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Vertical-to-horizontal response spectral ratio for offshore ground motions: Analysis and simplified design equation

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Abstract: In order to study the differences in vertical component between onshore and offshore motions, the vertical-to-horizontal peak ground acceleration ratio (V/H PGA ratio) and vertical-to-horizontal response spectral ratio (V/H) were investigated using the ground motion recordings from the K-NET network and the seafloor earthquake measuring system (SEMS). The results indicate that the vertical component of offshore motions is lower than that of onshore motions. The V/H PGA ratio of acceleration time histories at offshore stations is about 50% of the ratio at onshore stations. The V/H for offshore ground motions is lower than that for onshore motions, especially for periods less than 0.8 s. Furthermore, based on the results in statistical analysis for offshore recordings in the K-NET, the simplified V/H design equations for offshore motions in minor and moderate earthquakes are proposed for seismic analysis of offshore structures.

Key words: offshore ground motion; vertical component; simplified design equation; vertical-to-horizontal response spectral ratio (V/H); vertical-to-horizontal peak ground acceleration ratio (V/H PGA ratio); K-NET network; seafloor earthquake measuring system (SEMS)

1 Introduction

Owing to lack of real ground motion recordings on the seafloor, onshore recordings are commonly selected for seismic design of offshore structures. The American Petroleum Institute (API) presented that the seismic analysis of a fixed offshore platform should input a combination of vertical and horizontal ground motions, and it recommends vertical-to-horizontal response special ratio (V/H)=0.5 [1]. However, CHEN et al [2] found that the vertical component for offshore ground motions is significantly different with onshore ground motions. The V/H for offshore ground motions is much lower than that for onshore ground motions at short periods. In fact, the natural period for some offshore structures in shallow sea is lower than 1 s. For example, the natural period of some gravity platforms in China Bohai Sea (the water depth is lower than 50 m) is around 1 s [3]. If the V/H (V/H=0.5) is used in seismic analysis of these offshore structures for low natural period, the vertical ground motion will be overestimated. In order to reasonably confirm the V/H for offshore ground motion, the simplified V/H design equations for offshore motions are presented in this article based on the offshore ground motion recordings selected from the K-NET in Japan.

The research on vertical ground motion on the seafloor were mostly used the recordings from the SEMS project in the past decades. BOORE and SMITH [4] analyzed the vertical-to-horizontal response spectral ratio (V/H) for offshore ground motions from 8 earthquakes. The ground motions were recorded at 5 offshore stations from the SEMS project in the USA. The result indicated that the vertical component of offshore motions was low, particularly at short periods. DIAO et al [5] analyzed the vertical motions for the same recordings with Boore and Smith, and studied the effect of seawater on the vertical motion by a theoretical method. It concluded that the seawater and soft surface can influence on the vertical component of offshore motions. The effect of seawater on P waves from the seabed is more important than SV waves. Moreover, research on the offshore ground motions from the SEMS remained insufficient due to a lack of enough offshore motion recordings, especially for

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the recordings including both onshore and offshore motions in the same earthquake event. It is difficult to directly compare the differences in the V/H between onshore and offshore ground motions. Recently, six seismographs on the seafloor were upgraded by the K-NET since 2006 and recorded some high-quality offshore recordings. Fortunately, the adjacent onshore stations also recorded many high-quality ground motions. Therefore, some onshore and offshore ground motion recordings during 9 earthquake events were selected from the K-NET to study the characteristics of vertical ground motion on the seafloor.

Although the study on the vertical ground motion on the seafloor is limited due to a lack of offshore recordings, the vertical ground motion on land has been researched much [6–9]. Many remarkable vertical ground motions on land were recorded and some structures were directly damaged by those motions. Examples include the Loma Prieta earthquake in 1989 [10], the Kobe earthquake in 1995 [11], and the Wenchuan earthquake in 2008 [12]. Furthermore, many ground motion recordings indicated that the PGA of vertical component may be even higher than that of horizontal component, such as in 1994 Northridge earthquake, the recorded vertical acceleration was 1.18 g, while the vertical-to-horizontal peak ground acceleration ratio (V/H PGA ratio) was 1.79 [13]. In 1979 Imperial Valley earthquake, the mean value for V/H PGA ratios of 30 vertical recordings was 0.77, and the mean value for V/H PGA ratios of 11 near-fault recordings (epicentral distances are about 10 km) was 1.12 [14]. Based on the research methods of vertical ground motion on land, the analysis for the vertical ground motion on the seafloor were discussed in this study.

2 Ground motion recordings

2.1 Recording selection

With more than 1000 accelerometers, the K-NET is a strong-motion seismograph network covering the whole Japan [15, 16]. Within the coverage area of the K-NET, the distance between adjacent earthquake stations is less than 25 km. The onshore recordings from the K-NET have been used by some researches [17].

The current research selected the ground motions from 6 offshore stations and 8 adjacent onshore stations in the K-NET. The details on 6 offshore stations are listed in Table 1. Figure 1 shows the location of the stations used in this article. Black circles represent the onshore stations; while white circles represent the offshore stations. The distances among the 6 offshore stations range between 10 and 20 km in Sagami Bay. And the distances between the onshore stations used in this study and their adjacent offshore station are less than 50 km. The water depths of these offshore stations range from 933 m to 2339 m.

Table 1 Details on offshore stations in K-NET database

Site No.	Site name	Latitude	Longitude	Water depth/m
KNG201	HIRATSUKA-ST1	34.5956N	139.9183E	2197
KNG202	HIRATSUKA-ST2	34.7396N	139.8393E	2339
KNG203	HIRATSUKA-ST3	34.7983N	139.6435E	902
KNG204	HIRATSUKA-ST4	34.8931N	139.5711E	933
KNG205	HIRATSUKA-ST5	34.9413N	139.4213E	1486
KNG206	HIRATSUKA-ST6	35.0966N	139.3778E	1130

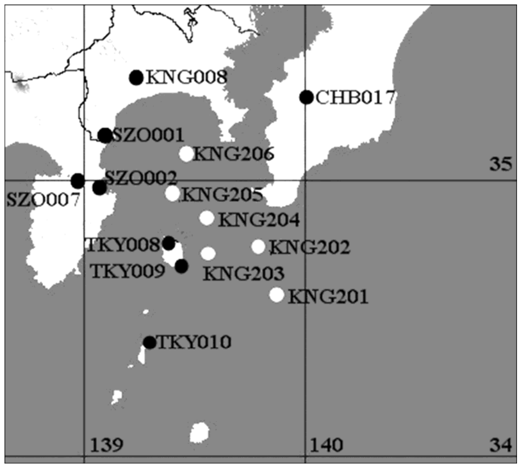

Fig. 1 Distribution of onshore and offshore stations used in this work

In order to select effective offshore ground motions in the K-NET, the earthquake events are selected based on the follow criteria. At first, the earthquake magnitude should be larger than M_w 5.0. Then, the PGA of horizontal ground motions at 6 offshore stations should be larger than 30 gal in one earthquake. At last, there should be some effective recordings at adjacent onshore stations. In addition, to compare the differences in vertical ground motions between onshore and offshore stations reasonably, the onshore stations are selected by the criteria as follows: Firstly, the onshore stations should be close to the offshore stations. Secondly, the PGA of horizontal components should be larger than 30 gal. Thirdly, the onshore sites should be on stiff soil site and the average of shear-wave velocity should be between 180 m/s and 360 m/s.

