

An empirical vertical-to-horizontal (V/H) spectral ratio model for shallow-crustal and upper-mantle earthquakes: insights from the S-net seafloor stations in the Japan Trench region

Shili Sheng

Hubei Key Laboratory of Disaster Prevention and Mitigation

Jingyang Tan

Hubei Key Laboratory of Disaster Prevention and Mitigation

Qinghui Lai

18845117968@qq.com

Hubei Key Laboratory of Disaster Prevention and Mitigation

Qi Zhang

Hubei Key Laboratory of Disaster Prevention and Mitigation

Research Article

Keywords: offshore ground motion, H/V spectral ratio, shallow crustal earthquake, upper mantle earthquake, V/H model

Posted Date: September 30th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11064297/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

An empirical vertical-to-horizontal (V/H) spectral ratio
model for shallow-crustal and upper-mantle earthquakes:
insights from the S-net seafloor stations in the Japan Trench
region

Sheng Shili^{1,2} Tan Jingyang^{1,2} Lai Qinghui^{1,2,3} Zhang Qi^{1,2}

1. Hubei Key Laboratory of Disaster Prevention and Mitigation (China Three Gorges University), No. 8, Daxue Road, Yichang 443002, Hubei, China;

2. College of Civil Engineering and Architecture, China Three Gorges University, No. 8, Daxue Road, Yichang 443002, Hubei, China;

3. Wenzhou Key Laboratory of Intelligent Lifeline Protection and Emergency Technology for Resilient City, College of Architecture and Energy Engineering, Wenzhou University of Technology, Wenzhou 325000, China.

Abstract

This study develops an empirical vertical-to-horizontal (V/H) spectral ratio model for offshore ground motions of shallow-crustal and upper-mantle earthquakes from the S-net in the Japan Trench region, integrated with seafloor station based on dominant frequency identification and site classification (SC1 - SC4). Using the Mw 7.5 offshore earthquake off northeastern Japan on 8 December 2025, as a representative event, we quantitatively compare offshore and onshore V/H spectral characteristics and systematically assess the influence of moment magnitude, focal depth, rupture distance, fault mechanism, station burial condition, and site condition on offshore V/H spectral ratios. Model performance is evaluated through between-event and within-event residual analysis and benchmarked against established onshore V/H ratio models from global onshore regions. The results indicate that offshore V/H spectral ratios are generally significantly lower than those observed on onshore ones, which is consistent with the pronounced attenuation of high-frequency vertical ground-motion components by the water layer. The effect of moment magnitude exhibits clear period dependence, while focal depth shows an attenuating effect

Corresponding author: Qinghui, Lai, 18845117968@qq.com

primarily in the intermediate- and long-period ranges. Overall, offshore V/H tends to increase with increasing rupture distance, and burial conditions exert a significant influence on the offshore V/H ratios. In the long-period range ($T > 1.0$ s), offshore V/H decreases progressively from site class SC1 to SC4 regardless of whether the stations are buried. The proposed offshore V/H spectral ratio model provides a useful reference for offshore seismic hazard assessment and the seismic design of offshore structures, particularly for the vertical component of ground motion.

Key words: offshore ground motion; H/V spectral ratio; shallow crustal earthquake; upper mantle earthquake; V/H model

1 Introduction

With the rapid expansion of the global marine economy and the increasing adoption of integrated onshore-offshore seismic zonation frameworks, there is a pressing need for offshore-specific seismic design provisions. Well-documented discrepancies exist between offshore and onshore ground motions in both vertical-component amplitude characteristics and the vertical-to-horizontal (V/H) spectral ratio (Chen et al. 2015; Tan and Hu, 2021). Previous studies have shown that the vertical component of offshore ground motions is systematically attenuated relative to onshore motion, particularly in the short-period range (Boore and Smith 1999; Diao et al. 2014; Li et al. 2015; Chen et al. 2017). Owing to differences in seismic-wave propagation environments between offshore and onshore regions, offshore ground motions exhibit distinct characteristics in terms of spectral properties, energy distribution, and vertical response (Chen et al. 2015, 2018; Zhang and Zheng 2019; Kaynia 2019; Hu et al. 2023). Therefore, the applicability of V/H prediction models developed using onshore strong-motion records to offshore environments requires further investigation. The V/H ratio characterizes the spectral features and relative intensity of vertical ground motion with respect to horizontal ground motion and is an important parameter for describing vertical ground-motion characteristics and developing vertical ground-motion prediction models (Bozorgnia and Campbell 2004; Bommer et al. 2011). In addition, V/H prediction models have been widely used in probabilistic seismic hazard analysis and in the estimation of vertical ground motions (Bommer et al. 2011; Gülerce and Abrahamson 2011; Pezeshk et al. 2022).

With the development of marine resource exploitation and the growing demand for tsunami and earthquake early warning systems, submarine seismic observation networks have gradually been established in various regions worldwide, providing valuable seismic records for investigating the characteristics of offshore ground motions. The United States was among the first to initiate offshore seismic observations and established the Seafloor Earthquake Measurement System (SEMS) near offshore oil platforms in southern California (Boore and Smith 1999). Subsequently, several seafloor strong-motion observation networks were developed in Japan, including the Earthquake and Tsunami Monitoring System (ETMC) deployed in Sagami Bay (Eguchi et al. 1998), the Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net) (Kanazawa 2013), and the DONET1 and DONET2 networks deployed along the Nankai Trough (Kaneda et al. 2015). Based on SEMS offshore ground motions, Diao et al. (2014) conducted numerical simulations and demonstrated that P-wave resonance effects within the water column reduce vertical ground motion amplitudes, resulting in significantly lower offshore V/H ratios than those observed on onshore motions at short periods. As vibration period increases, the influence of the water column gradually weakens, and the difference between offshore and onshore V/H ratios gradually decreases. Chen et al. (2015, 2016, 2017) systematically compared the response spectra and V/H spectral ratios of offshore and onshore motions using records obtained from the K-net and ETMC networks and the SEMS. Their results showed that offshore V/H ratios are significantly lower than those of onshore ones in the short-periods, and they further proposed a simplified prediction relationship for offshore V/H that accounts for the effects of earthquake magnitude and period. However, owing to the limited number of available offshore ground-motion records in earlier studies, the effects of source, path, and site conditions on offshore V/H spectral ratios have not yet been sufficiently investigated. Based on a large number of offshore and onshore ground-motion records from the Sagami Bay region of Japan, Zhang and Zheng (2019, 2020) further revealed that offshore ground motions are characterized by longer durations, stronger long-period energy, and lower V/H spectral ratios, and developed design spectra applicable to offshore environments.

Compared with offshore V/H studies, the development of onshore V/H prediction models is more mature. In recent years, researchers have developed region-specific V/H models incorporating source, path, and site effects for

different parts of the world, including Europe and the Middle East (Bommer et al. 2011), northern Iran (Zolfaghari and Darzi 2019), Italy (Ramadan et al. 2021), and southwestern China (Jiang et al. 2025). In addition, for the Japanese subduction zone, several studies have proposed V/H models applicable when detailed source and path information is unavailable and have demonstrated that the inclusion of source- and distance-related parameters can improve predictions of the vertical-to-horizontal acceleration response spectral ratio (He et al. 2024; Zhao et al. 2025). However, studies on V/H models for offshore ground motions recorded by the S-net network along the Japan Trench remain limited. Existing offshore V/H models have mainly been developed using records from a limited number of ocean-bottom stations in the Sagami Bay region. In contrast, the S-net network covers a vast offshore area along the Japan Trench and has accumulated a large number of ground-motion records, providing a valuable data basis for systematically investigating the factors controlling offshore V/H spectral ratios and developing a regionalized prediction model. Therefore, it is necessary to develop an offshore V/H prediction model based on S-net strong-motion records that explicitly considers source, path, and site effects. Such a model can provide a reference for offshore vertical ground-motion prediction, the development of design response spectra, and the seismic design of offshore engineering structures.

To characterize the variability of offshore V/H ratios, this study first compares the V/H ratios of offshore and onshore motions using a recent earthquake event in Japan, thereby demonstrating the necessity of developing V/H models specifically for offshore regions. Subsequently, the effects of moment magnitude, focal depth, fault type, rupture distance, burial condition, and site condition on offshore V/H ratios are systematically investigated. Finally, an empirical offshore V/H spectral ratio prediction model is developed for shallow crustal and upper-mantle earthquakes in the Japan Trench region. The proposed model is further used to examine the variations in predicted V/H spectral ratios associated with different influencing factors and to compare its predictions with those of existing onshore V/H models.

2 Offshore ground-motion data and HVSR-based site classification

Following the 2011 Great East Japan Earthquake, the National Research Institute for Earth Science and Disaster Resilience (*NIED*) established the Seafloor

137 observation network for earthquakes and tsunamis along the Japan Trench (S-
138 net) (Kanazawa 2013). The network extends from offshore Hokkaido to the
139 waters off the Boso Peninsula, Chiba Prefecture, and comprises 150 ocean-
140 bottom observation stations (Aoi et al. 2020). The S-net stations are deployed in
141 complex marine environments and can be classified into buried and unburied
142 stations according to their installation conditions. Stations located in water
143 depths of less than 1500 m are installed in trenches approximately 1 m deep
144 beneath the seafloor to reduce the potential impacts of fishing activities and are
145 referred to as buried stations. Owing to construction and installation limitations,
146 stations deployed in water depths greater than 1500 m are placed directly on
147 the seafloor and are referred to as unburied stations (Dhakal et al. 2023).

148 Information on the earthquake events was obtained from the website of the
149 Full Range Seismograph Network of Japan (F-net). Following the classification
150 scheme for subduction-zone earthquakes proposed by Zhao et al. (2015), the
151 earthquakes in the Japanese subduction zone were classified into shallow crustal
152 and upper-mantle earthquakes, interplate earthquakes, and intraslab
153 earthquakes based on differences in epicentral location, focal depth, and
154 subduction-interface geometry, thereby accounting for the effects of
155 earthquake type. This study focuses on offshore ground motions generated by
156 shallow crustal and upper-mantle earthquakes. The geographical distribution of
157 the epicenters of the selected events and the locations of the S-net stations is
158 shown in Fig. 1.

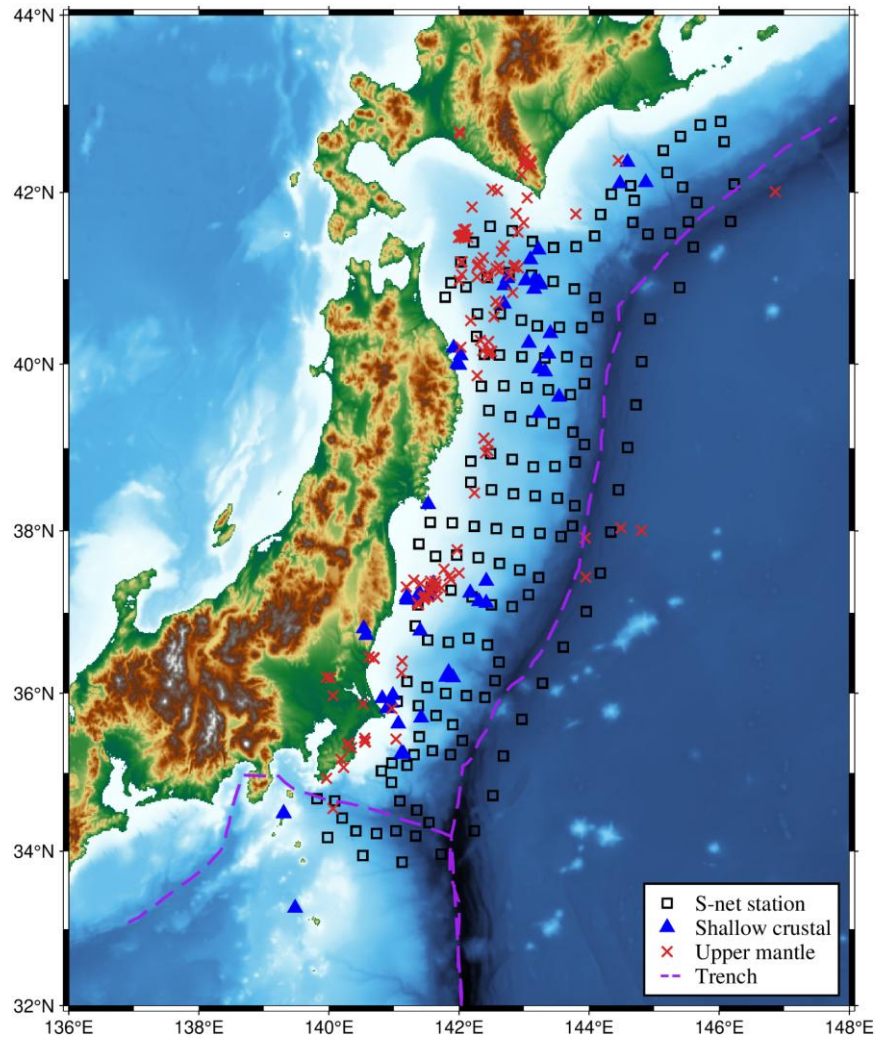


Fig. 1 Distribution of S-net stations and shallow crustal and upper-mantle earthquakes in the subduction zone investigated in this study.

Because the strong-motion sensors of the S-net stations may experience rotation during strong earthquakes, the recorded ground motions require orientation correction. Therefore, the procedures proposed by Takagi et al. (2019) and Dhakal et al. (2021) were adopted to process the S-net strong-motion records. The processing and selection criteria for the S-net ocean-bottom ground-motion records were as follows: (1) records from S-net stations with sensor rotation angles greater than 0.1° were excluded to avoid the effects of significant sensor rotation (Takagi et al. 2019); (2) baseline correction and filtering were performed, and records with waveform errors, incomplete waveforms, or multiple inseparable earthquake events were removed; (3) three-component offshore ground-motion records were excluded if the signal-to-noise ratio (SNR) of any component was less than 3 within the frequency range

of 0.1–20 Hz; (4) only earthquakes with a moment magnitude of $M_w \geq 4.0$ were retained; and (5) only earthquake events with at least three high-quality three-component ground-motion records were selected.

After the earthquake records were processed and screened according to the criteria described above, a total of 9,892 ground-motion records from shallow crustal and upper-mantle earthquakes recorded by the S-net network were selected. The distributions of moment magnitude versus rupture distance and moment magnitude versus focal depth are shown in Fig. 2. To calculate the offshore V/H spectral ratios, the horizontal component was characterized by the orientation-independent RotD50 intensity measure, which represents the median horizontal acceleration response spectrum obtained from the two horizontal components over all possible orientations (Boore 2010). The offshore V/H spectral ratio was then calculated as the ratio of the vertical acceleration response spectrum to the RotD50 horizontal acceleration response spectrum.

Because site information such as (V_{s30}) and (T_n) is unavailable for the S-net ocean-bottom stations, Tan et al. (2026) investigated the applicability of different HVSr methods for identifying the fundamental resonance frequencies of S-net stations and their capability to characterize seafloor site conditions. They recommended using the frequency corresponding to the maximum peak of the S-wave Fourier spectral ratio after Parzen-window smoothing as the optimal explanatory variable for characterizing the S-net ocean-bottom stations. In this study, the offshore site classification results derived from the offshore site predominant frequencies for 150 S-net ocean-bottom stations under different burial conditions are summarized in Table 1.

