/15	3.5
NE of Shawville	2015/09/09	3.2

3. Computation of V/H PGA and SA Ratios

In the initial studies regarding the seismic design of structures, the PGA was identified as a crucial input for assessing structural damage and seismic design force (Ambraseys & Douglas, 2003). Yet, relying solely on the PGA ratio may not adequately reflect the combined impact of both the vertical and horizontal ground motions on structures because the vertical ground motion carries greater significance in the shorter period range. Consequently, the SA ratio is considered a more accurate parameter for establishing vertical spectra relative to horizontal ones (Ambraseys & Douglas, 2003). Therefore, both the V/H PGA and SA ratios were considered in the investigations of this study. Hence, the horizontal and vertical response spectra with a 5% damping ratio were derived for each set of records using the SeismoSignal software (SeismoSoft, 2018).

Each record set of an earthquake typically contains three orthogonal components, including one vertical and two horizontal time history accelerations. Therefore, calculating the V/H ratio in the presence of two horizontal components is a critical step for analysis. Moreover, analysing the horizontal components individually yields two distinct V/H values and involves a considerable computational effort, which can introduce complexity and potential confusion in the calculation process (Douglas, 2003; Albarello & Lunedei, 2013). Hence, merging horizontal response spectra is advisable due to the correlation between the earthquake components recorded at each station. To obtain a reliable estimation of the V/H ratio, the geometric mean method using the relation presented in Equations 1 and 2, which was suggested and verified by Douglas (2003), Albarello & Lunedei (2013), and NBC 2015, was applied for each set of records.

$$PGA_H = \sqrt{PGA_{H1} \times PGA_{H2}} \quad (1)$$

$$SA_H = \sqrt{SA_{H1} \times SA_{H2}} \quad (2)$$

Then, the V/H PGA and SA ratios for each set of records at different periods were computed as PGA_V/PGA_H and SA_V/SA_H, respectively.

4. Assessment of the Effect of Ground Motions Parameters on PGA Ratios

This section discusses the effective parameters, namely earthquake magnitude, fault distance and soil condition on the PGA_V/PGA_H ratio of selected historical ground motions in Eastern Canada, as shown in Figure 1 in the form of scatter plots and corresponding linear trendlines. An average PGA ratio of 0.78 was obtained based on the selected ground motions.

4.1. Earthquake Magnitude (M_w)

It is notable that in all cases, the obtained linear trendlines of the PGA_V/PGA_H exceeded the empirical ratio of 2/3. Investigating the effect of the earthquake magnitude (M_w) on the PGA ratio shows a slight incremental tendency from small to large earthquake magnitude. The average ratio ranges from 0.73 for a magnitude of 3.0 to 0.89 for a magnitude of 6.0, which represents an increase of almost 21%. Despite a lack of earthquakes with greater magnitudes in the Eastern Canada seismic region and, subsequently, in the collected records of this study, the high impact of available earthquakes with greater magnitudes on the V/H PGA ratio is still evident. According to the obtained ratios, the vertical component can still be as critical in earthquakes with a smaller magnitude.

4.2. Epicentral Distance (R_{epi})

The obtained trendline in assessing the epicentral distance (R_{epi}) on the PGA ratio shows that the PGA_V increases as distance gets closer to the earthquake's epicentre. Accordingly, an average ratio of 0.70 was estimated for earthquakes recorded on sites located at 150 km from the epicentre, while a ratio of 0.85 was obtained for sites very close to the epicentre (2.3 km). Therefore, the PGA ratio of greater than 2/3 can be predicted for the earthquakes with an epicentral distance of less than 150 km.