Considering the above criteria, 9 earthquake events with magnitudes from M_w 4.9 to M_w 9.0 are selected. Of these, the hypocenters in 6 earthquakes are on the seafloor, and the other 3 are on land. Their hypocenter depths range from 7 to 88 km. Each earthquake event is listed by its occurrence date. Table 2 presents the detailed information about the 9 earthquake events.

A total of 54 offshore and 30 onshore motion recordings in 9 earthquake events from the K-NET are selected. There should be 6 offshore and 5 onshore recordings in each earthquake. But only offshore recordings were selected in 3 earthquake events due to the lack of effective onshore recordings. The detailed information about these recordings is provided in Appendix.

The offshore recordings in the SEMS project were selected to compare with the statistical results of offshore motions in the K-NET. The SEMS project is carried out by the Sandia National Laboratory. All the offshore stations are embedded on the seafloor of Southern California under the water depth from 50 m to 217 m. The recordings in 8 earthquake events from 1971 to 1997 are selected. The earthquake magnitudes selected in the SEMS range from M_w 4.7 to M_w 6.1. The earthquake events in the SEMS are listed in Table 3. The information of offshore stations in the SEMS is summarized in Table 4. More information can be found in Ref. [4]. Because of a scarcity of onshore recordings, only offshore motions can be selected from the SEMS database.

2.2 Site condition

The average shear wave velocity is one important parameter to evaluate the site condition. In the K-NET, the total calculative depth of soil layer (H) range between 10 and 20 m. The average shear wave velocity $\bar{V}_s$ can be defined by

$$\bar{V}_s = \frac{H}{\sum h_i / V_{si}} \tag{1}$$

where H and h_i are the total depth of soil layer and the depth of each soil layer respectively, and V_{si} is the shear wave velocity of corresponding soil layer.

The K-NET provides geotechnical characterizations for onshore stations. Detailed site condition and data about stations in the K-NET can be found on the website http://www.kyoshin.bosai.go.jp. Unfortunately, the K-NET does not provide soil information of offshore stations (KNG201–KNG206). So, some estimations of offshore site condition are given as follow.

EGUCHI et al [18] pointed out that the most of the offshore stations in the K-NET were underlain not by soft or unconsolidated soil layers, but by sediments consisting of sand, small-sized rocks or pebbles. Moreover, the $\bar{V}_s$ values of onshore stations near Sagami Bay in the K-NET (these onshore stations are near the

Table 2 Information of 9 earthquake events from K-NET database

No.	Earthquake location	Date	Time	Latitude	Longitude	Magnitude M_w	Hypocenter Depth/km	Hypocenter location
1	Izu Peni	2006−04−21	02:50	34.940N	139.195E	5.8	7	Seafloor
2	Sagami Bay	2006−05−02	18:24	34.917N	139.330E	5.1	15	Seafloor
3	Katsuura*	2006−10−14	06:38	34.893N	140.303E	5.1	64	Seafloor
4	Odawara*	2007−10−01	02:21	35.225N	139.118E	4.9	14	Land
5	Suruga Bay	2009−08−11	05:07	34.785N	138.498E	6.5	23	Seafloor
6	Chiba Peni*	2011−02−05	10:56	34.855N	140.618E	5.2	64	Seafloor
7	Northeast Pac	2011−03−11	14:46	38.103N	142.860E	9.0	24	Seafloor
8	Mount Fuji	2011−03−15	22:31	35.308N	138.713E	6.4	14	Land
9	Tokyo Bay	2012−07−03	22:31	35.000N	139.870E	5.2	88	Land

Note: * represents no onshore records in the earthquake event.

Table 3 Data of earthquake events in SEMS

Eq ID	Earthquake location	Date	Time	Latitude	Longitude	M_w
SB81	Santa Barbara Island	1981−09−04	15:50	33.66N	119.10W	5.95
NP86	North Palm Springs	1986−07−08	09:20	34.00N	116.61W	6.10
OS86	Oceanside	1986−07−13	13:47	32.97N	117.87W	5.84
UP90	Upland	1990−02−28	23:43	34.14N	117.70W	5.63
RC95	Ridgecrest	1995−09−20	23:27	35.76N	117.64W	5.56
CL97	Calico	1997−03−18	15:24	34.97N	116.82W	4.85
S97A	Simi Valley	1997−04−26	10:37	34.37N	118.67W	4.81
S97B	Simi Valley	1997−04−27	11:09	34.40N	118.64W	4.72

Table 4 Information of offshore stations in SEMS

Station	Latitude	Longitude	Water depth/m
S1HN	34.3367N	119.560W	50
S2EE	33.5867N	118.123W	73
S3EE	33.5700N	118.130W	64
S4GR	34.1800N	119.470W	99
S4IR	34.6117N	120.730W	76

offshore stations and at the shoreline) are 90–380 m/s, and the average value is about 230 m/s. It should be noted that a thick sludge layer being on the Sagami Bay seafloor [19], so the $\bar{V}_s$ values of some offshore stations in K-NET may be lower than those of the onshore stations.

Moreover, it was estimated that the $\bar{V}_s$ value of the SEMS offshore sites near Southern California in the United States is about 220 m/s [4].

3 Analysis of V/H PGA ratio

3.1 V/H PGA ratio

Figure 2 shows the acceleration time histories at offshore station KNG203 for 2009−08−11 and 2011−03−11 earthquakes. Figure 2, the vertical PGA (U-D) is 6 and 18 gal respectively, which is only about 20% of the horizontal PGA (34 and 91 gal in the E−W direction; 35 and 69 gal in the N−S direction). Figure 3 shows the acceleration time histories at onshore station TKY010 for 2009−08−11 and 2011−03−11 earthquakes. As shown in Fig. 3, the vertical PGA is 38 and 135 gal, which is about