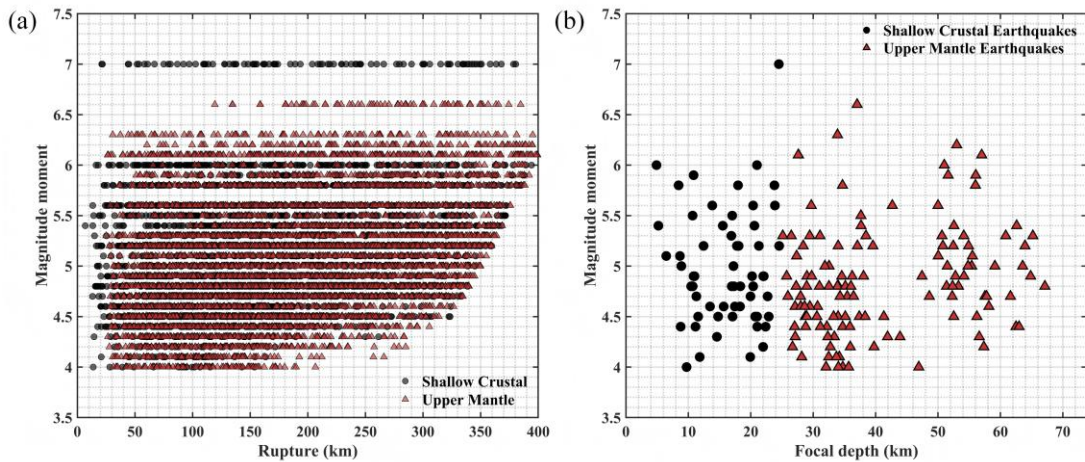


Fig. 2 Distribution of earthquake records used in this study: (a) magnitude versus rupture distance; (b) magnitude versus focal depth.

Table 1 Site conditions of S-net stations based on the offshore site peak frequencies.

Category	Predominant period, T_n (s)	Corresponding approximate range of V_{s30} (m/s)	Mean ln-standard deviation of per-station HVRSR peaks. (in natural logarithm units).	Number of records under buried condition	Number of records under unburied conditions
SC0	HVSR<2	--	--	--	509
SC1	$T_n \leq 0.2$	$V_{s30} \geq 600$	0.34	653	1619
SC2	$0.2 \leq T_n \leq 0.4$	$370 \leq V_{s30} < 600$	0.33	725	3143
SC3	$0.4 \leq T_n \leq 0.8$	$230 \leq V_{s30} < 370$	0.37	1084	1454
SC4	$T_n > 0.8$	$V_{s30} \leq 230$	0.32	562	143
Total				3024	6868

3 Comparison of offshore and onshore V/H spectral ratios

Before developing the offshore V/H prediction model, the differences in V/H ratios between offshore and onshore motions were investigated. For this purpose, ground-motion records from the Mw 7.5 offshore Japan earthquake of 8 December 2025, recorded by the K-net and S-net networks, were analyzed. Fig. 3 compares the V/H ratios of offshore and onshore ground motions for different site conditions. The blue dashed, red dash-dotted, and black solid lines represent the mean V/H spectral ratios for buried offshore stations, unburied offshore stations, and onshore stations, respectively. As shown in Fig. 3, the mean V/H spectral ratios of offshore ground motions are generally lower than those of onshore ground motions, while their overall variation trends with period are broadly similar. This finding is consistent with the results of Cui et al. (2023), who analyzed S-net records from the Mw 7.1 Fukushima offshore earthquake in Japan in 2021. The observed difference may be primarily attributed to the suppressive effect of the water column on vertical components. Further analysis shows that the offshore V/H

spectral ratios are generally distributed within the range of 0.15-0.50, corresponding to approximately 0.5 of the onshore V/H values. These values are substantially lower than the V/H ratio of 0.65 recommended by the current Chinese seismic design code (GB 50011-2010, 2016). Because this recommended value was developed primarily based on onshore ground-motion data, it may be relatively conservative for offshore site conditions. Therefore, it is necessary to develop V/H spectral ratio prediction models specifically for offshore environments based on observed ground-motion records from S-net and other offshore observation networks, thereby improving the understanding of the offshore vertical motions.

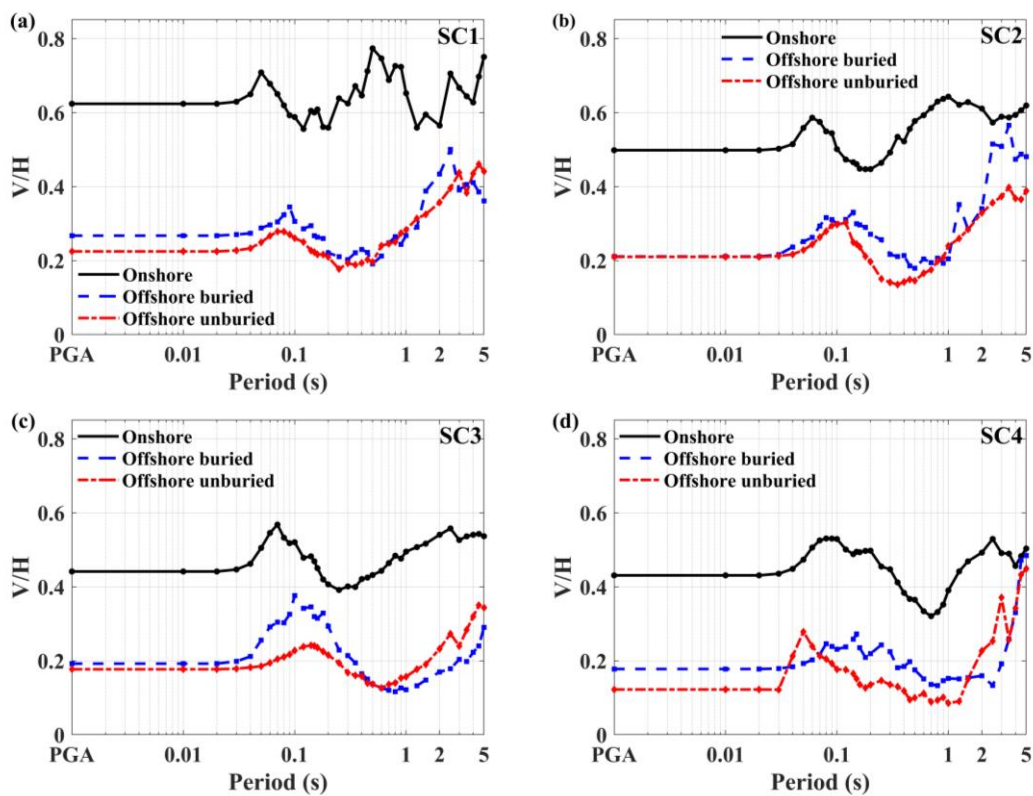


Fig. 3 Comparison of average V/H spectral ratios between offshore and onshore records for different site classes.

4 Model formulation

4.1 Source term

In V/H models, the functional form of the magnitude term is generally determined according to whether magnitude saturation is considered. Commonly adopted formulations include piecewise functions (Haji-Soltani et al., 2017), quadratic functions (Zolfaghari and Darzi, 2019), and linear functions

(Bommer et al., 2011; Tan and Hu, 2021; Pezeshk et al., 2022). To reasonably determine the functional form of the magnitude term, a two-step approach proposed by Haji-Soltani et al. (2017) was adopted to investigate the magnitude-dependent coefficients. Fig. 4 illustrates the variation of the regression-derived magnitude-term coefficients with magnitude, based on the V/H ratios of shallow-crustal and upper-mantle earthquakes recorded in the Japan Trench region.

Fig. 4 Variation of the magnitude-dependent coefficient of the V/H model with earthquake magnitude. illustrates the relationship between the magnitude-term coefficients and magnitude for PGA and periods of $T = 0.02, 0.2, 0.4, 1.0,$ and $2.0s$. The solid red, blue, and black lines represent the quadratic fitting results for shallow-crustal earthquakes, upper-mantle earthquakes, and the combined dataset, respectively, whereas the dashed lines denote the corresponding linear fitting results. As shown in the figure, the magnitude terms for shallow-crustal and upper-mantle earthquakes exhibit certain differences, although the overall discrepancy is relatively small. In the short-period range (PGA and periods of $T=0.02$ and $0.2s$), a change in the variation trend of the magnitude-term coefficients can be observed when the magnitude exceeds approximately 5.5, resulting in an increased difference between the quadratic and linear fitting results. However, the physical mechanism underlying this behavior remains unclear. In addition, for upper-mantle earthquakes, the differences between the linear and quadratic fitting results are generally small across all periods, suggesting that the nonlinear characteristics of the magnitude term are not pronounced. Given that no significant systematic differences in site effects have been found between shallow crustal and upper-mantle earthquakes (He et al., 2024), the records from these two earthquake types were combined for regression analysis in this study. On this basis, to reduce model complexity and ensure the stability of the regression coefficients, a linear function was ultimately adopted as the functional form of the magnitude term.

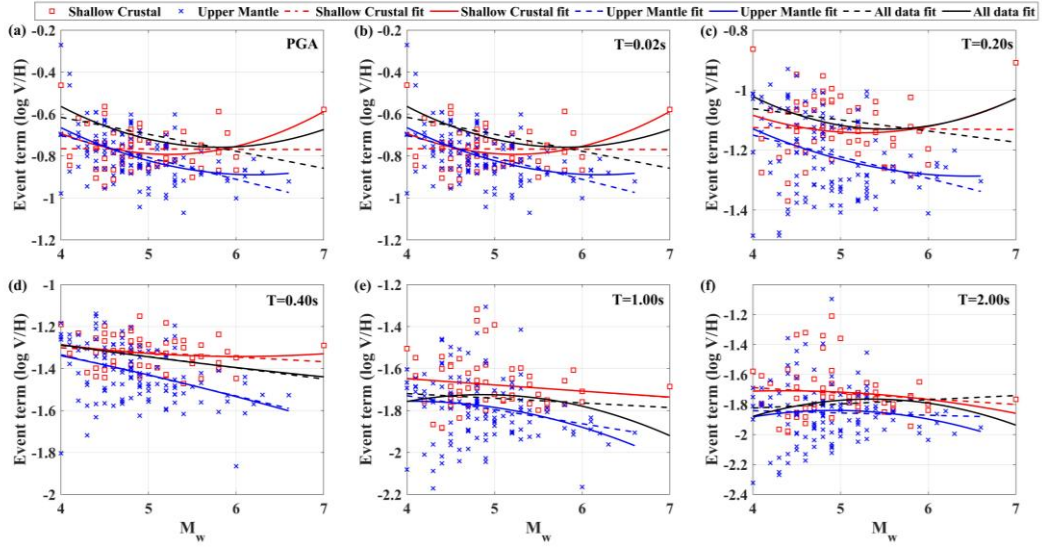


Fig. 4 Variation of the magnitude-dependent coefficient of the V/H model with earthquake magnitude.

The effect of focal depth on the V/H ratio is modeled using the same functional form as the focal-depth term adopted by Tan and Hu (2021). It is worth noting that the source term for both shallow-crustal and upper-mantle earthquakes should account for the effect of fault type, as suggested by Tan et al. (2025). Accordingly, the functional form of the source term is given in Eq. (1):

$$f_{\text{source}} = b_1 + b_2 M_w + b_3 h + b_4 F_N + b_5 F_R \quad (1)$$

in which h denotes the focal depth; F_N and F_R represent the normal- and reverse-faulting indicators, respectively. For normal-faulting earthquakes, $F_N=1$ and $F_R=0$; for reverse-faulting earthquakes, $F_N=0$ and $F_R=1$; otherwise, $F_N = F_R = 0$. The coefficients b_1 – b_5 are regression coefficients.

4.2 Path term

The path term is used to characterize the attenuation of ground-motion amplitude with increasing distance as seismic waves propagate from the source to the ground-surface observation site. This attenuation mainly consists of two components: geometric spreading attenuation caused by the expansion of the wavefront and energy dissipation resulting from the inelastic properties of the propagation medium. However, for V/H spectral ratios, previous studies have shown that the effect of inelastic attenuation is relatively weak. Therefore, following the path-term formulations proposed by Bommer et al. (2011), Zolfaghari and Darzi (2019), and Tan and Hu (2021), A path term without an anelastic attenuation component is adopted, as expressed in Eq. (2):

293

$$f_{\text{path}} = (b_6 + b_7 M_w) \ln \left(\sqrt{R_{\text{rup}}^2 + h_1^2} \right) \quad (2)$$

294

295

296

297

298

299

300

301

302

303

304

305

306

307

308

309

310

311

312

313

314

315

316

in which where b_6 and b_7 are regression coefficients, R_{rup} denotes the rupture distance, and h_1 is set to 5km (Bommer et al. 2011; Zolfaghari and Darzi 2019; Tan and Hu 2021). The coefficient b_7 represents the coupling between magnitude and geometric attenuation. However, previous studies have indicated that the correlation between magnitude and geometric attenuation may not be statistically significant in some regions (Bommer et al. 2011; Zolfaghari and Darzi 2019; Tan and Hu 2021; Pezeshk et al. 2022). To further investigate the variation characteristics of offshore V/H spectral ratios with rupture distance and the potential coupling effect between magnitude and geometric attenuation, the earthquakes were divided into six magnitude intervals: $4 \leq M_w < 4.5$, $4.5 \leq M_w < 5$, $5 \leq M_w < 5.5$, $5.5 \leq M_w < 6$, $6 \leq M_w < 6.5$, and $6.5 \leq M_w < 7.1$. The variation of offshore V/H ratios with rupture distance for different magnitude groups under PGA conditions was analyzed, as shown in Fig. 5. As shown in Fig. 5, the variation trends of V/H ratios with rupture distance exhibit certain differences among different magnitude groups under PGA conditions. Specifically, the V/H ratios decrease with increasing rupture distance for earthquakes with $4 \leq M_w < 4.5$ whereas an increasing trend is observed for earthquakes with $6 \leq M_w < 6.5$, (Fig. 5 a and e). This phenomenon suggests that a potential interaction may exist between magnitude effects and the path term. However, overall, the variation trends are not consistent across different magnitude intervals and spectral periods, and the data exhibit considerable scatter. This indicates that the coupling effect between magnitude and geometric spreading attenuation has a relatively limited influence on V/H spectral ratios.