4.3. Soil Conditions (V_{s30})

An assessment of soil conditions on the PGA ratio shows an increasing trend from hard rock soil types, known as Site Class A in NBC 2015, with an average shear wave velocity (V_{s30}) of greater than 1500m/s, to soft soil types, known as Site Class E (V_{s30} < 180 m/s). Despite the lack of recorded earthquakes on weaker soils, the effect of these soil types on the PGA_V is still evident. According to the obtained results, it is predicted that the ratio may exceed unity for soils with an average shear wave velocity (V_{s30}) of less than 450m/s. The average PGA ratio increased from the ratio of 0.83 in the sites with a V_{s30} equal to 2000 m/s to 1.03 in the sites with a V_{s30} of 150 m/s.

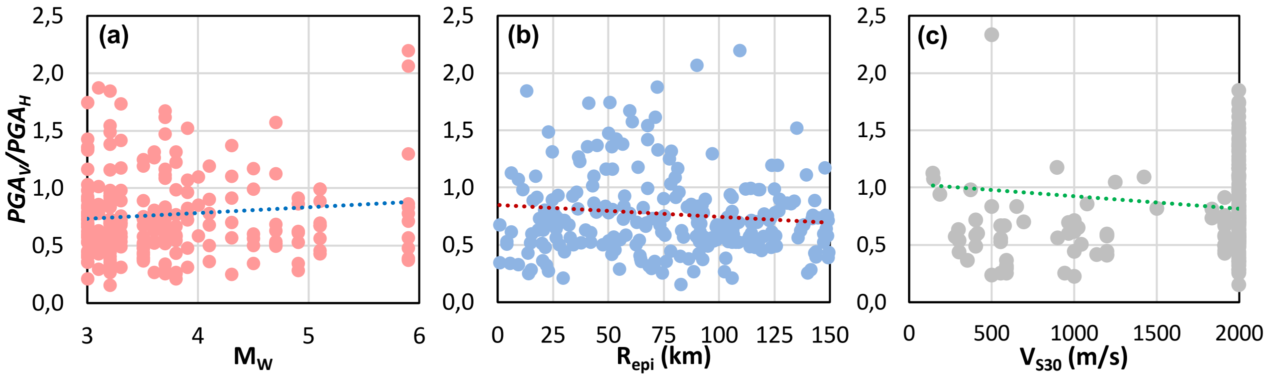

Figure 1. Effect of (a) earthquake magnitude, (b) epicentral distance, and (c) soil condition on PGA ratios of selected events in Eastern Canada

5. Assessment of the Effect of Ground Motions Parameters on SA Ratios

In this section, the effect of the mentioned parameters on SA ratios was assessed for short and large period ranges, in line with the previous approach. The results are presented in scattered forms of SA_V/SA_H ratios in a series of particular periods (T = 0.05, 0.075, 0.10, 0.20, 0.50, 1.0, 2.0, 4.0 sec) corresponding to the earthquake magnitude, M_w, distance from the epicentre of the earthquake, R_{epi}, and soil condition, in terms of the average shear wave velocity (V_{s30}), in Figures 2, 3, and, 4, respectively. Notably, the obtained linear trendlines of SA ratios exceeded the empirical ratio of 2/3 at all considered periods.

5.1. Earthquake Magnitude (M_w)

The linear trendlines achieved from the scattering of the V/H ratios for the earthquake magnitudes of the studied events (Figure 2) show the explicit incremental orientation of the ratio from weaker to stronger earthquakes for periods of less than 2.0 sec and the virtually insignificant effect of the magnitude for a period larger than 2.0 sec. The impact of the earthquake magnitude is more visible at the period 0.20 sec. The average ratios at this period increased from the value of 1.02 for the moment magnitude of 6.0 to the value of 0.76 for the moment magnitude of 3.0. Therefore, for the period range of less than 2.0 sec, an average increase of about 25% in the V/H SA ratio is estimated for earthquakes with a moment magnitude of 6.0 compared to a magnitude of 3.0 for this seismic region.