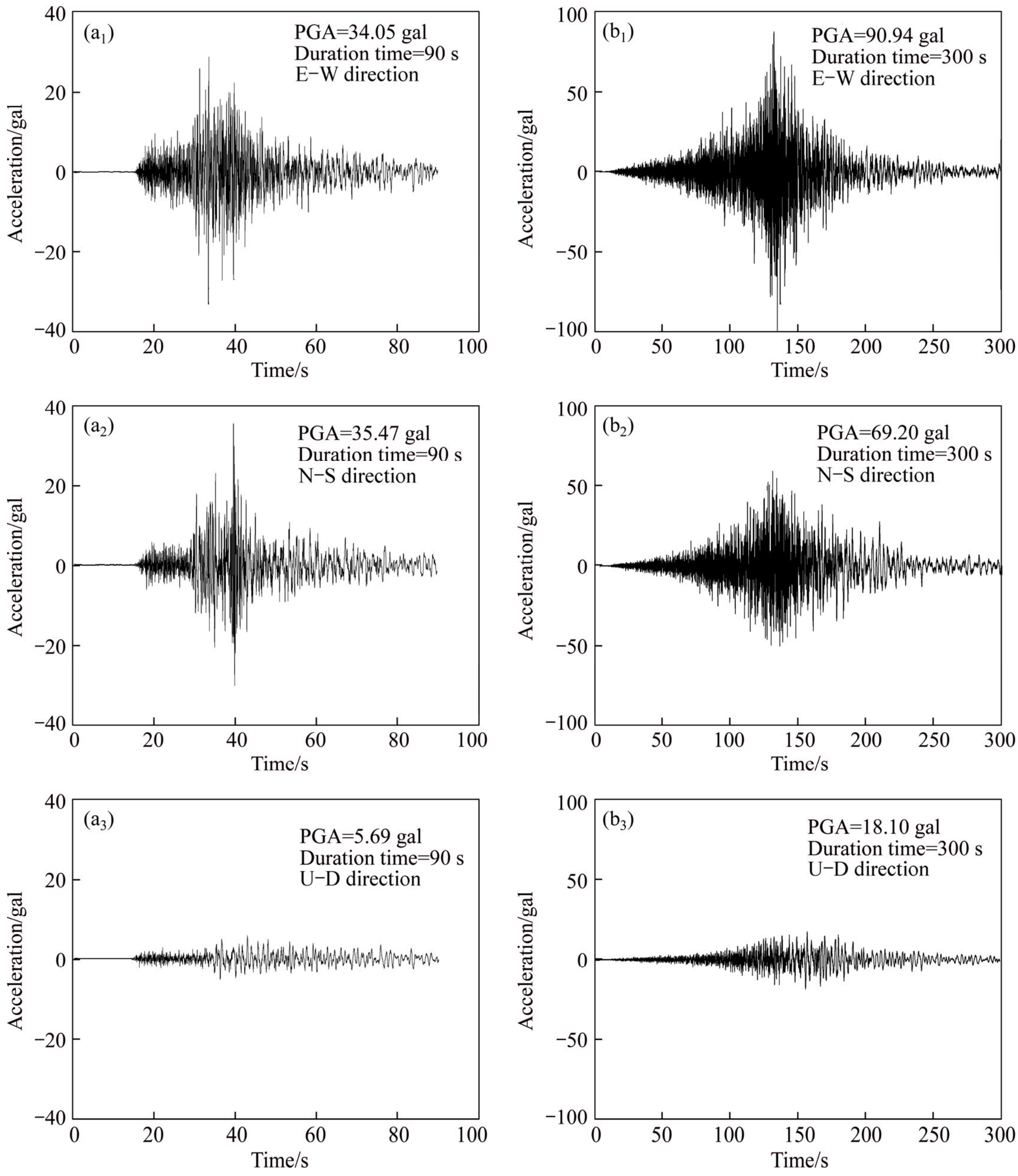

Fig. 2 Two suites of acceleration time histories for offshore station KNG203: (a_1–a_3) Acceleration time histories in 2009−08−11 earthquake; (b_1–b_3) Acceleration time histories in 2011−03−11 earthquake

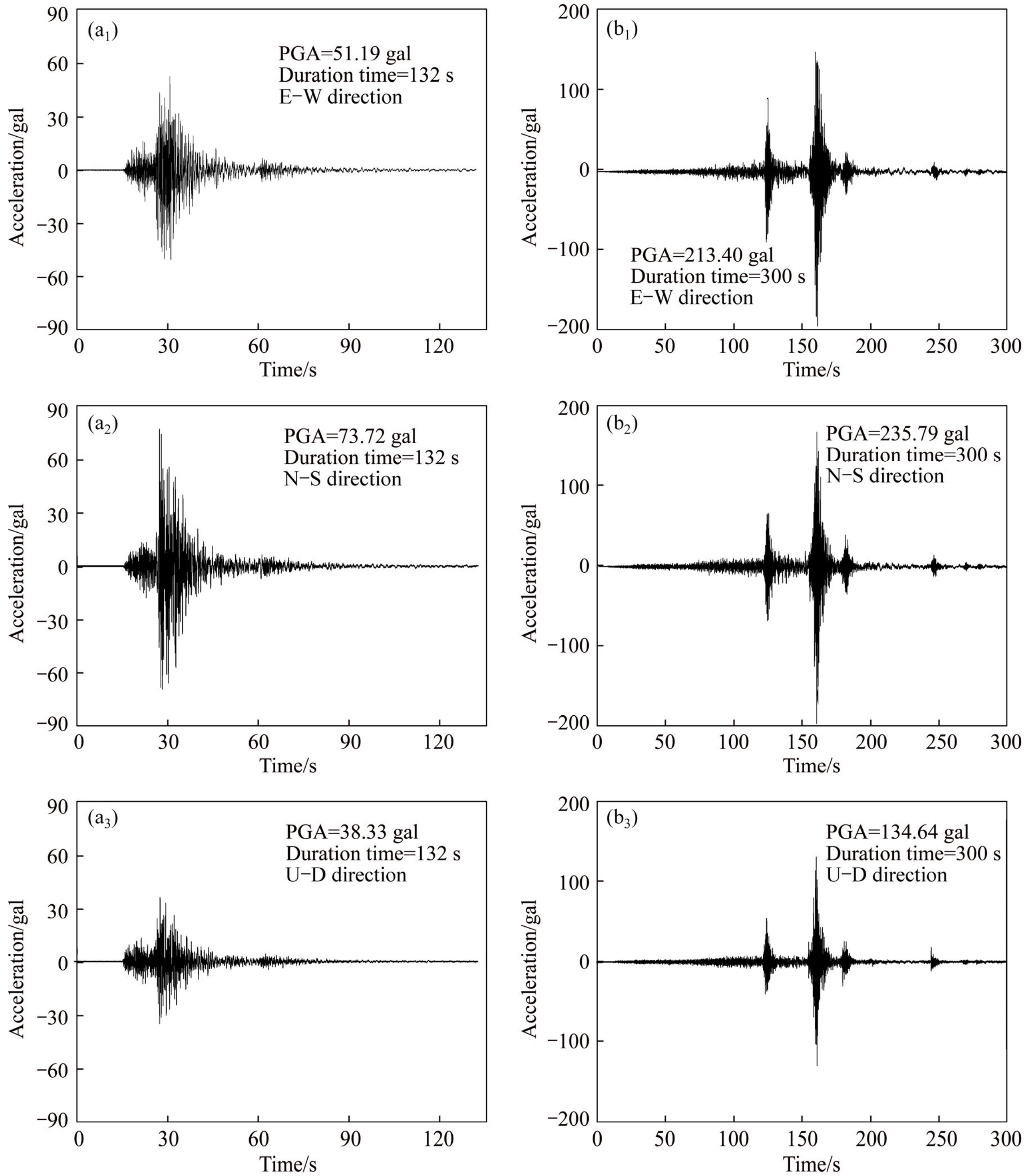

Fig. 3 Two suites of acceleration time histories for onshore station TKY010: (a_1–a_3) Acceleration time histories in 2009−08−11 earthquake; (b_1–b_3) Acceleration time histories in 2011−03−11 earthquake

50% of the horizontal PGA (51 and 213 gal in the E-W direction; 74 and 236 gal in the N−S direction). The vertical components of acceleration time histories at offshore stations are lower than at onshore stations. Noted, these acceleration time histories are randomly selected from the ground motions used in this work.

The Vertical-to-Horizontal PGA ratio (V/H PGA ratio) is used to further compare the PGA of vertical component between onshore and offshore motions. The V/H PGA ratio is calculated as a_v/a_h, where a_v is vertical PGA, and a_h is the PGA of one horizontal component. So, there are two V/H PGA ratios for one three-dimensional recording. The average V/H PGA ratio for offshore ground motions used in this research is 0.213; while it is 0.474 for onshore ground motions in the K-NET.