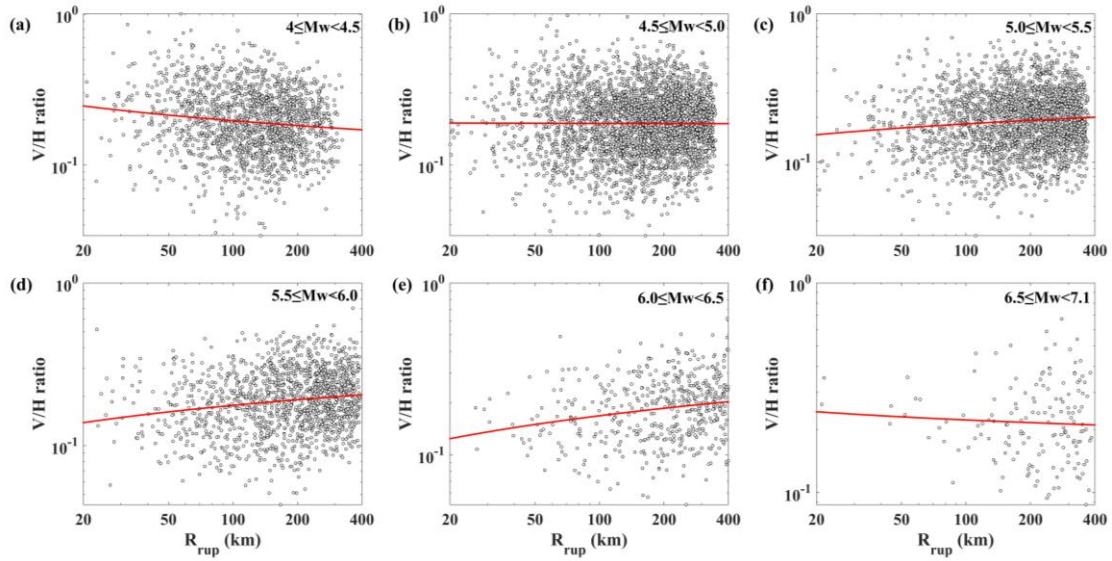


Fig. 5 Variation of V/H ratios with rupture distance at PGA.

To quantitatively evaluate the potential coupling effect between magnitude and geometric attenuation, period-by-period regressions were performed for the magnitude–geometric attenuation interaction term across all 37 periods, and its statistical significance was assessed based on the 95% confidence interval (Fig. 6). The results indicate that this interaction term exhibits a pronounced period-dependent character. In the short-period range (PGA–0.06s), the interaction term is predominantly significantly positive. At approximately 0.08–0.25s, it becomes negative and reaches statistical significance at several periods. At approximately 0.3–2s, its absolute value is relatively small, and the confidence intervals for some periods cross zero. In the longer-period range (approximately 2.5–10s), the interaction term again exhibits relatively stable, significantly negative values.

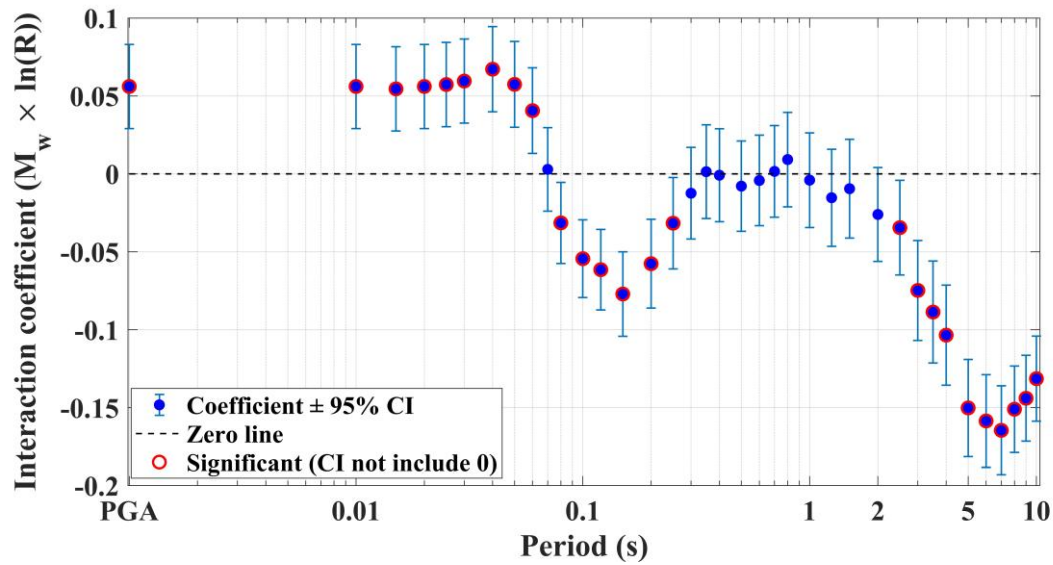


Fig. 6 Variation of significance and confidence intervals of the magnitude–distance interaction term coefficient with spectral period.

These results indicate that the magnitude–distance coupling effect is clearly period-dependent, and its sign is not consistent across different period ranges. Given that this study aims to establish a unified V/H spectral ratio prediction model applicable to the entire period range, directly incorporating this interaction term would require describing its period-varying coefficient on a period-by-period basis, which could increase model complexity and reduce the uniformity of the model form. Moreover, although the interaction term is statistically significant at some periods, its significance and sign are not consistent over the entire period range. Therefore, after comprehensively considering statistical significance, period-dependent characteristics, model parsimony, and parameter interpretability, the magnitude–geometric attenuation interaction term was not included in the final prediction model. Accordingly, the coefficient b7 was set to zero.

4.3 Site term

The S-net stations consist of both buried and unburied stations. To evaluate the influence of station burial conditions on the V/H spectral ratio, comparative analyses of V/H values were conducted for the two burial conditions. Specifically, the records were classified into three magnitude groups: $4 \leq M_w < 5$, $5 \leq M_w < 6$, and $6 \leq M_w < 7.1$. Meanwhile, the rupture distance was divided into four intervals: 0–50 km, 50–100 km, 100–200 km, and 200–400 km. Based on these classifications, the median V/H spectral ratios of buried and unburied stations

under different magnitude–distance combinations were calculated and compared (Fig. 7). The results indicate significant differences in the V/H spectral ratios between buried and unburied stations, and these differences exhibit a clear period-dependent characteristic. At short periods ($T < 0.7$ s), the V/H values of buried stations are generally higher than those of unburied stations. As the period increases, the V/H values of unburied stations gradually exceed those of buried stations. However, in some cases, the V/H values of buried stations become higher again when the period approaches approximately 3 s. These observations indicate an empirical association between the V/H spectral ratio and station burial condition. This effect has been accounted for as a site-effect term in Section 2, rather than being treated as an independent effect.

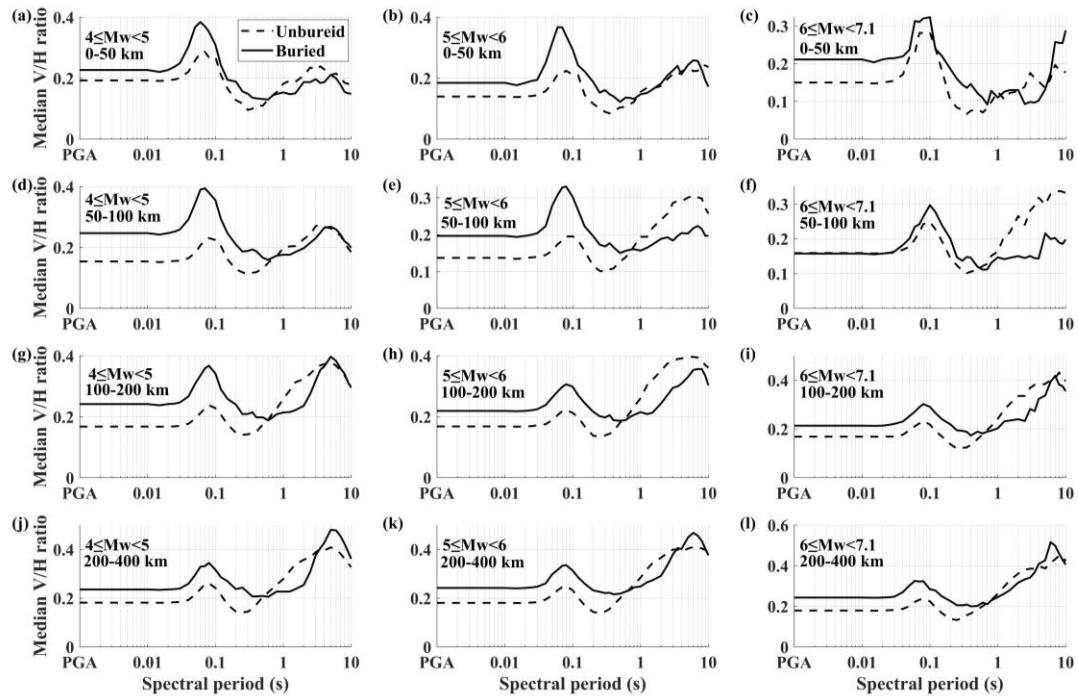


Fig. 7 Variation of median V/H ratios with spectral period under different burial conditions.

In addition, because conventional site classification parameters (e.g., V_{s30}) are difficult to obtain for offshore stations, Tan et al. (2026) proposed an offshore site classification scheme based on the identification of site fundamental frequency using the HVFSR and HVRSR spectral ratio methods. In this study, the site term is derived based on site classification and site fundamental frequency, and Three site terms are adopted, as expressed in Eqs. (3)-(5):

$$f_{Site1} = \begin{cases} p_1 S_b \times \ln(f_{p_parzen}), & \text{for buried} \\ p_2 S_u \times \ln(f_{p_parzen}), & \text{for unburied} \end{cases} \quad (3)$$

$$f_{Site2} = \begin{cases} p_3 S_b \times \ln(f_{p_PSA}), & \text{for buried} \\ p_4 S_u \times \ln(f_{p_PSA}), & \text{for unburied} \end{cases} \quad (4)$$

$$f_{Site3} = \begin{cases} c_i S_b \times SC_i, & (i = 1, 2, 3, 4), \text{ for buried} \\ c_{i+4} S_u \times SC_i, & (i = 1, 2, 3, 4), \text{ for unburied} \end{cases} \quad (5)$$

in which f_{Site1} , f_{Site2} , and f_{Site3} represent the three different formulations of the site term, respectively; f_{p_parzen} denotes the site fundamental frequency identified from the Fourier spectrum, and f_{p_PSA} represents the site fundamental frequency obtained from the response spectrum. $SC_i (i=1, \dots, 4)$ is an indicator variable for site class: $SC_i=1$ if a station belongs to site class SC_i , and $SC_i=0$ otherwise. S_b and S_u denote buried and unburied stations, respectively: $S_b=1$ and $S_u=0$ for a buried station, whereas $S_u=1$ and $S_b=0$ for an unburied station. p_1 - p_4 and c_1 - c_8 are regression coefficients.

To determine the optimal formulation of the site term, the Akaike information criterion (AIC) was used to compare the three site-term formulations, as shown in Fig. 8a. A lower AIC value indicates better model performance. The results show that the AIC values of the f_{Site3} term are lower than those of the other two formulations for most periods, indicating its superior fitting performance. In addition, because the within-event residual includes uncertainties associated with both site and path effects (Tan et al. 2025), the within-event standard deviation and total standard deviation obtained from the three site-term formulations were further compared, as shown in Fig. 8 b and c. The results indicate that the f_{Site3} formulation produces the lowest within-event and total standard deviations among the three models. Therefore, the f_{Site3} formulation is adopted as the site term in the final V/H prediction model.

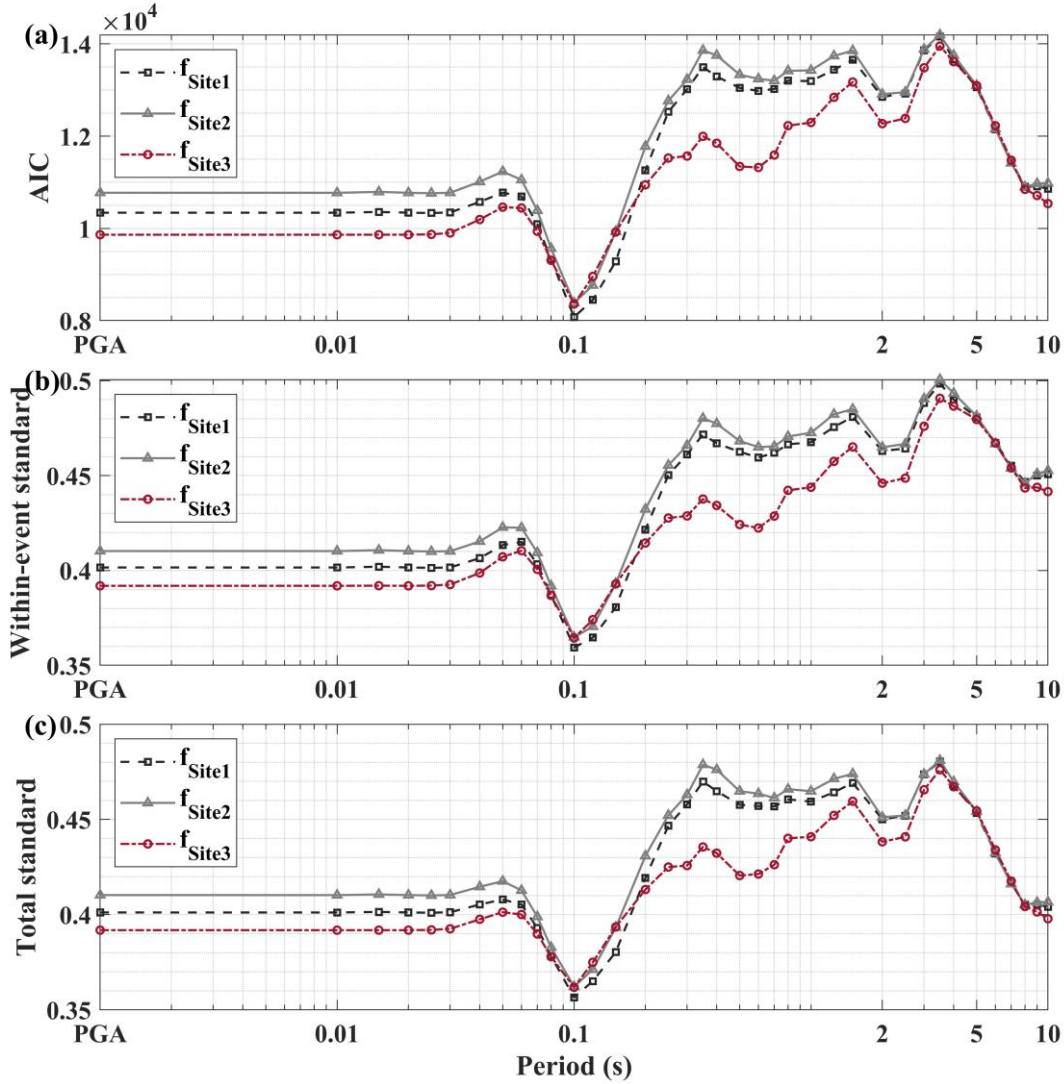
399

400 5 Model regression and residual analysis

401 5.1 Regression coefficients of the V/H prediction model

In this study, the random-effects approach proposed by Abrahamson and Youngs (1992) was employed to regress the model coefficients, and the resulting regression coefficients are listed in Table 2. The deviation between the model predictions and observations can be decomposed into between-event

406 and within-event variability, with the corresponding standard deviations
 407 denoted as τ and σ , respectively. Fig. 9 illustrates