5.2. Epicentral Distance (R_{epi})

Figure 3 shows the effect of the epicentral distance with the obtained linear trendlines of the scattered ratios over different periods for the studied events recorded in sites with a distance of up to 150 km from the fault. Contrary to what was obtained in the case of the PGA ratios, the results show the negligible impact of the epicentral distance on the SA ratios. However, for periods longer than 1.0 sec, a slight increase of 10% in SA ratio was observed with increasing distance from the epicentre compared to the near-field records. Therefore, it can be pointed out that the epicentral distance has no significant effect on the SA ratio up to a distance of 150 km, and further investigations may be needed to assess the impact of this parameter for earthquakes recorded at a distance of over 150 km. In the study of Atkinson (1993) on earthquakes recorded in the distance range from 10 to 1000 km in the Eastern North America (ENA) seismic region, it is also pointed out that the ratio of horizontal-to-vertical component earthquakes is independent of distance from the fault.

5.3. Soil Conditions (V_{s30})

Moreover, an evaluation of the soil condition effect on SA ratios, as presented in Figure 4, highlights its significant effect in the short period range of less than 0.50 sec. The obtained ratios at the mentioned period limits indicate an upward trend for earthquakes recorded on hard rock (Site Class A) to Soft Soil (Site Class E). The obtained trendlines show an increase of about 65% in the SA ratio for the period 0.05 sec on Site Class E, compared to that recorded on Site Class A. The average ratio in this period range (less than 0.5 sec) starts from 0.65 in soil with an average shear wave velocity (V_{s30}) of 2000 m/s and increases to about 1.0 in soil with an average shear wave velocity (V_{s30}) of 150 m/s.