3.2 Influence of earthquake magnitude, epicentral distance, and site condition on V/H PGA ratio

Magnitude, epicentral distance, and site condition are important parameters that affect the V/H PGA ratio. Figure 4 shows the influence of epicentral distance on the V/H PGA ratio in earthquakes with the same magnitude. The ratios in this figure include the data of 8 earthquakes in the K-NET except for the data in the

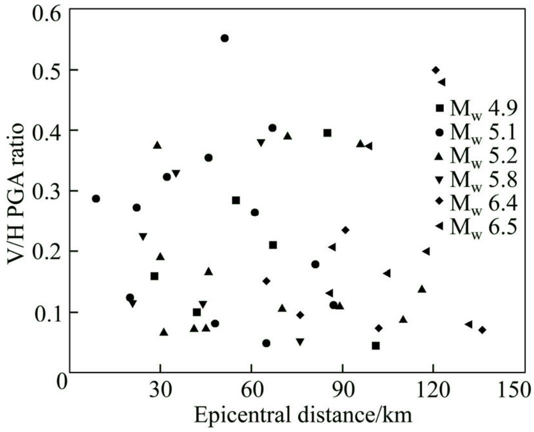

Fig. 4 Distribution of V/H PGA ratios for offshore motions along with epicentral distances in earthquakes with same magnitude

Northeast Pacific earthquake (M_w 9.0) occurred on 2011−03−11. The epicentral distance and magnitude have a large gap of the data between the Northeast Pacific earthquake and other earthquakes. In the earthquakes for same magnitude, the V/H PGA ratio does not present remarkable regularity along with the epicentral distances.

Figure 5 illustrates the influence of earthquake magnitude on the average V/H PGA ratio for offshore motions in each earthquake. The offshore recordings are classified whether the earthquakes occurred on the seafloor or land. It is found that the V/H PGA ratio of offshore motions for earthquakes occurring on the seafloor (the ratios are between 0.2 and 0.28) is higher than that occurring on land (the ratios are between 0.15 and 0.2). The influence of the site condition, magnitude, hypocenter depth, and epicentral distance are little in the earthquakes for different hypocenter locations. For example the magnitude, hypocenter depth, and epicentral distance of offshore recordings are similar between 2006−05−02 (hypocenter occupied on the seafloor) and 2007−10−01 (hypocenter occupied on land) earthquake

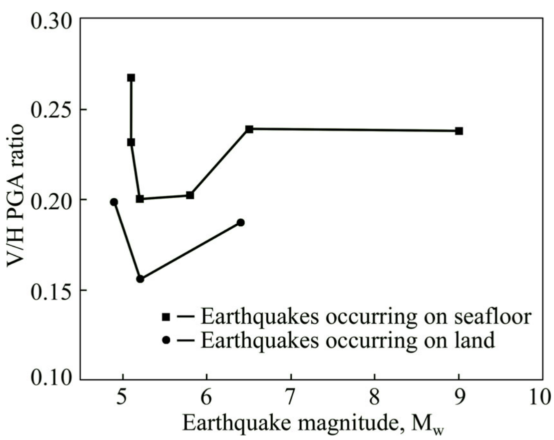

Fig. 5 Relationship between magnitude and average V/H PGA ratios for offshore motions in each earthquake

and the recordings are selected from the same offshore stations. So, it is speculated that the propagation path may be a reason for the difference in the average V/H PGA ratio for offshore ground motions between different hypocenter locations.

Figure 6 shows a histogram of the V/H PGA ratio for offshore motions arranged for earthquake events and offshore stations. The earthquake events are arranged as the numbers listed in Table 2. The V/H PGA ratios are from 6 offshore stations (KNG201–KNG206) in each earthquake. It is found some regularity for the V/H PGA ratios between different offshore stations. For example, in all earthquake events, the V/H PGA ratios at KNG201 station are all less than 0.15, which is almost the lowest among the offshore stations. And the V/H PGA ratios at KNG202 station are between 0.35 and 0.55, which is almost the largest in each earthquake. The V/H PGA ratios at other stations also present the same characteristic. Because the earthquake magnitude and the hypocenter depth are the same and the epicentral distances between different offshore stations are similar in the same earthquake, the V/H PGA ratio between different offshore stations might be influenced by topography or local site condition. The detailed analysis cannot be done due to a lack of the information about the topography and the site condition at offshore sites. However, the V/H PGA ratio at onshore stations can be influenced by the topography and site condition [20, 21].

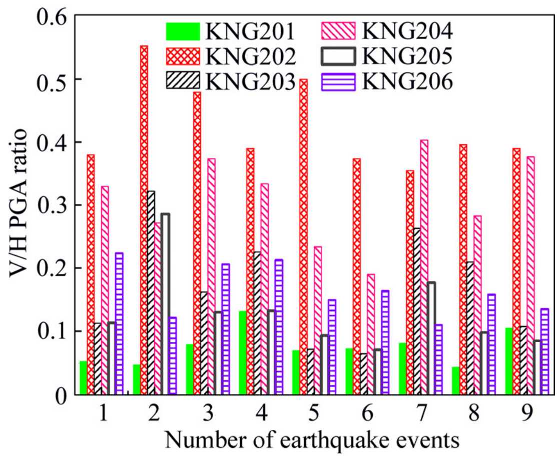

Fig. 6 A comparison of V/H PGA ratio at 6 offshore stations for 9 earthquake events (earthquake events are arranged as the numbers listed in Table 2)

4 Analyses of response spectra and vertical-to-horizontal response spectral ratio

4.1 Elastic response spectra

Some recordings in the K-NET are selected to investigate the differences in response spectra between onshore and offshore motions. Figures 7 and 8 show the

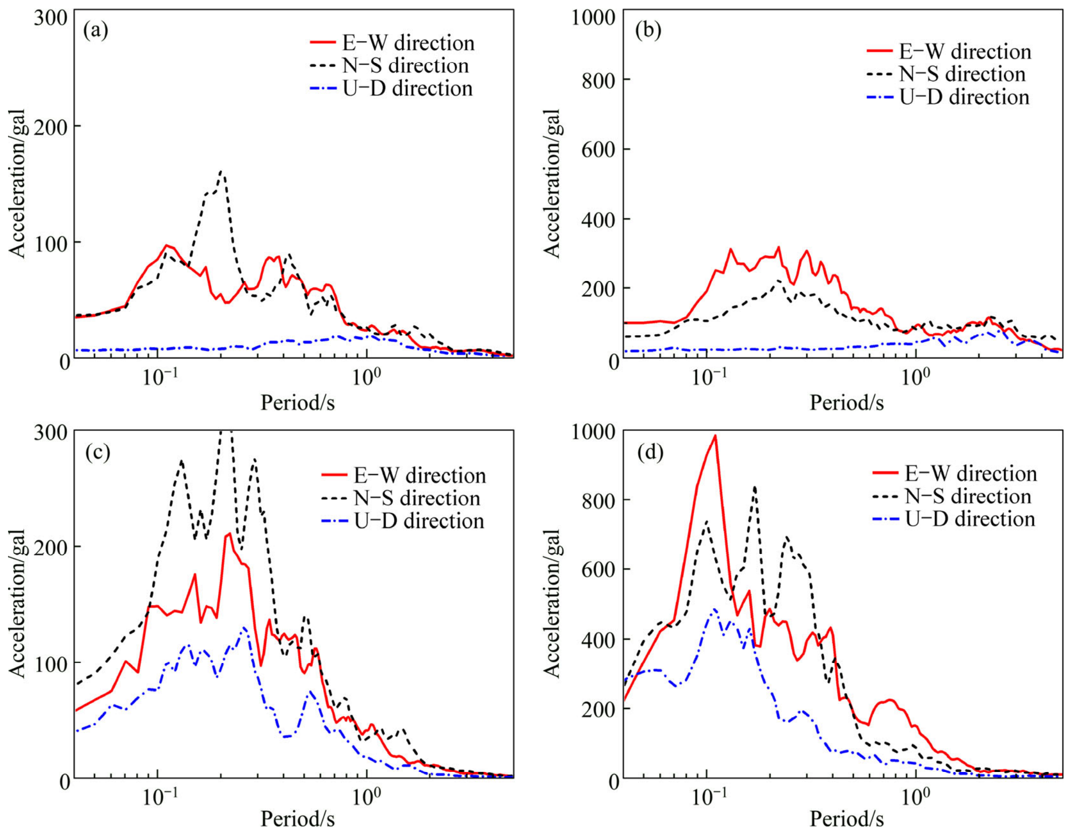

Fig. 7 Vertical and horizontal acceleration response spectra at offshore station KNG203, and onshore station TKY010: (a) 2009−08−11 earthquake, offshore station: KNG203; (b) 2011−03−11 earthquake, offishore station: KNG203; (c) 2009−08−11 earthuake, onshore station: TKY010; (d) 2011−03−11 earthquake, onshore station: TKY010