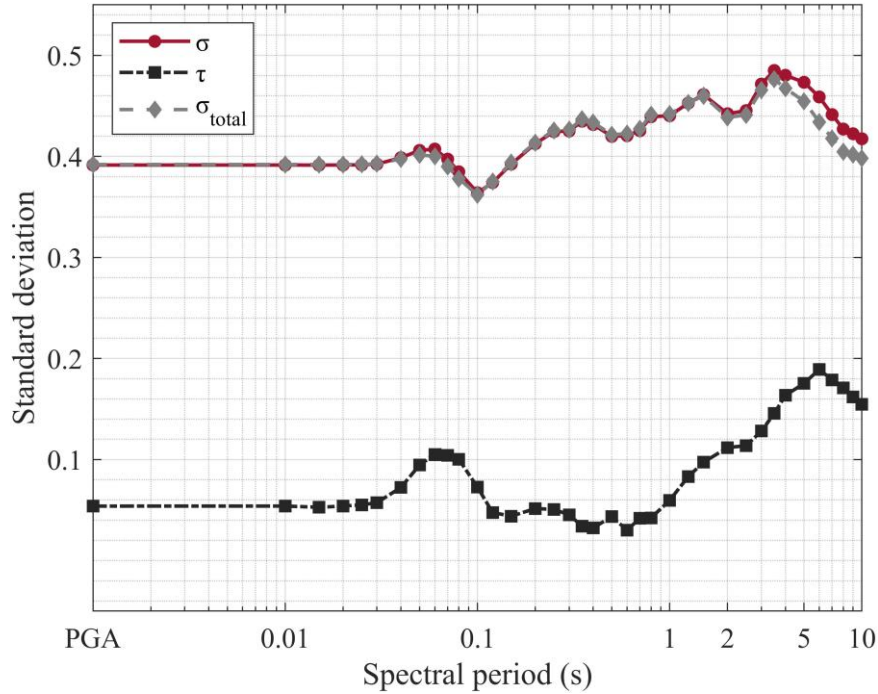


409 **Fig. 8 Period-dependent variations of AIC values and standard deviations for different**
 410 **site-term models.**

411 the variation of the between-event standard deviation, within-event standard
 412 deviation, and total standard deviation of the V/H model with spectral period.
 413 The results show that the total standard deviation reaches its maximum value at
 414 $T=4s$, with a value of approximately 0.46. Further analysis (Fig. 9) indicates that
 415 the between-event variability contributes relatively little to the total variability
 416 and represents a secondary source of uncertainty (Crempien and Archuleta,
 417 2017). The total standard deviation is expressed as Eq. (6):

$$\sigma_{total} = \sqrt{\sigma^2 + \tau^2} \quad (6)$$

419 in which σ_{total} denotes the total standard deviation, and σ and τ represent the
 420 within-event and between-event standard deviations, respectively.



421
 422 **Fig. 9 Variation of standard deviations with spectral period.**

423 5.2 Residual analysis

424 Residuals are generally defined as the difference between the natural logarithm
 425 of the observed V/H spectral ratio and the value predicted by the ground-
 426 motion model (GMM). Model residuals can be used to characterize prediction
 427 errors and quantify model uncertainty (Baltay et al., 2017). To verify the reliability
 428 and applicability of the proposed model, a systematic residual analysis was
 429 conducted. **Error! Reference source not found.** Fig. 11 show the variation of
 430 between-event residuals of V/H ratios for shallow-crustal and upper-mantle
 431 earthquakes in the Japan Trench region with magnitude and focal depth. Figs.
 432 12-15 present the variation of within-event residuals with rupture distance,
 433 sediment thickness, water depth, and f_{p_parzen} , respectively. As shown in Figs. 10
 434 and 11, the between-event residuals exhibit no systematic bias with respect to
 435 magnitude or focal depth, except for slight deviations at large magnitudes,
 436 which may be attributed to the limited number of large-magnitude records. Fig.
 437 12 indicates that the within-event residuals of V/H ratios are unbiased with
 438 respect to rupture distance, suggesting that the adopted path term is

Table 2 Regression coefficients of the V/H prediction model for shallow crustal and upper-mantle earthquakes in the Japan subduction zone.

Period(s)	b ₁	b ₂	b ₃	b ₄	b ₅	b ₆	c ₁	c ₂	c ₃	c ₄	c ₅	c ₆	c ₇	c ₈
PGA	-1.370	-0.035	-0.002	0.073	-0.002	0.109	-0.408	-0.333	-0.491	-0.378	-0.574	-0.847	-0.842	-0.776
0.01	-1.369	-0.035	-0.002	0.073	-0.002	0.109	-0.408	-0.332	-0.491	-0.377	-0.574	-0.847	-0.842	-0.776
0.015	-1.402	-0.033	-0.002	0.073	-0.001	0.114	-0.418	-0.345	-0.502	-0.387	-0.579	-0.853	-0.847	-0.782
0.02	-1.369	-0.035	-0.002	0.073	-0.002	0.109	-0.408	-0.333	-0.491	-0.378	-0.574	-0.847	-0.842	-0.776
0.025	-1.340	-0.037	-0.002	0.073	-0.003	0.105	-0.398	-0.321	-0.481	-0.369	-0.571	-0.842	-0.837	-0.772
0.03	-1.298	-0.041	-0.001	0.074	-0.006	0.099	-0.382	-0.304	-0.467	-0.358	-0.565	-0.836	-0.830	-0.766
0.04	-1.115	-0.053	0.000	0.075	-0.021	0.073	-0.306	-0.221	-0.401	-0.310	-0.537	-0.824	-0.812	-0.749
0.05	-0.878	-0.068	0.002	0.056	-0.037	0.037	-0.231	-0.116	-0.299	-0.224	-0.475	-0.782	-0.775	-0.693
0.06	-0.769	-0.075	0.003	0.035	-0.031	0.019	-0.181	-0.075	-0.210	-0.146	-0.418	-0.689	-0.697	-0.615
0.07	-0.778	-0.079	0.003	0.026	-0.027	0.024	-0.157	-0.033	-0.173	-0.066	-0.400	-0.602	-0.616	-0.535
0.08	-0.878	-0.078	0.003	0.031	-0.018	0.038	-0.074	-0.014	-0.114	-0.028	-0.371	-0.511	-0.512	-0.436
0.10	-1.073	-0.053	0.001	0.040	-0.030	0.040	-0.057	-0.014	-0.037	0.038	-0.384	-0.413	-0.375	-0.287
0.12	-1.214	-0.032	-0.001	0.059	-0.021	0.057	-0.240	-0.144	-0.127	-0.044	-0.581	-0.520	-0.438	-0.309
0.15	-1.366	-0.015	-0.002	0.048	-0.024	0.089	-0.481	-0.345	-0.260	-0.187	-0.729	-0.771	-0.644	-0.417
0.20	-1.469	-0.019	-0.004	0.052	-0.034	0.119	-0.631	-0.392	-0.365	-0.270	-0.668	-1.059	-0.878	-0.625
0.25	-1.543	-0.034	-0.005	0.060	-0.023	0.159	-0.589	-0.411	-0.613	-0.354	-0.610	-1.183	-1.102	-0.935
0.30	-1.592	-0.051	-0.005	0.060	-0.002	0.205	-0.645	-0.513	-0.774	-0.474	-0.662	-1.250	-1.261	-1.177
0.35	-1.589	-0.055	-0.005	0.061	0.010	0.220	-0.555	-0.664	-0.851	-0.567	-0.663	-1.233	-1.352	-1.321
0.40	-1.662	-0.053	-0.005	0.069	0.023	0.233	-0.554	-0.736	-0.901	-0.666	-0.629	-1.146	-1.400	-1.403
0.50	-1.784	-0.061	-0.005	0.071	0.022	0.277	-0.582	-0.752	-1.037	-0.877	-0.586	-1.010	-1.393	-1.497
0.60	-1.942	-0.052	-0.005	0.058	0.008	0.289	-0.422	-0.624	-0.975	-0.974	-0.494	-0.872	-1.256	-1.470

Corresponding author: Qinghui, Lai, 18845117968@qq.com

0.70	-1.985	-0.052	-0.005	0.060	-0.003	0.295	-0.334	-0.561	-0.952	-0.929	-0.426	-0.750	-1.093	-1.366
0.80	-2.078	-0.052	-0.005	0.046	-0.019	0.309	-0.263	-0.452	-0.841	-0.912	-0.351	-0.624	-0.906	-1.271
1.00	-2.160	-0.033	-0.005	0.046	-0.026	0.310	-0.162	-0.445	-0.743	-0.950	-0.268	-0.547	-0.748	-1.080
1.25	-2.382	-0.023	-0.006	0.059	-0.027	0.347	-0.136	-0.385	-0.714	-0.791	-0.209	-0.453	-0.611	-1.004
1.50	-2.483	-0.015	-0.005	0.056	-0.032	0.355	-0.137	-0.274	-0.643	-0.686	-0.143	-0.361	-0.517	-0.756
2.00	-2.539	0.007	-0.005	0.049	-0.051	0.353	-0.003	-0.205	-0.573	-0.712	-0.183	-0.312	-0.417	-0.553
2.50	-2.368	-0.016	-0.005	0.072	-0.038	0.343	0.048	-0.136	-0.558	-0.704	-0.153	-0.292	-0.367	-0.423
3.00	-2.253	-0.055	-0.005	0.088	-0.037	0.375	0.011	-0.133	-0.546	-0.684	-0.153	-0.323	-0.401	-0.492
3.50	-2.238	-0.084	-0.006	0.115	-0.022	0.400	0.018	-0.103	-0.466	-0.599	-0.158	-0.310	-0.351	-0.433
4.00	-2.173	-0.099	-0.006	0.110	-0.040	0.405	0.020	-0.052	-0.398	-0.474	-0.142	-0.308	-0.325	-0.391
5.00	-2.326	-0.098	-0.006	0.125	-0.048	0.443	-0.034	-0.033	-0.295	-0.349	-0.173	-0.330	-0.368	-0.368
6.00	-2.770	-0.010	-0.007	0.145	-0.020	0.443	-0.065	-0.093	-0.228	-0.282	-0.171	-0.313	-0.353	-0.357
7.00	-3.091	0.049	-0.008	0.174	0.003	0.447	-0.106	-0.142	-0.236	-0.310	-0.189	-0.307	-0.331	-0.300
8.00	-3.372	0.095	-0.009	0.177	-0.003	0.456	-0.154	-0.178	-0.294	-0.328	-0.211	-0.316	-0.345	-0.338
9.00	-3.508	0.119	-0.010	0.182	0.015	0.461	-0.193	-0.223	-0.377	-0.394	-0.246	-0.374	-0.385	-0.412
10.0	-3.530	0.123	-0.010	0.193	0.035	0.460	-0.215	-0.252	-0.467	-0.458	-0.286	-0.423	-0.434	-0.467

appropriate. Because direct site-condition parameters are difficult to obtain for offshore stations, previous studies have used sediment thickness and water depth as proxies for site effects (Tan et al., 2025). Therefore, to further evaluate the effectiveness of the site term, Figs. 13 and 14 illustrates the distribution of within-event residuals with sediment thickness and water depth. The results show that, after incorporating site classification, the residuals exhibit no obvious dependence on either sediment thickness or water depth. This indicates that the developed site term can effectively capture the relevant site effects, and thus the additional consideration of sediment thickness and water depth is unnecessary. Furthermore, Fig. 15 presents the variation of within-event residuals with f_{p_parzen} . Since the site classification adopted in the V/H prediction model is based on the site fundamental frequency, the residuals show nearly unbiased distributions with respect to f_{p_parzen} . This confirms the applicability and stability of the proposed site classification method for establishing the site term of the V/H model.

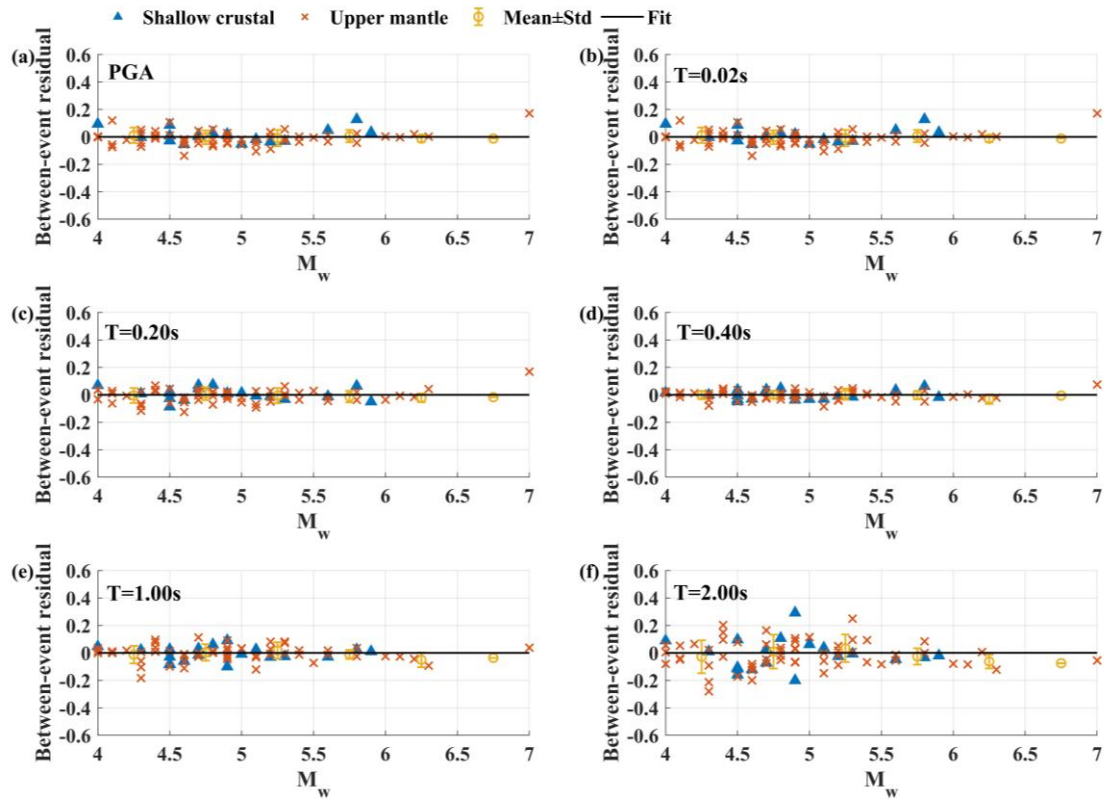


Fig. 10 Variation of between-event residuals with earthquake magnitude.