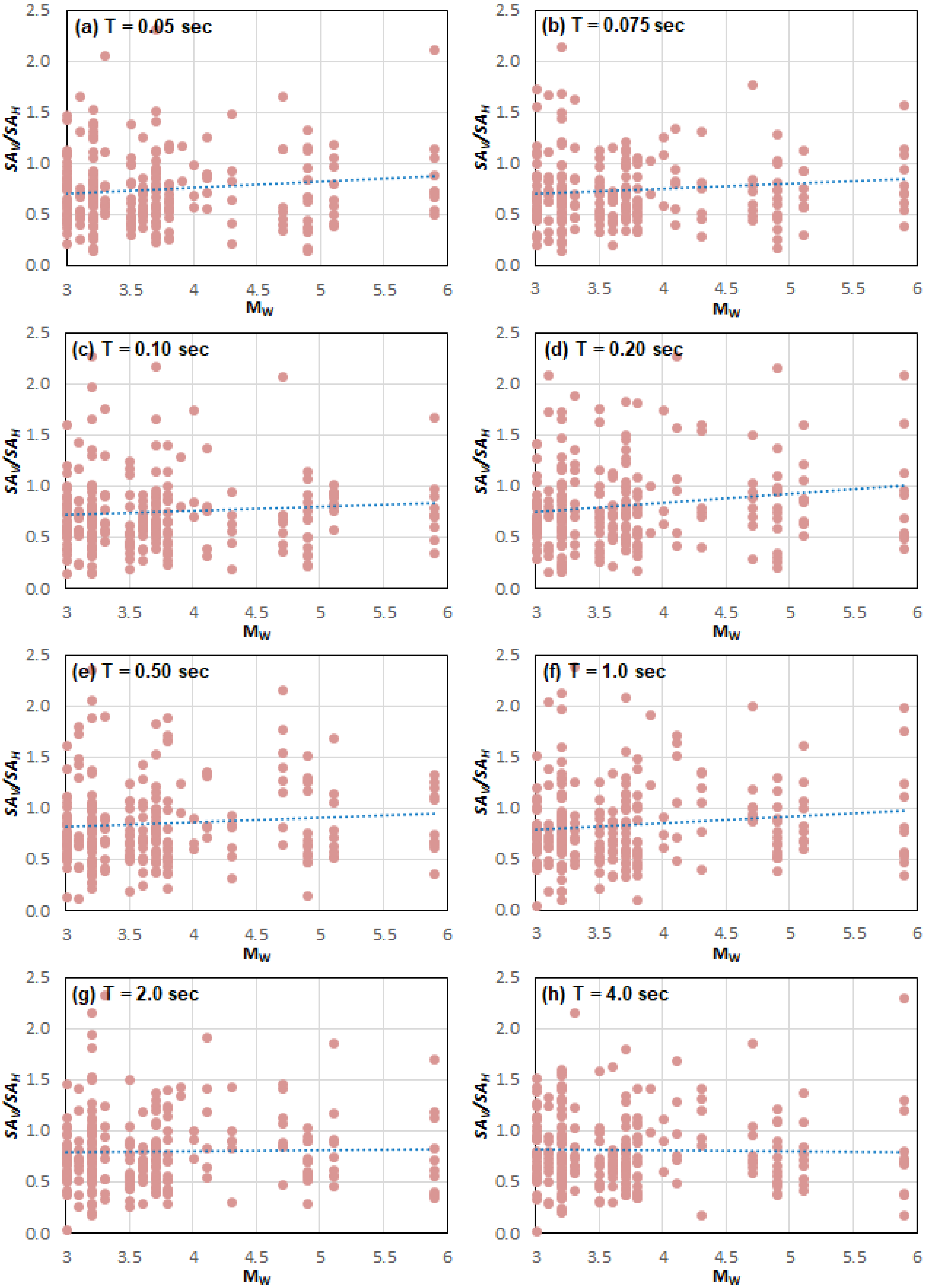

Figure 2. Effect of earthquake magnitudes on spectral acceleration ratios

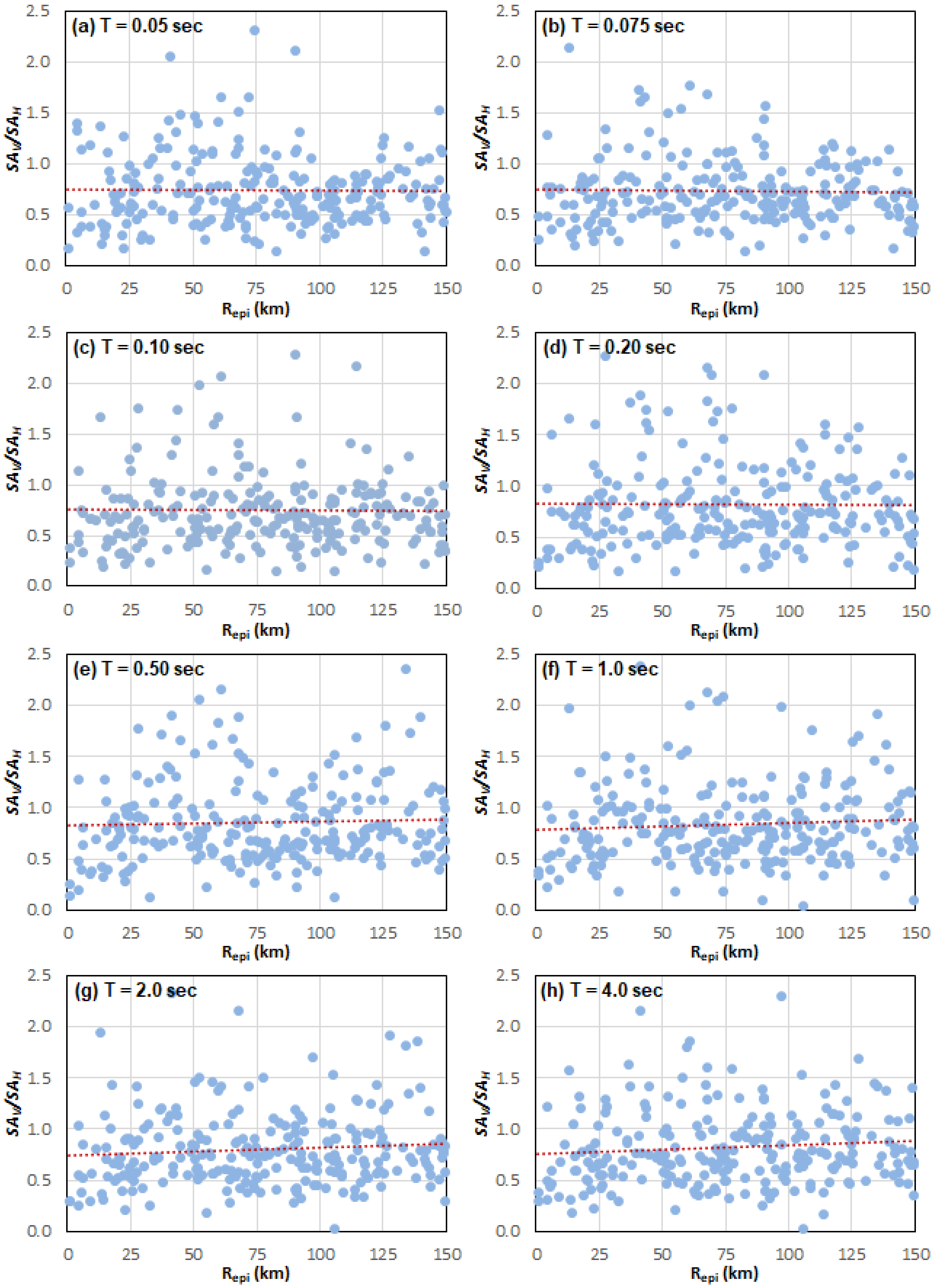

Figure 3. Effect of fault distance on spectral acceleration ratios

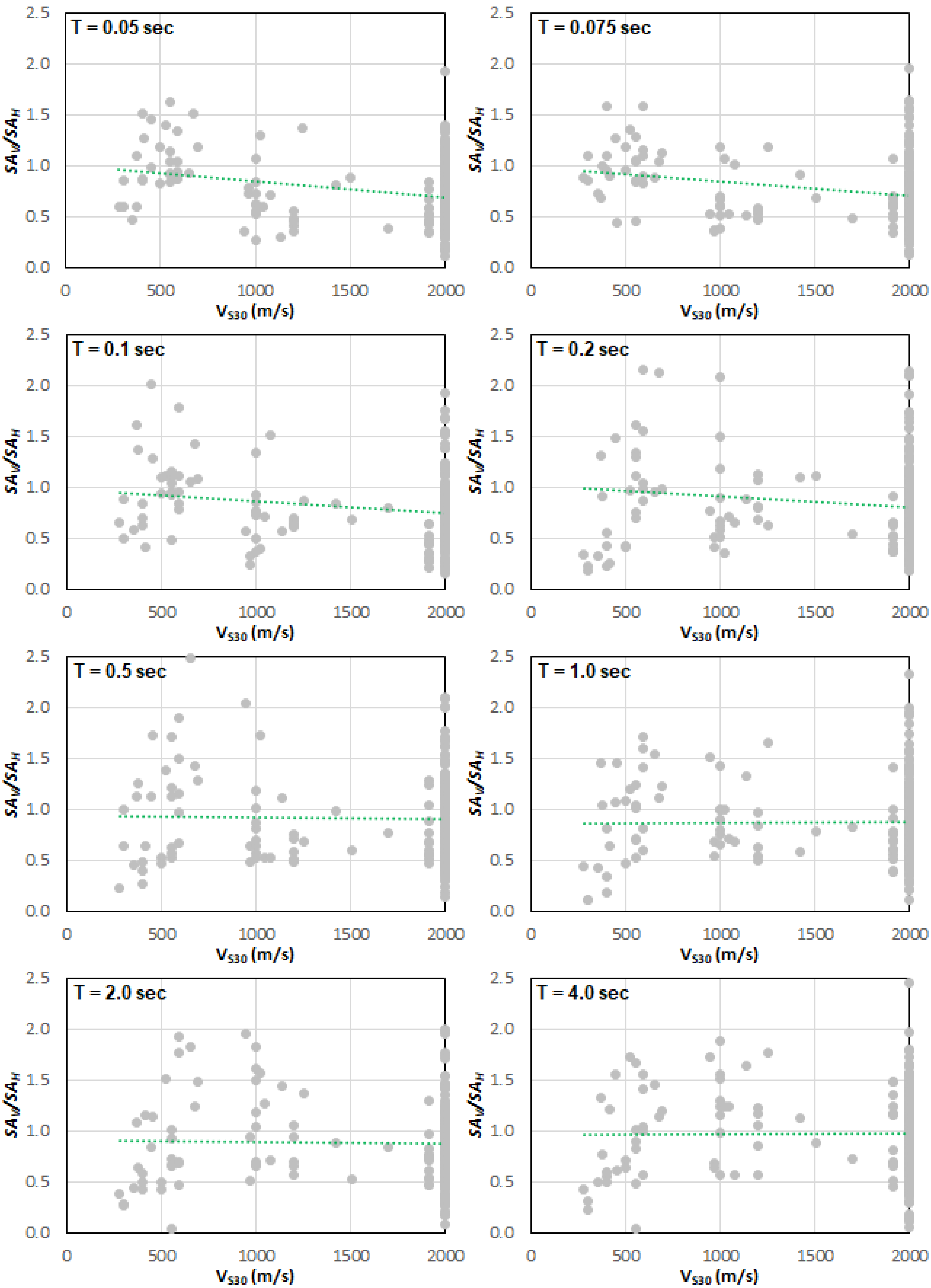

Figure 4. Effect of soil condition on spectral acceleration ratios

6. Conclusion

This paper evaluated the influence of earthquake magnitude (M_w), epicentral distance (R_{epi}), and soil condition (V_{s30}) on the V/H PGA and SA ratios in the Eastern Canada seismic region. A database of 248 historical record sets from 67 earthquakes that occurred in this region was used, with a magnitude greater than 3.0 for the sites with an epicentral distance of less than 150 km. In all cases, the obtained average PGA and PSA ratios exceeded the empirical V/H ratio of 2/3 suggested by NBC 2015.