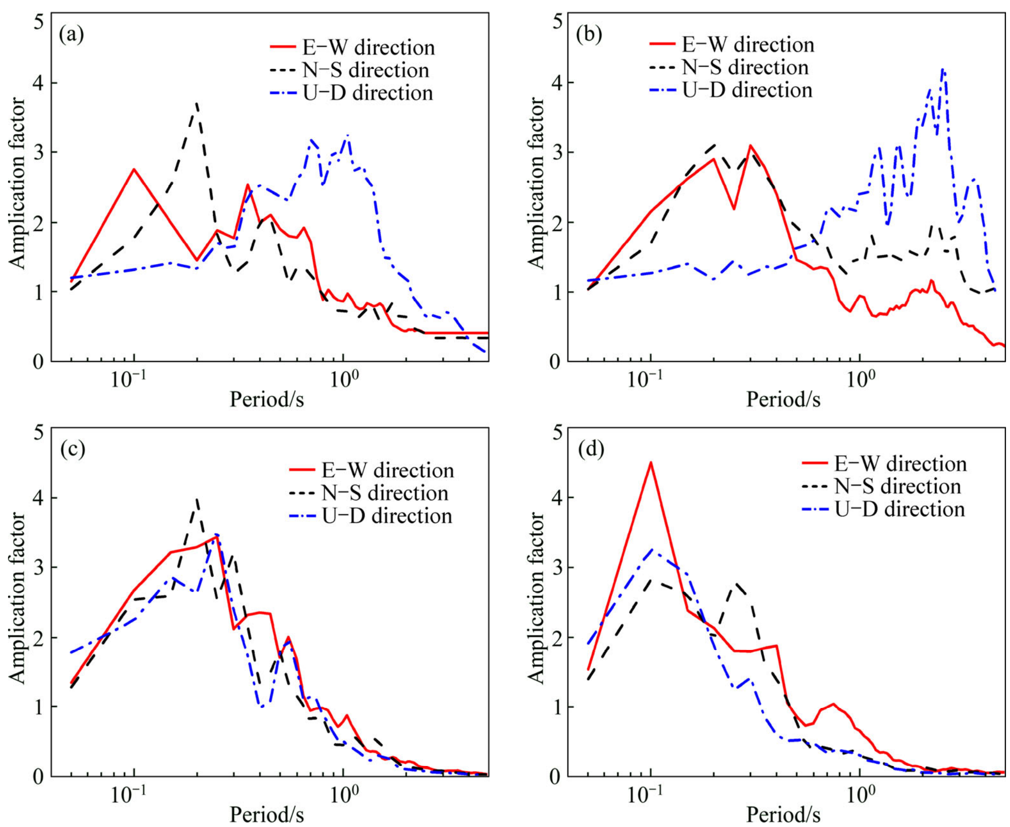

Fig. 8 Vertical and horizontal normalized response spectra at offshore station KNG203 and onshore station TKY010: (a) 2009−08−11 earthquake, offshore station: KNG203; (b) 2011−03−11 earthquake, offishore station: KNG203; (c) 2009−08−11 earthuake, onshore station: TKY010; (d) 2011−03−11 earthquake, onshore station: TKY010

5% damped acceleration response spectra and normalized response spectra (amplification factor spectrum), respectively. The period of acceleration response spectra and normalized response spectra is 0.04–5.0 s. The ground motion recordings are selected from offshore station KNG203 and onshore station TKY010 in 2009−8−11 and 2011−3−11 earthquakes, which are as the same as the recordings in Figs. 2 and 3. A normalized response spectrum is calculated by the acceleration response spectra dividing by the PGA of acceleration time histories.

For the acceleration response spectra shown in Fig. 7, the horizontal response spectra between onshore and offshore motions are similar. However, the spectral values for vertical component are only 1/10 to 1/3 of the values for horizontal components at offshore station KNG203 for periods less than 0.8 s, which is significantly lower than that at onshore station TKY010 (the onshore response spectral values for vertical components are 1/3 to 1/2 of the values for horizontal components). The peak of vertical response spectra for offshore motions is at the periods longer than 1 s and that for onshore motions is at the periods around 0.2 s.

For the normalized response spectra that removing the influence of the PGA for offshore ground motion in Fig. 8, the vertical response spectra for offshore motions in both 2009−08−11 and 2011−03−11 earthquake are lower than horizontal response spectra for periods less than 0.5 s. Then, the vertical response spectra for offshore ground motions increase rapidly with the periods and exceed the horizontal spectra for periods longer than 0.8 s. However, the vertical and horizontal response spectra for onshore motions are similar for periods ranging from 0.04 to 5 s. The peak of vertical response spectra for offshore motions is at the periods longer than 1 s, but that for onshore motions being at the periods around 0.2 s.

As shown in Figs. 7 and 8, the vertical component for offshore ground motion is suppressed at short to intermediate period. This observation result is consistent with the theory calculation of CROUSE and QUILTER [22]. They predicted that vertical ground motion can be affected at the frequency of P wave resonance in the seawater. Near the romance frequency zones, the reduction of vertical ground motion is probably due to a conversion of S wave motion into P wave motion on the seafloor [23]. Moreover, the seawater layer can increase the pore pressure and saturation of the sediments on the seafloor. YANG and SATO [24] presented that the degree of saturation may produce substantial influence on the amplification, both amplitude and frequency content.

4.2 Vertical-to-horizontal response spectral ratio

Through calculating vertical and horizontal acceleration response spectra respectively, the vertical-to-horizontal response spectral ratio (V/H) can be obtained by vertical acceleration response spectral value divided by the mean value of two horizontal response spectra. Then, the V/H can be plotted as a curve of the ratio along periods.

When some ground motions are used to calculate an average V/H, a statistical variation coefficient is proposed to measure the statistical dispersion. The variation coefficient can be calculated as the standard deviation divided by the mean value.

The average V/H for 54 offshore and 30 onshore motions in the K-NET are compared in Fig. 9. The differences in the V/H between onshore and offshore motions are summarized as follows: For periods less than 0.8 s, the V/H for offshore motions is between 0.2 and 0.3, which is smaller than the V/H for onshore motions (30 to 50% of the onshore values). For periods between 0.8 and 2 s, the V/H for offshore motions increases along with the period. For periods longer than 2 s, the V/H for onshore and offshore motions both fluctuates between 0.4 and 0.6. On the whole, the curve of the V/H for offshore motions ascends as Z-shaped, while the V/H for onshore motions fluctuates between 0.4 and 0.6 for periods between 0.04 and 5 s.