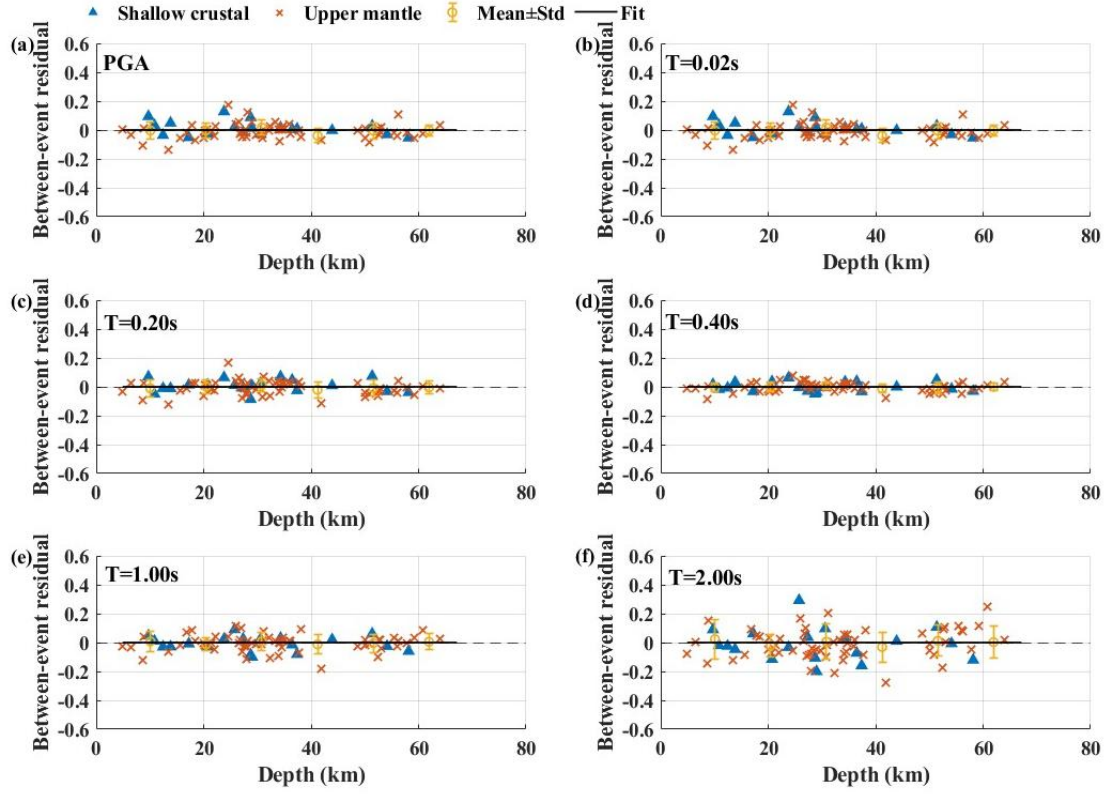


Fig. 11 Distribution of between-event residuals as a function of focal depth.

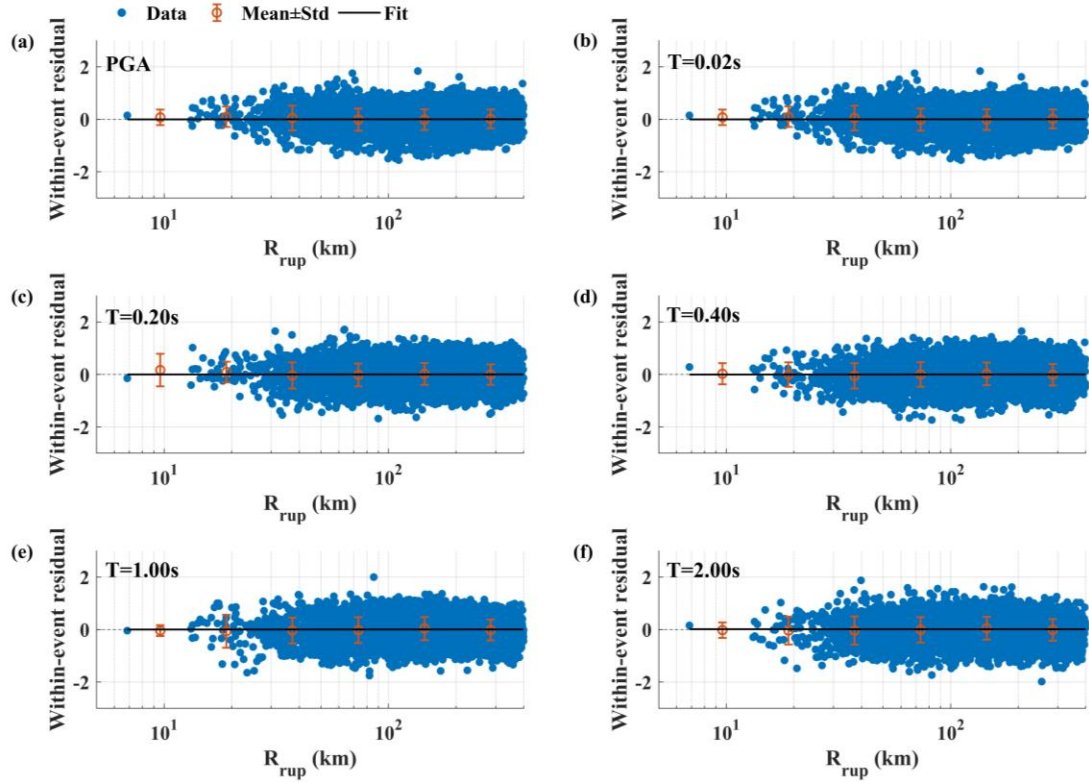


Fig. 12 Variation of within-event residuals with rupture distance.

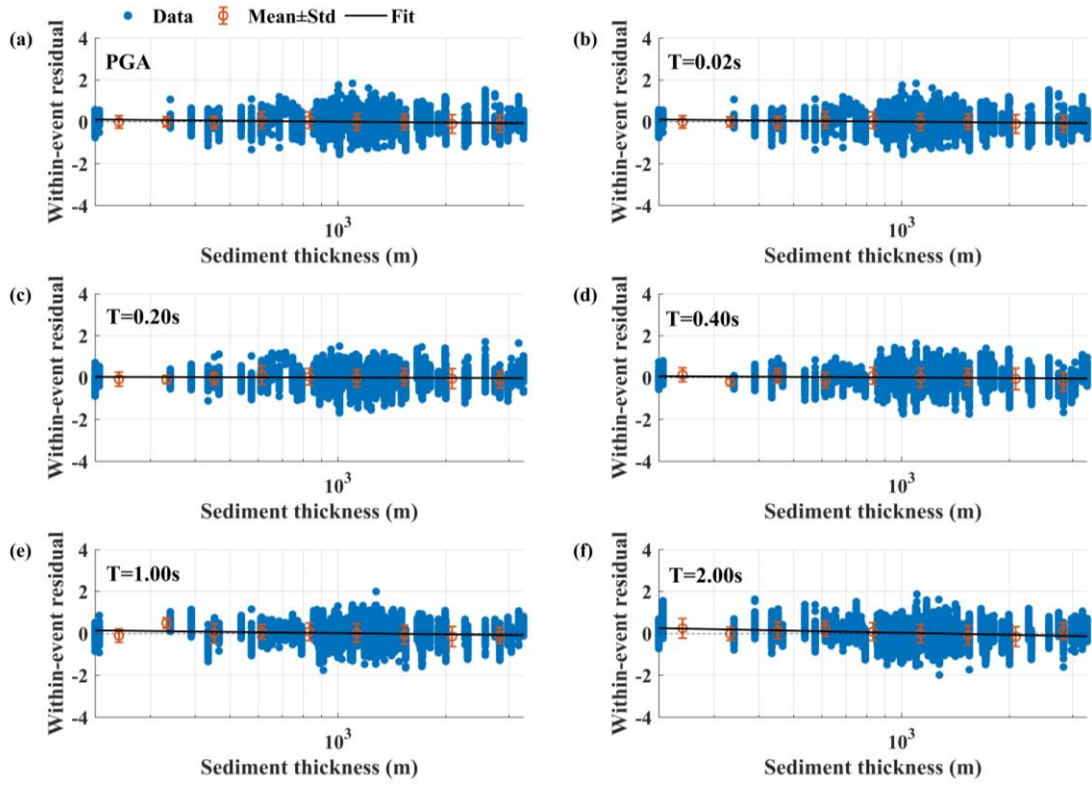


Fig. 13 Variation of within-event residuals with sediment layer thickness.

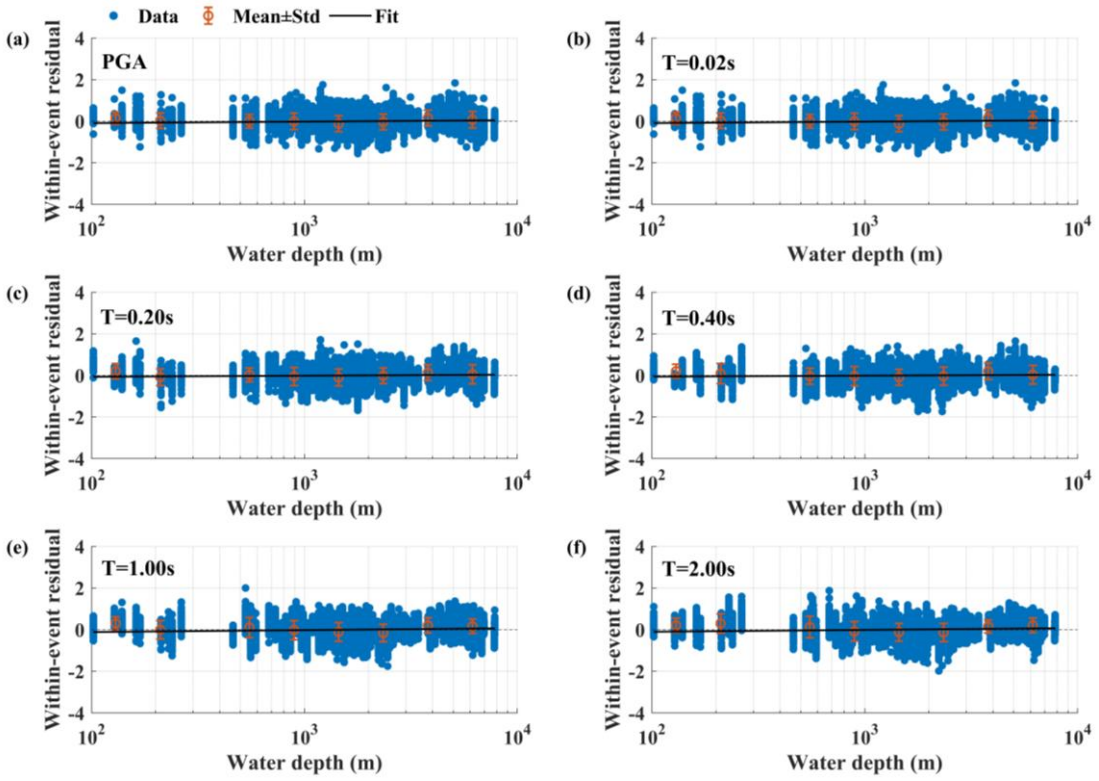


Fig. 14 Variation of within-event residuals with water depth.

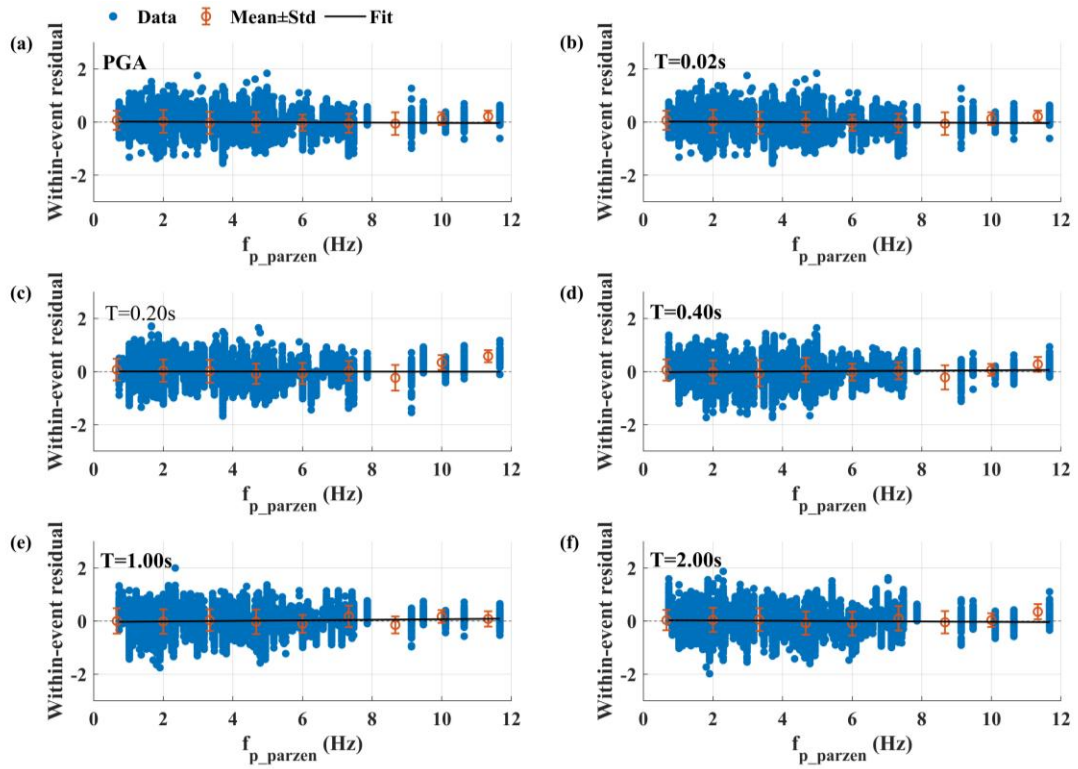


Fig. 15 Variation of within-event residuals with f_{p_parzen} .

6 V/H spectral ratio prediction model

6.1 V/H prediction models for different magnitude groups

Fig. 16 illustrates the variation of the predicted V/H spectral ratios with period for different magnitudes under buried conditions, with a focal depth of $h=30\text{km}$, rupture distances of $R_{rup}=30\text{km}$ and 200km , and site classes of SC1 and SC2. As shown in Figs. 16a–b, under buried conditions, the variation of V/H with magnitude exhibits a clear period-dependent pattern for both near-field ($R_{rup}=30\text{km}$) and far-field ($R_{rup}=200\text{km}$) cases. Specifically, for periods of $T<0.15\text{s}$ and $2.5<T<6\text{s}$, the V/H ratios generally decrease with increasing magnitude, whereas for periods longer than 6.0s , the V/H ratios gradually increase with increasing magnitude. In addition, within the intermediate-period range ($0.15\leq T\leq 2\text{s}$), the V/H curves corresponding to different magnitudes are relatively close to each other, indicating a relatively weak magnitude dependence.

Fig. 17 presents the variation of the predicted V/H spectral ratios with period for different magnitudes under unburied conditions, using the same focal

depth ($h=30\text{km}$), rupture distances ($R_{\text{rup}}=30\text{km}$ and 200km), and site classes (SC1 and SC2). As shown in Figs. 19a–d, the magnitude-dependent variation of V/H under unburied conditions is generally consistent with that under buried conditions. The magnitude dependence characteristics across different period ranges remain largely unchanged, with only minor differences in amplitude occurring at some specific periods.