The investigation of the above-mentioned parameters indicated a significant impact of all three parameters on the computed V/H PGA ratios. As a result, the highest values of V/H PGA ratios were obtained in the near-field of the strongest earthquakes and on weaker soil types. The average PGA ratios range from 0.73 for a magnitude (M_w) of 3.0 to 0.89 for a magnitude of 6.0. Also, average PGA ratios ranging from 0.70 for earthquakes recorded on sites with the distance of 150 km to the epicentre to 0.85 for the sites with a distance of 2.3 km were obtained. In terms of the soil conditions, the obtained trendline of the V/H PGA ratio shows an increasing trend from 0.83 at the location with a V_{s30} of 2000 m/s (Site Class A) to 1.03 at the site with a V_{s30} of 150 m/s (Site Class E).

On the other hand, a significant influence of the earthquake magnitude and soil type condition on the V/H SA ratio was noticed, especially at shorter periods, while a minor impact of epicentral distance was observed. This is particularly evident in the case of earthquakes with large magnitude, for periods less than 2.0 sec, and in the case of soil conditions, with the average shear wave velocity, V_{s30}, less than 450 m/s, for periods less than 0.5 sec. While the majority of data were recorded on hard rock sites, this study confirms the impact of the available weaker soil types on the V/H SA ratio, as previously indicated in other studies such as Campbell and Bozorgnia (2003) and Ambraseys et al. (2005). Further investigation may be required to validate if earthquakes recorded at a distance of more than 150 km could affect the V/H SA ratio. It can also be mentioned that a large number of earthquakes with greater magnitude may be required before generalizing the conclusions.

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