In Fig. 9, we also compared the average V/H for offshore motions in the SEMS with that in the K-NET. The water depth above the offshore sites in the K-NET is 902–2339 m, which is obviously deeper than that in the SEMS (50−217 m), but the V/H for offshore motions between the K-NET and the SEMS database are almost consistent with each other. It indicates that the influence of water depth on the V/H for offshore motion is not clear. So, it should be further study. The variation coefficients of V/H for both the onshore and offshore motions are less than 1.0 in Fig. 9(b). So, the statistical dispersion of the data can be accepted.

4.3 Influence of earthquake magnitude, and epicentral distance on vertical-to-horizontal response spectral ratio

The offshore ground motions from the K-NET are classified into 5 groups according to the magnitude and the epicentral distance R. For $4.9 \le M_w \le 5.2$ and $R \le 50$ km, the offshore recordings are classified to MiSR (minor earthquake and small epicentral distance) group. For $4.9 \le M_w \le 5.2$ and 50 km<R<135 km, the recordings are classified to MiMR (minor earthquake and moderate epicentral distance) group. For $5.8 \le M_w \le 6.5$ and $R \le$ 50 km, the recordings are classified to MoSR (moderate earthquake and small epicentral distance) group. For $5.8 \le M_w \le 6.5$ and 50 km<R<135 km, the recordings are classified to MoMR group (moderate earthquake and

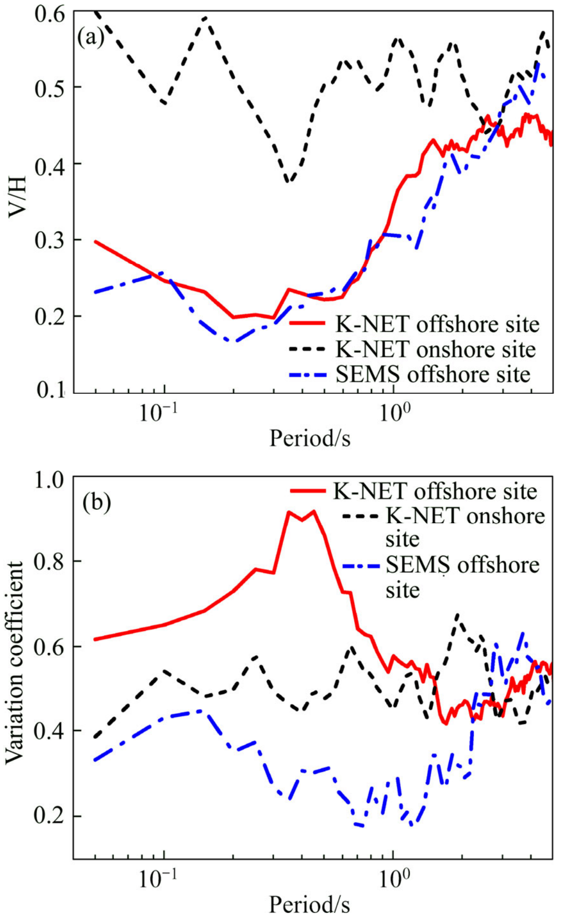

Fig. 9 Average V/H (a) and corresponding variation coefficient (b) for onshore and offshore motions in K-NET and for offshore motions in SEMS

moderate epicentral distance). For M_w>8.0 and *R*> 300 km, the recordings are classified to LFR group (large earthquake and far epicentral distance). Every group includes at least 6 three-dimensional recordings from 6 different offshore stations (KNG201-KNG206). Only in the Northeast Pacific earthquake were offshore ground motions recorded in large earthquake (M_w>8.0). Therefore, no recording for small or moderate R is in large earthquake group.

Figure 10 shows the V/H and corresponding variation coefficient for offshore motions in different groups. As shown in Fig. 10, the V/H in each group is less than 0.3 for periods less than 0.6 s. The V/H for offshore motions in minor earthquake is less than 0.4 for periods longer than 0.9 s, and the V/H is similar in MiSR and MoSR groups. Moreover, the V/H for offshore motions in moderate and large earthquakes is between 0.4 and 0.7 for periods longer than 0.9 s, and the V/H in MoSR group is larger than the V/H in MoMR. The Peak for the V/H in moderate or large earthquake is 0.6 to 0.7 for periods around 3 s. The statistical variation coefficients are less than 1.0 in Fig. 10(b).

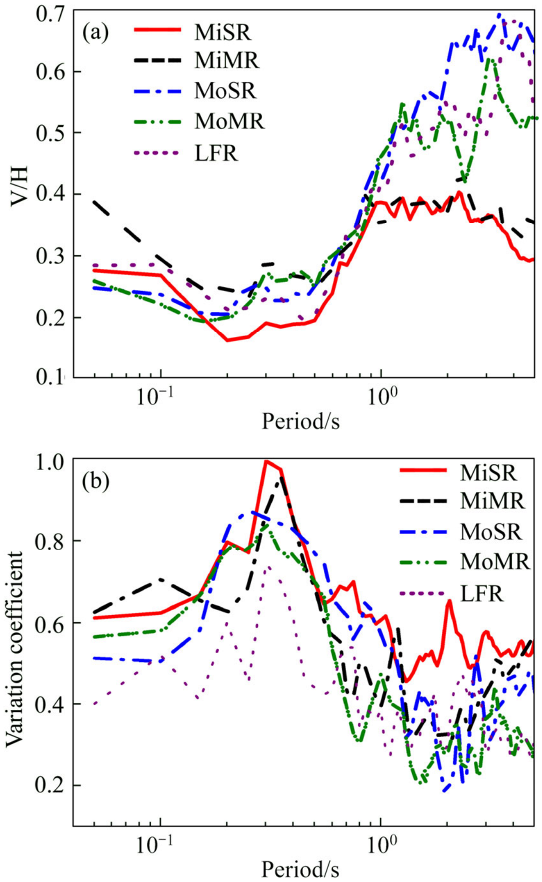

Fig. 10 V/H (a) and corresponding variation coefficient (b) for offshore motions with different magnitudes and epicentral distances

5 Simplified design equations of V/H for offshore motions

The vertical ground motion need be inputted in seismic analysis of offshore structures in some cases. This research found that it is unreasonable to use a constant V/H value (for example V/H=0.5) for different offshore structures. So, a tentative simple V/H for offshore ground motions and its simple design equation are proposed.

The epicentral distances of offshore recordings in the Northeast Pacific earthquake are all larger than 400 km, which is so different with other earthquakes. Therefore, the recordings in the Northeast Pacific earthquake are removed from the statistical analysis for simplified V/H. design equation. Although the V/H is different for offshore ground motions between short and moderate epicentral distances, the difference is not large enough and can be ignored for seismic design of offshore structure. But the difference in the V/H for offshore ground motions between minor and moderate earthquakes is obvious at long periods. Therefore, the simplified V/H for offshore ground motions and its simplified design equations are summarized for minor and moderate earthquakes base on real offshore recordings. Simplified design equations for large earthquake will be presented for selecting more recordings in future. The earthquake magnitude in minor earthquake is between M_w 4.9 and M_w 5.2, and that in moderate earthquake is between M_w 5.8 and M_w 6.5. This classification is as the same as the above section. The epicentral distances of offshore ground motions in minor and moderate earthquakes are all smaller than 136 km.