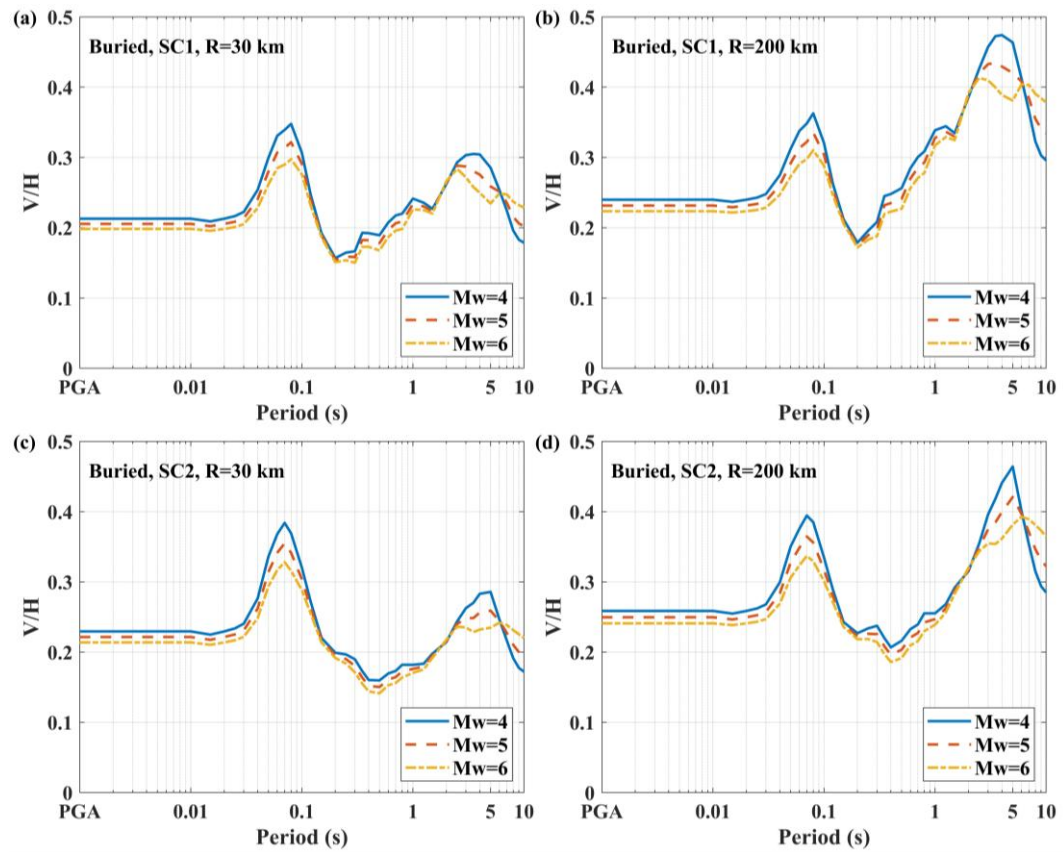


Fig. 16 Predicted V/H ratios for different magnitude groups under buried conditions.

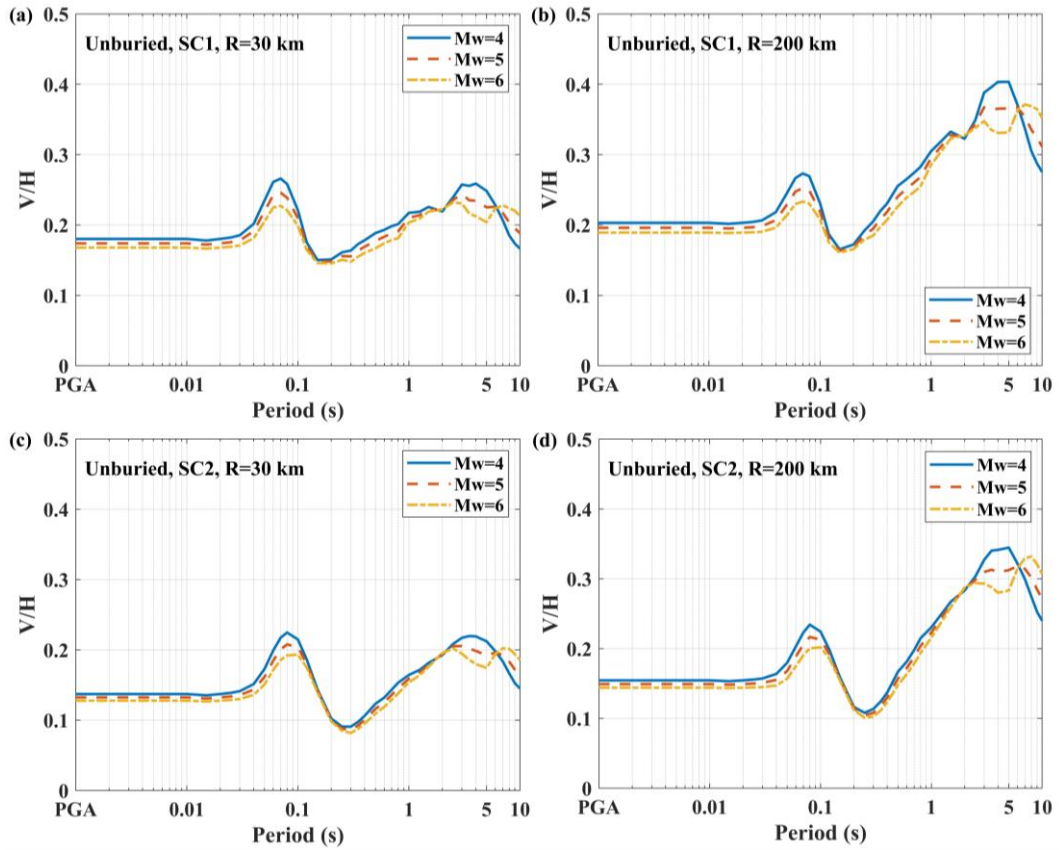


Fig. 17 Predicted V/H spectral ratios for different magnitude groups under unburied conditions.

6.2 V/H prediction models for different focal depths

Fig. 18 illustrates the variation of predicted V/H spectral ratios with period for different focal depths ($h=5, 10, 15, 30, 40,$ and 50km) under buried and unburied conditions, with $M_w=5$, $R_{rup}=100\text{km}$, and site classes of SC1 and SC2. As shown in Fig. 18, the overall shapes of the predicted V/H curves corresponding to different focal depths are generally consistent under both burial conditions, indicating that focal depth has a limited influence on the spectral shape but can moderately affect the amplitude of V/H ratios. Specifically, at short periods (PGA and $T<0.04\text{s}$), the differences in V/H ratios among different focal depths are relatively small, suggesting that the influence of focal depth is insignificant. However, as the period increases $T>0.12\text{s}$, the V/H ratios exhibit a clear decreasing trend with increasing focal depth. This trend remains consistent for different site classes (SC1 and SC2) and under both buried and unburied conditions.

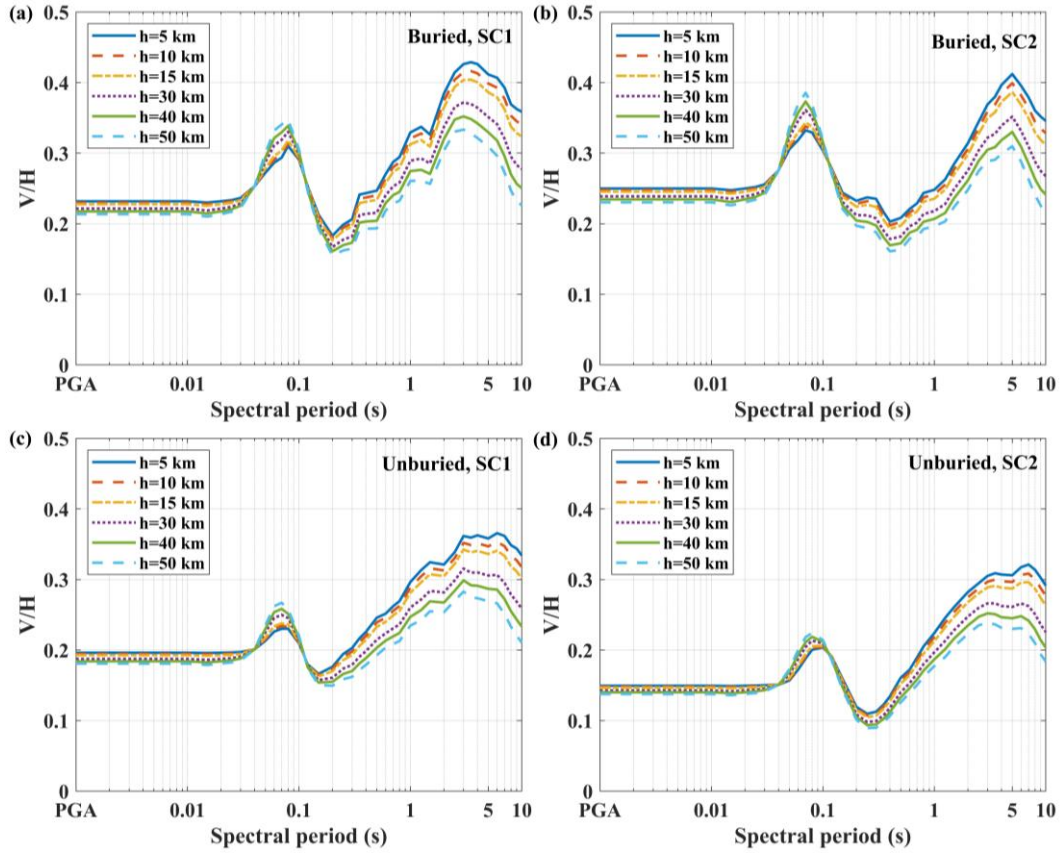


Fig. 18 Variation of predicted V/H spectral ratios with earthquake magnitude for different focal depths.

6.3 V/H prediction models for different fault types

Fig. 19 illustrates the variation of the predicted V/H spectral ratios with period for different fault types under the conditions of $M_w=5$, $R_{rup}=100\text{km}$, and $h=30\text{km}$, considering both buried and unburied stations with site classes SC1 and SC2. As shown in Figs. 19a–d, different fault types have an influence on the V/H spectral ratios. The V/H values under normal-faulting conditions are generally higher than those under reverse- and strike-slip-faulting conditions. In contrast, the V/H curves corresponding to reverse and strike-slip faulting are relatively similar, with only minor differences.

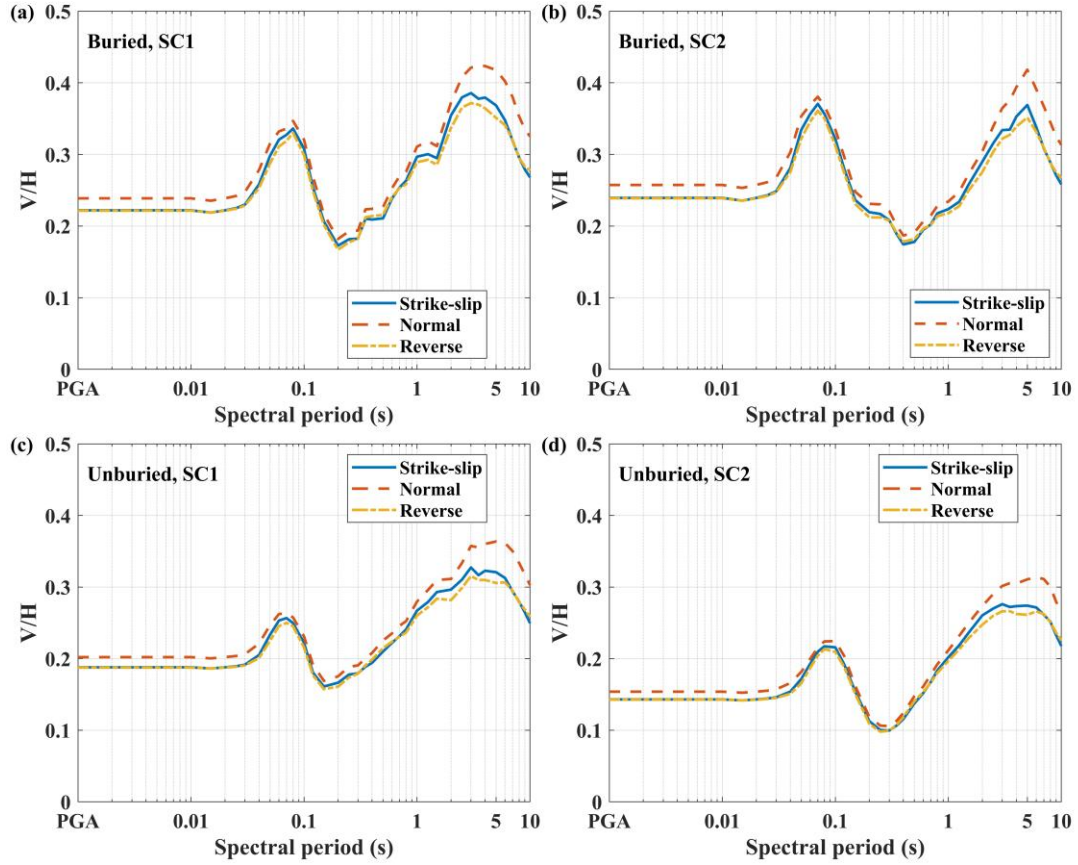


Fig. 19 Effects of different fault types on V/H spectral ratios ($M_w=5$, $R_{rup}=100$ km, $h=30$ km).

6.4 V/H prediction models for different rupture distances and burial conditions

Based on the developed V/H prediction model, the effects of rupture distance on the V/H spectral ratio were investigated by considering $M_w=5$, $h=30$ km, and reverse-faulting conditions. Different burial conditions and site classes (SC1 and SC2) were considered. In this section, the influence of rupture distance on V/H was quantitatively evaluated by comparing the predicted V/H ratios at different rupture distances while keeping other influencing factors unchanged.

As shown in Fig. 20, the variation patterns of V/H with period are generally consistent for different burial conditions and site classes (SC1 and SC2). At short periods ($T < 0.06$ s), V/H gradually increases with increasing rupture distance. Within the period range of $0.06 \leq T \leq 0.15$ s, the differences in V/H among different rupture distances are relatively small, and a local peak appears near $T=0.08$ s. With further increasing period, the differences in V/H among different

rupture distances gradually become larger; however, V/H generally continues to increase with increasing rupture distance.

To investigate the influence of propagation path effects on the V/H spectral ratio of offshore ground motions, the variation of V/H with rupture distance was calculated based on the proposed prediction model. Fig. 21 presents the variation of V/H with R_{rup} for normal-faulting earthquakes, with a fixed focal depth of $h=30\text{km}$ and site class SC1. The results are presented for different magnitudes $M_w=4, 5$, and 6. Both buried and unburied offshore stations were considered, and representative periods including PGA and $T=0.02, 0.10, 0.40, 1.0$, and 3.0 s were selected for analysis.

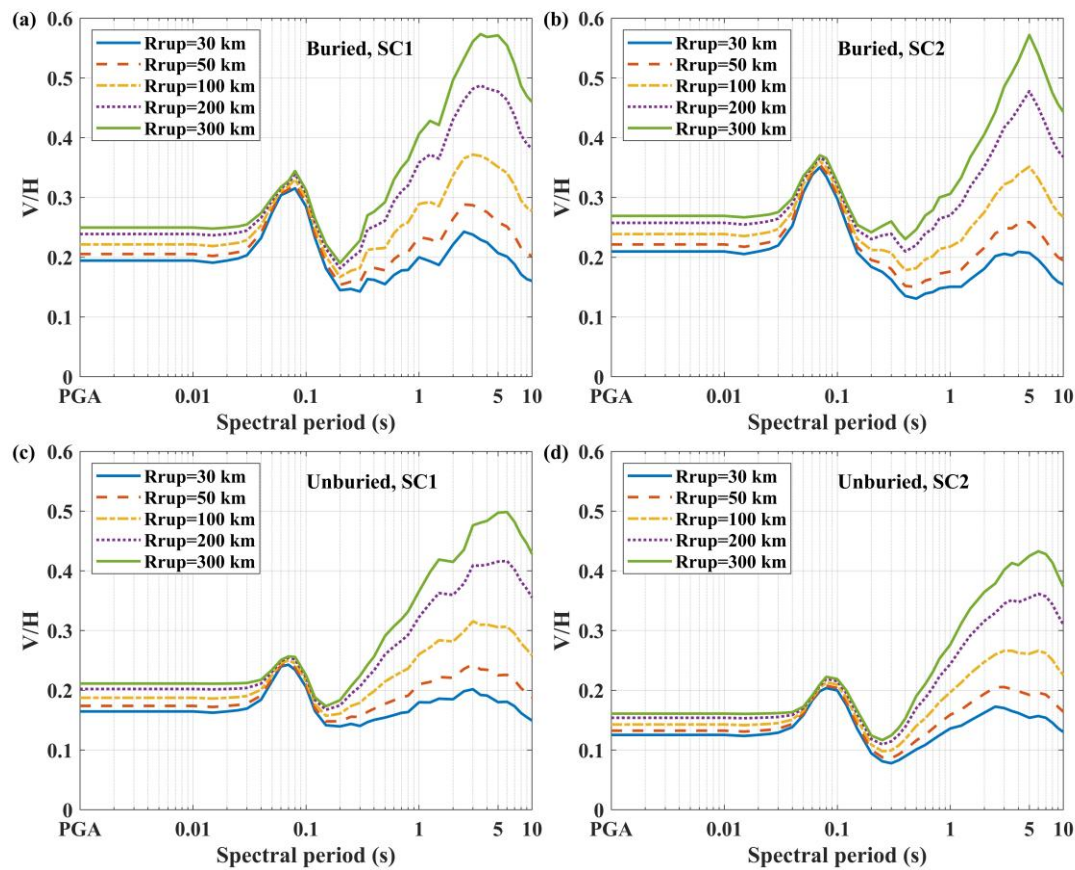


Fig. 20 Variation of V/H spectral ratios with spectral period for different rupture distances ($M_w=5$, $h=30$ km, Reverse).

As shown in Fig. 21, the V/H spectral ratio generally increases with increasing R_{rup} , indicating that propagation path effects have a significant influence on the vertical-to-horizontal spectral ratio of offshore ground motions. For PGA and short periods ($T=0.02\text{s}$), the variation of V/H with distance is relatively weak, showing only a slight increase over the range of 20–400km.

With increasing period, the distance dependence becomes more pronounced, particularly at $T=1.0$ and 3.0 s, where V/H exhibits a clearer increasing trend with increasing R_{rup} . In addition, Fig. 24 clearly shows that the V/H ratios for buried stations are higher than those for unburied stations.

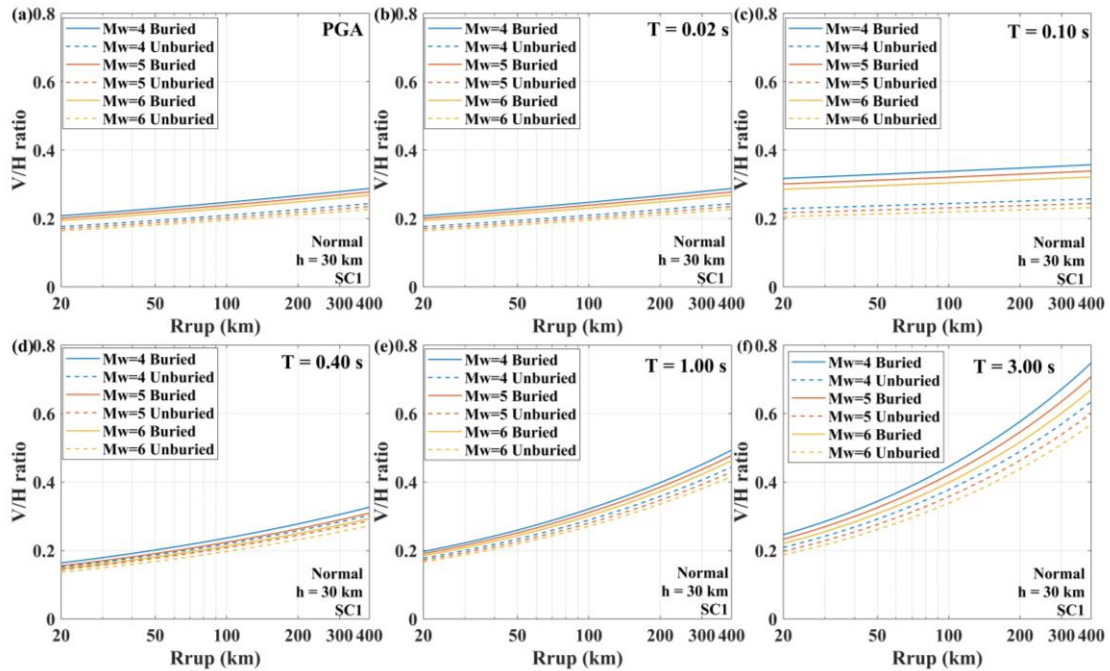


Fig. 21 Variation of V/H spectral ratios with rupture distance under buried and unburied conditions for different magnitudes and spectral periods ($M_w = 4, 5, 6$; PGA, $T = 0.02, 0.1, 0.5, 1.0$, and 3.0 s).

6.5 V/H prediction Models for different site conditions

Fig. 22 illustrates the variation of predicted V/H spectral ratios with period for different site classes under buried and unburied conditions, considering $M_w=5$, $h=30$ km, reverse-faulting conditions, and rupture distances of $R_{rup}=30$ km and 200 km. As shown in Figs. 22a–d, under buried conditions, the V/H ratios gradually decrease with increasing site class from SC1 to SC4 when the period exceeds 1 s. Under unburied conditions, the V/H ratios for site class SC0 are significantly higher than those for other site classes. Moreover, for periods longer than 1 s, the V/H ratios also exhibit a decreasing trend with increasing site class from SC0 to SC4.

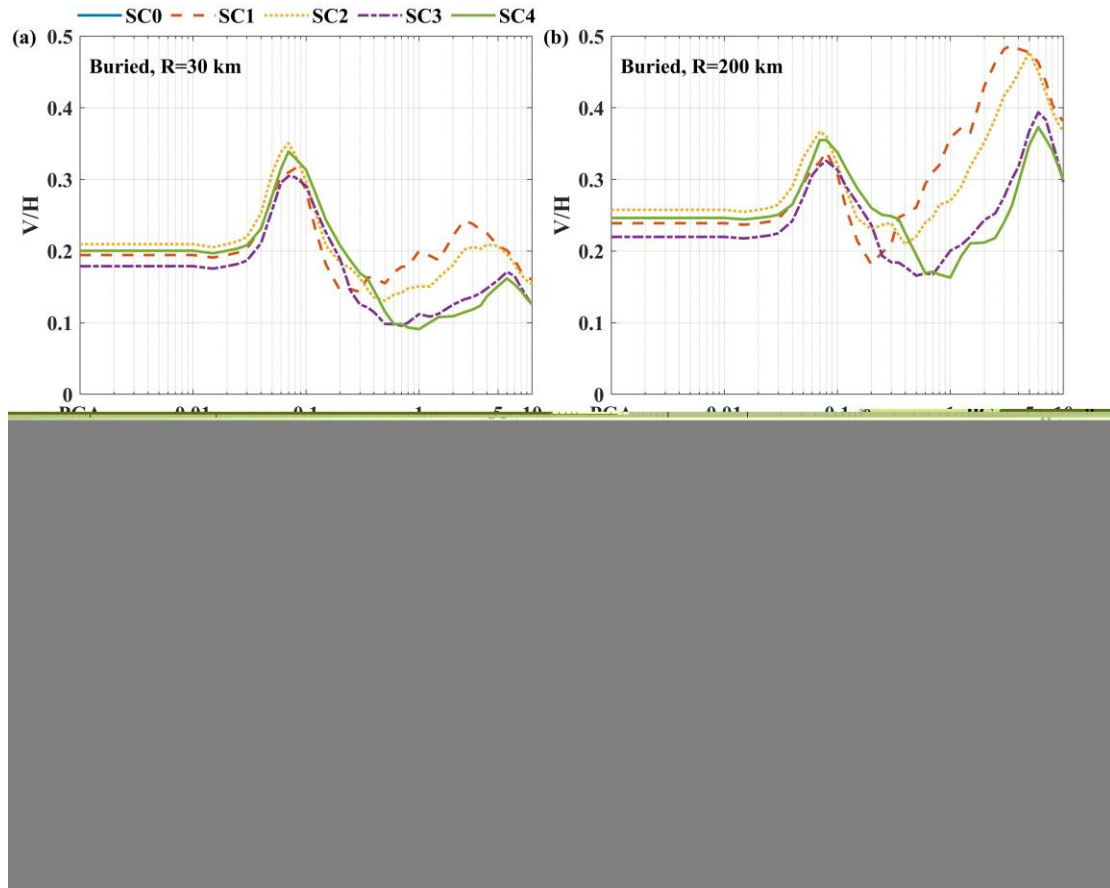


Fig. 22 Predicted V/H spectral ratios for different site classes under buried and unburied conditions for reverse faults ($M_w=5$, $h=30$ km).

7 Comparison with existing V/H models from other regions

In this study, the proposed offshore V/H model was compared with four existing regional V/H models. The comparison models include the V/H model developed by Bommer et al. (2011) for Central and Eastern Europe (hereafter referred to as Bommer2011), the V/H model proposed by Pezeshk et al. (2022) for the Central and Eastern United States (hereafter referred to as Pezeshk2022), and the V/H model proposed by Tan and Hu (2021) for the Sagami Bay region, Japan (hereafter referred to as Tan2021); note that only their onshore model is adopted in this study to ensure a consistent comparison with the onshore models. First, the predicted V/H ratios from these models were compared for hypothetical earthquakes occurring at rock sites with magnitudes of 5 and 6, considering reverse- and strike-slip-faulting mechanisms. The comparison results are shown in Fig. 23.



Fig. 23 Comparison of different V/H prediction models with spectral period.

As shown in Fig. 23, the overall variation trends of the V/H spectral ratios with period are generally consistent among the models. At short periods ($T < 0.05\text{s}$), the V/H ratios vary relatively smoothly. With increasing period, some models exhibit a peak near $T = 0.1\text{s}$, followed by a gradual decrease with increasing period, reaching a relatively low level around $T = 0.2\text{s}$. These results indicate that the V/H spectral ratio exhibits a clear period-dependent characteristic, and that the models developed for different regions can generally capture the fundamental variation pattern of the vertical-to-horizontal spectral ratio with period. However, differences exist among the models in terms of the predicted V/H spectral ratio amplitudes. Overall, the V/H ratios predicted by the Bommer2011, Pezeshk2022, and Tan2021 models are higher than those predicted by the present model. The primary reason for these differences lies in the variations in data sources and applicable regions. The existing models were mainly developed based on onshore earthquake records, whereas the present model was established using offshore strong-motion recordings from the S-net observation network in the Japan Trench region. During the propagation of offshore seismic waves, the presence of the water layer, seafloor sedimentary

layers, and the sea–solid interface effects may significantly attenuate the high-frequency components of vertical ground motions, resulting in lower V/H spectral ratios for offshore environments compared with those predicted by onshore models (Bommer et al. 2011; Diao et al. 2014; Cui et al. 2023; Li et al. 2015). Therefore, although models developed for different regions exhibit similar spectral-shape characteristics, systematic differences exist in their predicted amplitudes. This indicates that offshore and onshore ground motions exhibit distinct vertical-to-horizontal response characteristics.

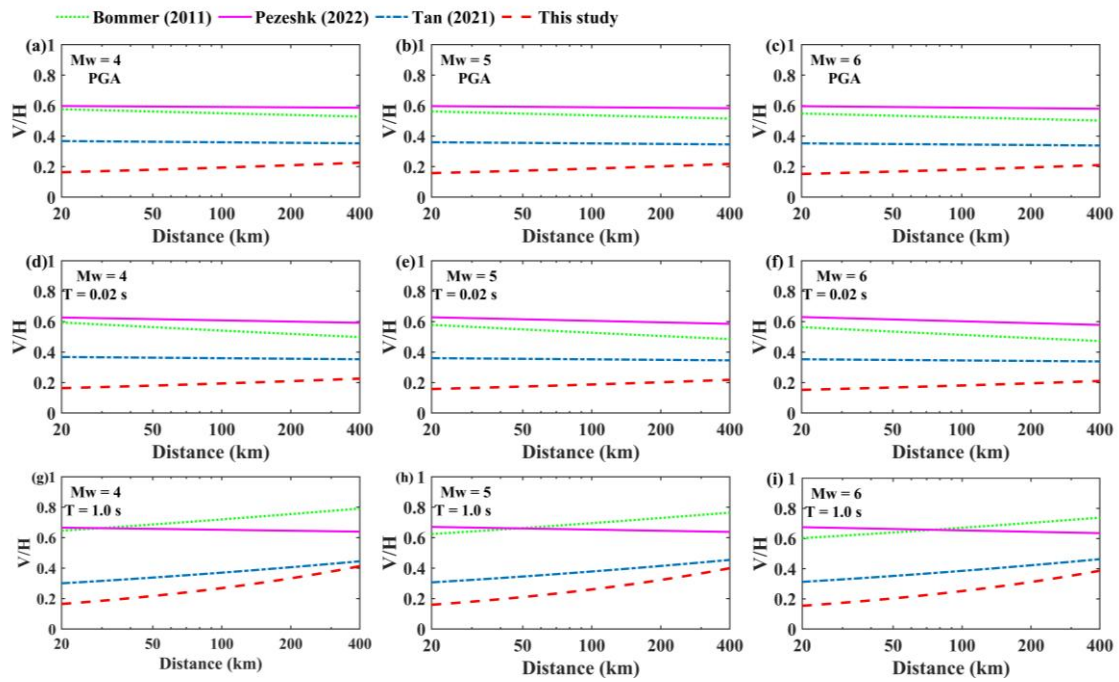


Fig. 24 Comparison of different V/H prediction models at different magnitudes and spectral periods ($M_w = 4, 5, 6$; PGA, $T = 0.02$ and 1.0 s).