The simplified V/H for offshore ground motions in minor and moderate earthquake is shown in Fig. 11 and its simplified design equations are given by Eqs. (2) and (3). The simplified V/H in both minor and moderate earthquake is 0.3 for periods less than 0.6 s. The simplified V/H in minor earthquake is 0.4 for periods longer than 0.9 s. The simplified V/H in moderate earthquake is 0.65 for periods longer than 1.5 s.

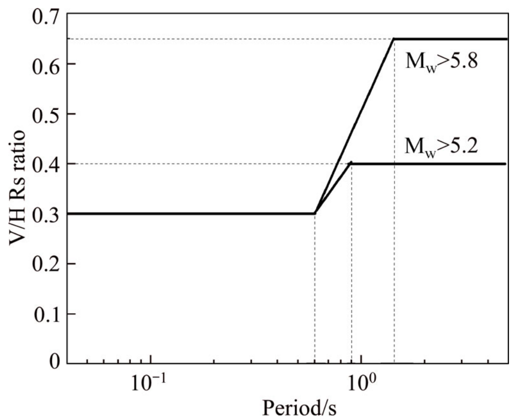

Fig. 11 Simplified V/H for offshore motions in minor and moderate earthquakes

The V/H shows a linear growth for periods between 0.6 s and 0.9 s for minor earthquake (between 0.6 s and 1.5 s for moderate earthquake). On the whole, the simplified V/H for offshore motions in minor earthquake is smaller than in moderate earthquakes for periods longer than 0.6 s.

When the magnitude is smaller than M_w 5.2, the simplified design equation of V/H for offshore ground motions is given by

$$\text{V/H}(M_\text{w} \le 5.2)=\begin{cases} 0.3 & \text{for } T \le 0.6 \text{ s} \\ (1/3)T+0.1 & \text{for } 0.6 \text{ s}<T<0.9 \text{ s} \\ 0.4 & \text{for } 0.9 \text{ s} \le T \le 5 \text{ s} \end{cases} \quad (2)$$

where T is the period. When the magnitude is between M_w 5.8 and M_w 6.5, the simplified design equation of V/H for offshore ground motions is given by

$$\text{V/H}(5.8 \le M_\text{w} \le 6.5)= \begin{cases} 0.3 & \text{for } T \le 0.6 \text{ s} \\ (7/18)T+1/15 & \text{for } 0.6 \text{ s}<T<1.5 \text{ s} \\ 0.65 & \text{for } 1.5 \text{ s} \le T \le 5 \text{ s} \end{cases} \quad (3)$$

Furthermore, the simplified V/H compares with the V/H for offshore motions in minor and moderate earthquake groups from the K-NET in Fig. 12. In practical engineering design, when the earthquake magnitude is between M_w 5.2 and M_w 5.8, the V/H for offshore motions should select Eq. (3) for safety.

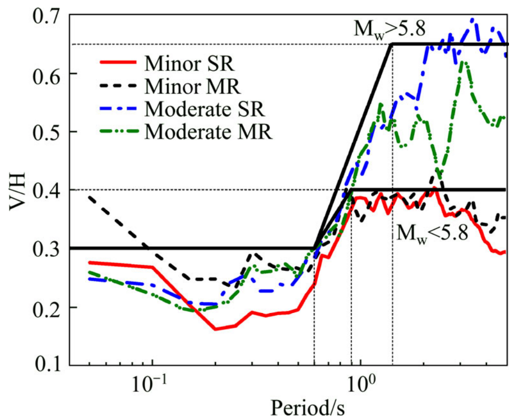

Fig. 12 A comparison between simplified and average V/H values for offshore motions in minor and moderate earthquakes

6 Conclusions

1) Through statistical analysis for the recordings in the K-NET, the average V/H PGA ratio at offshore stations and onshore stations is 0.213 and 0.474, respectively. Moreover, it is found that the V/H PGA ratio for offshore motions in the earthquake occurring on the seafloor is higher than that on land, and which may be induced by propagation path. Because the V/H PGA ratios at 6 offshore stations are different in every earthquake and have same regularity in 9 earthquakes, it is concluded that the topography and local site condition could influence on the V/H PGA ratio for offshore motions.

2) The differences in the V/H between onshore and offshore motions are obvious. The V/H for offshore motions is smaller than that for onshore motions, especially for periods less than 0.8 s. In spite of a large difference in water depths, the average V/H for offshore motions between the K-NET and the SEMS databases is similar. It is necessary to further study the influence of water depth on the V/H for offshore motions.

3) Base on the statistical analysis of V/H for offshore motions in the K-NET, the simplified V/H design equations for offshore ground motions in minor and moderate earthquakes are summarized. The results present that the simplified V/H for both minor and moderate earthquakes is 0.3 for periods lower than 0.6 s. Moreover, the simplified V/H for moderate earthquake is larger than that for minor earthquake at long periods. The simplified V/H for minor earthquake is 0.4 for periods longer than 0.9 s and that for moderate earthquake is 0.65 for periods longer than 1.5 s.

Appendix

A1 Information of ground motion recordings in 2006−04−21 earthquake (A group: offshore stations; B group: onshore stations)

Code	Station name	PGA/gal			Epicentral distance/km	$\bar{V}_s$/(m·s^{-1}) & h/m	Station location	
		EW	NS	Vertical			Latitude	Longitude
A1	KNG201	123.268	65.005	4.940	76	No data	34.595N	139.918E
A2	KNG202	37.017	22.455	11.296	63	No data	34.739N	139.839E
A3	KNG203	84.955	38.873	7.051	44	No data	34.798N	139.643E
A4	KNG204	52.418	39.795	15.227	35	No data	34.893N	139.571E
A5	KNG205	251.703	145.940	22.788	21	No data	34.941N	139.421E
A6	KNG206	119.569	81.320	22.542	24	No data	35.096N	139.377E
B1	SZO001	209.613	99.552	37.941	25	292/10	35.142N	139.079E
B2	SZO002	311.747	127.688	101.815	8.8	243/12	34.965N	139.103E
B3	SZO007	130.721	144.957	37.854	23	343/10	34.977N	138.946E
B4	TKY008	80.523	92.359	35.427	25	377/20	34.785N	139.390E
B5	TKY010	44.237	21.609	14.268	63	258/20	34.377N	139.257E

A2 Information of ground motion recordings in 2006−05−02 earthquake

Code	Station name	PGA/gal			Epicentral distance/km	$\bar{V}_s$/(m·s^{-1}) & h/m	Station location	
		EW	NS	Vertical			Latitude	Longitude
A7	KNG201	36.367	34.106	1.659	65	No data	34.5956N	139.9183E
A8	KNG202	24.845	22.287	13.008	51	No data	34.7396N	139.8393E
A9	KNG203	175.713	98.423	44.210	32	No data	34.7983N	139.6435E
A10	KNG204	101.279	104.738	28.061	22	No data	34.8931N	139.5711E
A11	KNG205	418.672	252.064	96.225	8.8	No data	34.9413N	139.4213E
A12	KNG206	233.129	77.748	19.095	20	No data	35.0966N	139.3778E
B6	KNG008	22.613	11.104	4.386	73	275/20	35.5751N	139.3265E
B7	SZO001	126.390	66.322	15.975	34	292/10	35.1424N	139.0795E
B8	SZO002	222.863	77.238	51.065	21	243/12	34.9652N	139.1031E
B9	TKY008	59.621	104.257	55.788	16	377/20	34.7852N	139.3909E
B10	TKY010	13.947	12.933	8.118	60	258/20	34.3779N	139.2573E

A3 Information of ground motion recordings in 2009−08−11 earthquake

Code	Station name	PGA/gal			Epicentral distance/km	$\bar{V}_s$/(m·s^{-1}) & h/m	Station location	
		EW	NS	Vertical			Latitude	Longitude
A13	KNG201	27.571	34.850	2.469	132	No data	34.5956N	139.9183E
A14	KNG202	17.477	15.402	7.881	123	No data	34.7396N	139.8393E
A15	KNG203	34.050	35.467	5.688	105	No data	34.7983N	139.6435E
A16	KNG204	20.806	25.566	8.662	99	No data	34.8931N	139.5711E
A17	KNG205	56.366	47.886	6.839	86	No data	34.9413N	139.4213E
A18	KNG206	89.002	94.936	19.046	87	No data	35.0966N	139.3778E
B11	KNG008	36.134	26.921	16.656	116	275/20	35.5751N	139.3265E
B12	SZO001	135.626	129.990	30.631	66	292/10	35.1424N	139.0795E
B13	SZO002	131.382	175.297	46.395	59	243/12	34.9652N	139.1031E
B14	TKY009	66.717	57.996	21.930	87	283/20	34.6874N	139.4412E
B15	TKY010	51.187	73.723	38.325	83	258/20	34.3779N	139.2573E

A4 Information of ground motion recordings in 2011−03−11 earthquake

Code	Station name	PGA/gal			Epicentral distance/km	$\bar{V}_s$/(m·s^{-1}) & h/m	Station location	
		EW	NS	Vertical			Latitude	Longitude
A19	KNG201	123.835	107.079	15.315	471	No data	34.5956N	139.9183E
A20	KNG202	149.993	94.919	47.687	462	No data	34.7396N	139.8393E
A21	KNG203	90.94	69.20	18.095	467	No data	34.7983N	139.6435E
A22	KNG204	65.196	59.817	20.874	463	No data	34.8931N	139.5711E
A23	KNG205	150.154	157.687	20.597	467	No data	34.9413N	139.4213E
A24	KNG206	367.516	208.749	61.542	457	No data	35.0966N	139.3778E
B16	CHB017	90.356	108.531	38.945	399	218/20	35.2988N	140.0755E
B17	KNG008	115.522	95.731	48.525	422	275/20	35.5751N	139.3265E
B18	SZO001	49.694	28.325	11.870	472	292/10	35.1424N	139.0795E
B19	SZO002	74.741	43.712	17.767	485	243/12	34.9652N	139.1031E
B20	TKY010	213.399	235.792	134.635	526	258/20	34.3779N	139.2573E

A5 Information of ground motion recordings in 2011−3−15 earthquake

Code	Station name	PGA/gal			Epicentral distance/km	$\bar{V}_s$/(m·s^{-1}) & h/m	Station location	
		EW	NS	Vertical			Latitude	Longitude
A25	KNG201	46.500	33.376	2.791	136	No data	34.5956N	139.9183E
A26	KNG202	24.063	14.840	9.716	121	No data	34.7396N	139.8393E
A27	KNG203	84.538	76.398	5.815	102	No data	34.7983N	139.6435E
A28	KNG204	40.794	22.652	7.429	91	No data	34.8931N	139.5711E
A29	KNG205	105.443	101.926	9.780	76	No data	34.9413N	139.4213E
A30	KNG206	103.410	70.254	13.106	65	No data	35.0966N	139.3778E
B21	CHB017	12.639	13.655	7.344	124	218/20	35.2988N	140.0755E
B22	KNG008	37.373	51.832	29.215	63	275/20	35.5751N	139.3265E
B23	SZO001	194.106	68.706	29.868	38	292/10	35.1424N	139.0795E
B24	SZO002	36.836	46.340	20.850	52	243/12	34.9652N	139.1031E
B25	TKY008	29.184	29.180	11.715	85	377/20	34.7852N	139.3909E

A6 Information of ground motion recordings in 2012−07−03 earthquake

Code	Station name	PGA/gal			Epicentral distance/km	$\bar{V}_s$/(m·s^{-1}) & h/m	Station location	
		EW	NS	Vertical			Latitude	Longitude
A31	KNG201	83.132	91.948	6.360	45	No data	34.5956N	139.9183E
A32	KNG202	135.746	106.527	45.247	29	No data	34.7396N	139.8393E
A33	KNG203	70.773	86.059	5.082	31	No data	34.7983N	139.6435E
A34	KNG204	56.191	54.516	10.545	30	No data	34.8931N	139.5711E
A35	KNG205	155.703	170.789	11.606	41	No data	34.9413N	139.4213E
A36	KNG206	118.567	74.272	15.893	46	No data	35.0966N	139.3778E
B26	CHB017	44.213	25.101	16.007	38	218/20	35.2988N	140.0755E
B27	KNG008	12.006	14.327	16.318	81	275/20	35.5751N	139.3265E
B28	SZO001	38.964	22.274	5.662	74	292/10	35.1424N	139.0795E
B29	SZO002	52.635	22.212	26.809	70	243/12	34.9652N	139.1031E
B30	TKY009	36.363	34.030	14.856	52	283/20	34.6874N	139.4412E

A7 Information of ground motion recordings in 2006−10−14 earthquake

Code	Station name	PGA/gal			Epicentral distance/km	$\bar{V}_s$/(m·s^{-1}) & h/m	Station location	
		EW	NS	Vertical			Latitude	Longitude
A37	KNG201	47.457	57.057	4.248	48	No data	34.5956N	139.9183E
A38	KNG202	229.218	68.835	52.828	46	No data	34.7396N	139.8393E
A39	KNG203	41.783	25.932	8.940	61	No data	34.7983N	139.6435E
A40	KNG204	32.542	36.482	13.897	67	No data	34.8931N	139.5711E
A41	KNG205	51.422	36.929	7.835	81	No data	34.9413N	139.4213E
A42	KNG206	66.709	51.699	6.596	87	——	35.0966N	139.3778E

A8 Information of ground motion recordings in 2007−10−01 earthquake

Code	Station name	PGA/gal			Epicentral distance/km	$\bar{V}_s$/(m·s^{-1}) & h/m	Station location	
		EW	NS	Vertical			Latitude	Longitude
A43	KNG201	16.044	30.385	1.007	101	No data	34.5956N	139.9183E
A44	KNG202	24.818	23.222	9.507	85	No data	34.7396N	139.8393E
A45	KNG203	131.573	123.381	26.765	67	No data	34.7983N	139.6435E
A46	KNG204	21.896	19.237	5.832	55	No data	34.8931N	139.5711E
A47	KNG205	108.734	140.121	12.367	42	No data	34.9413N	139.4213E
A48	KNG206	203.176	82.193	22.759	28	No data	35.0966N	139.3778E

A9 Information of ground motion recordings in 2011−02−05 earthquake

Code	Station name	PGA/gal			Epicentral distance/km	$\bar{V}_s$/(m·s^{-1}) & h/m	Station location	
		EW	NS	Vertical			Latitude	Longitude
A49	KNG201	118.871	77.797	10.412	70	No data	34.5956N	139.9183E
A50	KNG202	64.550	44.955	21.328	72	No data	34.7396N	139.8393E
A51	KNG203	31.150	30.101	3.325	89	No data	34.7983N	139.6435E
A52	KNG204	27.678	23.963	9.720	96	No data	34.8931N	139.5711E
A53	KNG205	62.311	59.821	5.230	110	No data	34.9413N	139.4213E
A54	KNG206	64.716	40.990	7.215	116	No data	35.0966N	139.3778E

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