In addition, to further investigate the influence of the distance terms in different models, the predicted variation of V/H spectral ratios with distance was compared among the models. The comparison was conducted under fixed conditions of a focal depth of $h=30\text{km}$, reverse-faulting mechanism, buried offshore stations, and $V_{s30}=760\text{m/s}$ (SC1). Three representative magnitudes $M_w=4, 5$, and 6 were considered, and the V/H spectral ratios predicted by different models were compared at PGA and periods of $T=0.02$ and 1.0 s, as shown in Fig. 24.

As shown in Figs. 24a–c, under PGA conditions, the V/H spectral ratios predicted by different models exhibit relatively weak distance dependence, with only minor variations as the distance increases. However, clear systematic

differences exist among the models in terms of the predicted amplitudes. The Bommer (2011) and Pezeshk (2022) models provide the highest predictions, with V/H values of approximately 0.55–0.60. The Tan (2021) model predicts intermediate values of approximately 0.35, whereas the model developed in this study based on S-net offshore strong-motion records gives the lowest predictions, with V/H values of only about 0.15–0.22. These results indicate that V/H models developed from onshore strong-motion records may overestimate the proportion of vertical ground motions in offshore environments, particularly for high-frequency ground-motion measures such as PGA. At the short period of $T=0.02\text{s}$ (Figs. 24d–f), the different models exhibit trends similar to those observed for PGA. Specifically, the V/H spectral ratios show weak variations with distance, while considerable differences remain among the model predictions. The Pezeshk (2022) model gives the highest V/H values, followed by the Bommer (2011) model, with the Tan (2021) model showing intermediate predictions. In contrast, the model developed in this study consistently provides the lowest V/H values. It is noteworthy that the relative differences among the models remain nearly unchanged with increasing magnitude, indicating that regional differences among the models have a stronger influence on short-period V/H spectral ratios than the magnitude effect.

Unlike the results at short periods, at the long period of $T=1.0\text{s}$ (Figs. 24 g–i), all models exhibit a more pronounced distance dependence. The V/H spectral ratios gradually increase with increasing distance, with the models developed in this study and by Tan (2021) showing relatively clear increasing trends. Under near-field conditions, considerable differences exist among the model predictions. As the distance increases, the predictions from the present model gradually approach those from the Tan (2021) model, but remain lower than those from the Bommer (2011) and Pezeshk (2022) models. Overall, Fig. 24 demonstrates that the predicted distance dependence varies significantly among different models and exhibits clear period-dependent characteristics. At short periods (PGA and $T=0.02\text{s}$), the V/H spectral ratios predicted by different models show only minor variations with rupture distance, whereas significant differences exist in the predicted amplitudes among models developed for different regions. In contrast, at long periods ($T>1.0\text{s}$), the influence of distance gradually becomes more pronounced, and different models exhibit distinct increasing trends. Overall, the offshore V/H model developed in this study consistently predicts lower V/H ratios than the existing onshore models. This further demonstrates

that the offshore environment has a significant influence on vertical ground motions and that onshore V/H models cannot be directly applied to offshore engineering ground-motion prediction.

8 Conclusions

This study develops an empirical V/H spectral ratio model for the Japan Trench region based on ground-motion data from shallow crustal and upper-mantle earthquakes recorded by the S-net array. The model is constructed in terms of source, path, and site terms. In the site term, a seafloor site classification based on the predominant frequency is applied separately to buried and unburied stations to characterize site effects. The main conclusions are as follows:

(1) The V/H spectral ratio in the Japan Trench region exhibits clear period-dependent and regional characteristics. Magnitude, focal depth, fault type, and rupture distance all have period-dependent effects on the V/H ratio. Magnitude and focal depth are significant within specific period ranges. Normal-faulting events generally produce higher V/H ratios than reverse-faulting and strike-slip events. The V/H ratio generally increases with rupture distance, and the distance effect is more pronounced at long periods.

(2) Burial condition significantly affects the V/H ratio. For $T < 0.7$ s, buried stations generally exhibit higher V/H ratios than unburied stations. Residual analysis based on the seafloor site classification using predominant frequency for stations under different burial conditions indicates that the site classification adequately captures seafloor site effects. For $T > 1$ s, the V/H ratio decreases progressively from SC1 to SC4 under both buried and unburied conditions.

(3) Comparisons with other models show that the models exhibit similar period-dependent spectral shapes, but the proposed empirical model generally predicts lower V/H amplitudes. The offshore environment significantly affects vertical ground motions, and onshore V/H models may not be directly applicable to offshore engineering ground-motion prediction.

Data and Resources

The offshore earthquake ground motions of the S-net are from the Hi-net (<https://www.hinet.bosai.go.jp/>, last accessed March 2026). The moment

magnitude, focal depth and longitude and latitude of the earthquake locations are all collected from the high-precision JMA (<https://www.jma.go.jp/>, last accessed March 2026) data in Japan, and the rupture model used to calculate the rupture distance is derived from NIED (<https://www.bosai.go.jp/>, last accessed March 2026).

Acknowledgments

This work was financially supported by the Scientific Research Fund of Institute of Engineering Mechanics, China Earthquake Administration (Grant No. 2024D10), and National Natural Science Foundation of China (52079072). Our special thanks go to the anonymous reviewers and the editor-in-chief for their valuable comments. We are grateful to the K-NET and Hi-net for providing valuable offshore ground motions.

Author contributions Conceptualization: Tan Jingyang and Lai Qinghui; Methodology: Tan Jingyang and Sheng Shili; Data Processing: Sheng Shili; Validation: Zhang Qi and Sheng Shili; Formal Analysis: Sheng Shili, Tan Jingyang, and Lai Qinghui. Manuscript writing: Sheng Shili. Manuscript Editing and Review: Sheng Shili, Tan Jingyang, and Lai Qinghui. All authors read and agreed to the publishing of the manuscript.

Data Availability The data presented in this study is available upon request to the corresponding author. The data is not available publicly due to institutional policy.

Declarations

Competing interests The authors declare no competing interests.

References

Abrahamson NA, Youngs RR (1992) A stable algorithm for regression analyses using the random effects model. *Bulletin of the Seismological Society of America*, 82(1):505–510.

- Aoi S, Asano Y, Kunugi T, et al. (2020) MOWLAS: NIED observation network for earthquake, tsunami and volcano. *Earth, Planets and Space*, 72:126.
<https://doi.org/10.1186/s40623-020-01250-x>.
- Baltay AS, Hanks TC, Abrahamson NA (2017) Uncertainty, variability, and earthquake physics in ground-motion prediction equations. *Bulletin of the Seismological Society of America*, 107(4):1754–1772.
- Boore DM (2010) Orientation-independent, nongeometric-mean measures of seismic intensity from two horizontal components of motion. *Bulletin of the Seismological Society of America*, 100(4):1830–1835.
- Boore, D. M., & Smith, C. E. (1999). Analysis of earthquake recordings obtained from the Seafloor Earthquake Measurement System (SEMS) instruments deployed off the coast of southern California. *Bulletin of the Seismological Society of America*, 89(1), 260–274.
- Bozorgnia Y, Campbell KW (2004) The vertical-to-horizontal response spectral ratio and tentative procedures for developing simplified V/H and vertical design spectra. *Journal of Earthquake Engineering*, 8(2):175–207.
- Bommer JJ, Akkar S, Kale Ö (2011) A model for vertical-to-horizontal response spectral ratios for Europe and the Middle East. *Bulletin of the Seismological Society of America*, 101(4):1783–1806.
- Chen B, Wang D, Li H, et al. (2015) Characteristics of earthquake ground motion on the seafloor. *Journal of Earthquake Engineering*, 19(6):874–904.
- Chen B, Wang D, Li H, et al. (2016) Characteristics of submarine ground motions and related spectra. *J Disaster Prev Mitig Eng* 36(1):38–43 (in Chinese).
- Chen B, Wang D, Li H, et al. (2017) Vertical-to-horizontal response spectral ratio for offshore ground motions: Analysis and simplified design equation. *Journal of Central South University*, 24(1):203–216.
- Chen S, Zhou Y, Li XJ, et al. (2018) Time-frequency characteristics and engineering properties of offshore ground motions. *Journal of Vibration and Shock*, 37(16):227–233 (in Chinese).
- Crempien JGF, Archuleta RJ (2017) Within-event and between-events ground motion variability from earthquake rupture scenarios. In: *Best practices in physics-based fault rupture models for seismic hazard assessment of nuclear installations*. Springer International Publishing, Cham, pp 127–141.
- Cui X, Hu J, Tan J, et al. (2023) Characteristics of S-net ocean-bottom ground motions during the 2021 Mw 7.1 Fukushima offshore earthquake in Japan. *Chinese Journal of Geophysics*, 66(1):260–271 (in Chinese).

- Diao H, Hu J, Xie L (2014) Effect of seawater on incident plane P and SV waves at ocean bottom and engineering characteristics of offshore ground motion records off the coast of southern California, USA. *Earthquake Engineering and Engineering Vibration*, 13(2):181–194.
- Dhakal YP, Kunugi T, Suzuki W, et al. (2021) Strong motions on land and ocean bottom: Comparison of horizontal PGA, PGV, and 5% damped acceleration response spectra in Northeast Japan and the Japan Trench Area. *Bulletin of the Seismological Society of America*, 111(6):3237–3260.
- Dhakal YP, Kunugi T, Yamanaka H, Wakai A, Aoi S, Nishizawa A (2023) Estimation of source, path, and site factors of S waves recorded at the S-net sites in the Japan Trench area using the spectral inversion technique. *Earth Planets Space* 75:23.
<https://doi.org/10.1186/s40623-023-01815-0>.
- Eguchi T, Fujinawa Y, Fujita E, et al. (1998) A real-time observation network of ocean-bottom-seismometers deployed at the Sagami trough subduction zone, central Japan. *Marine Geophysical Researches*, 20(2):73–94.
- Gülerce Z, Abrahamson NA (2011) Site-specific design spectra for vertical ground motion. *Earthquake Spectra*, 27(4):1023–1042.
- Haji-Soltani A, Pezeshk S, Malekmohammadi M, et al. (2017) A study of vertical-to-horizontal ratio of earthquake components in the Gulf Coast region. *Bulletin of the Seismological Society of America*, 107(5):2055–2066.
- He J, Wang LT, Hou RB (2024) Study on horizontal-to-vertical acceleration response spectral ratios of shallow crustal and upper-mantle earthquakes in Japan. *World Earthquake Engineering*, 40(3):83–93 (in Chinese).
- Hu J, Tian H, Tan J, et al. (2023) Correlation between seismic input energy and intensity measures for offshore and onshore ground motions. *Journal of Harbin Institute of Technology*, 55(9):7–18 (in Chinese).
- Hu JJ, Tan JY (2022) GMPEs for elastic input energy spectra of horizontal and vertical offshore ground motions based on the ETMC database in Japan. *Soil Dynamics and Earthquake Engineering*, 155:107198.
- Jiang Z, Li S, Zhang L, et al. (2025) A regional ground-motion model for vertical-to-horizontal spectral acceleration ratios in Southwestern China. *Journal of Seismology*, 29(6):1467–1496.
- Kanazawa T (2013) Japan Trench earthquake and tsunami monitoring network of cable-linked 150 ocean bottom observatories and its impact to earth disaster science. In: 2013 IEEE International Underwater Technology Symposium (UT). IEEE, pp 1–5.
- Kaneda Y, Kawaguchi K, Araki E, et al. (2015) Development and application of an advanced ocean floor network system for megathrust earthquakes and tsunamis. In: *Seafloor*

Observatories: A New Vision of the Earth from the Abyss. Springer, Berlin, Heidelberg, pp 643–662.

Kaynia AM (2019) Seismic considerations in design of offshore wind turbines. *Soil Dynamics and Earthquake Engineering*, 124:399–407.

Li C, Hao H, Li H, et al. (2015) Theoretical modeling and numerical simulation of seismic motions at seafloor. *Soil Dynamics and Earthquake Engineering*, 77:220–225.

Ministry of Housing and Urban-Rural Development of the People's Republic of China (2016) Code for seismic design of buildings (GB 50011-2010). China Architecture & Building Press, Beijing (in Chinese).

National Research Institute for Earth Science and Disaster Resilience (NIED) (2019) NIED S-net. National Research Institute for Earth Science and Disaster Resilience, Tsukuba. <https://doi.org/10.17598/NIED.0007>.

Pezeshk S, Farhadi A, Haji-Soltani A (2022) A new model for vertical-to-horizontal response spectral ratios for Central and Eastern North America. *Bulletin of the Seismological Society of America*, 112(4):2018–2030.

Ramadan F, Smerzini C, Lanzano G, et al. (2021) An empirical model for the vertical-to-horizontal spectral ratios for Italy. *Earthquake Engineering & Structural Dynamics*, 50(15):4121–4141.

Stewart JP, Boore DM, Seyhan E, Atkinson GM (2016) NGAWest2 equations for predicting vertical component PGA, PGV, and 5%-damped PSA from shallow crustal earthquakes. *Earthquake Spectra*, 32(2):1005–1021.

Tan J, Hu J (2021) A prediction model for vertical-to-horizontal spectral ratios of ground motions on the seafloor for moderate magnitude events for the Sagami Bay region in Japan. *Journal of Seismology*, 25(1):181–199.

Tan J, Hu J, Zhou X, et al. (2021) Quantitative analysis of response spectral ratios between seafloor and terrestrial ground motions. *Journal of Vibration and Shock*, 40(2):213–219, 227 (in Chinese).

Tan J, Meng D, Hu J (2026) HVSR-based peak frequency identification of S-net ocean-bottom stations for site characterization and ground-motion prediction models. *Bulletin of the Seismological Society of America*, 116(2):680–699.

Tan J, Yan S, Chen D, et al. (2025) Ground-motion prediction models for shallow crustal and upper-mantle earthquakes recorded by the S-net ocean-bottom seismographic network in the Japan Trench. *Chinese Journal of Geophysics*, 68(2):636–651 (in Chinese).

Zhang Q, Zheng XY (2019) Offshore earthquake ground motions: Distinct features and influence on the seismic design of marine structures. *Marine Structures*, 65:291–307.

- Zhang Q, Zheng XY (2020) Temporal and spectral characteristics of seismic ground motions: Offshore versus onshore. *Marine Structures*, 74:102812.
- Zhao JX, Zhou S, Gao P, et al. (2015) An earthquake classification scheme adapted for Japan determined by the goodness of fit for ground-motion prediction equations. *Bulletin of the Seismological Society of America*, 105(5):2750–2763.
- Zhao XQ, Huang B, Hou RB (2025) Study on horizontal-to-vertical acceleration response spectral ratios of intraslab earthquakes in subduction zones. *Journal of Shandong Jianzhu University*, 40(3):1–9 (in Chinese).
- Zhong ZL, Guo JX, Zhang B, et al. (2023) Preliminary investigation on the characteristics of seafloor ground motions based on the K-NET strong-motion observation network. *World Earthquake Engineering*, 39(4):7–14 (in Chinese).
- Zolfaghari MR, Darzi A (2019) A prediction model for vertical-to-horizontal ratios of PGA, PGV, and 5%-damped response spectra (0.01–10 s) for Iran. *Journal of Seismology*, 23(4):819–83