Influence of continental margin on regional seismic wavefield

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Regional seismic analysis is an only way to investigate the source properties of small or moderate-sized seismic events that occur in physically unaccessible regions such as oceanic regions and politically-prohibited regions. The ground motions by earthquakes need to be understood for better mitigation of seismic hazards particularly in continental margins that often incorporate high seismicity. It has not been fully understood how seismic waves interact with complex crustal structures in continental margins. Responses of regional waves to complex crustal structures need to be quantified. Analysis of regional waveforms from controlled sources is desirable for investigation of influence of crustal structures. The influence of continental margin around the Korean Peninsula is investigated in terms of spectral contents, horizontal-to-vertical (H/V) spectral ratios and quality factors using regional waveforms for the 2009 North Korean underground nuclear explosion test that was well recorded by stations in the southern Korean Peninsula. Regional waveforms and spectral amplitudes vary significantly by path. Spectral contents of regional phases are different among stations in common great-circle directions. All regional phases modulate highly in continental margins. Path-dependent seismic attenuation is strong in low frequencies (≤3 Hz), and weak in high frequencies (>3 Hz). Continental margins cause directional energy partition of regional waves depending on the path. Regional waves attenuate highly in passage across continental margin, and then regrow on continental paths. The growth rate is stronger than inherent attenuation rate, causing seismic amplification. The shapes of H/V ratios are similar among various regional phases at common stations. On the other hand, the H/V ratios for common phases vary by station in the same azimuths. Characteristic differences in H/V ratios between two horizontal components suggest directional partition of seismic energy by crustal structures in the paths.

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1. Introduction

Large earthquakes generate strong motions in local and regional distances. It was observed that regions in epicentral distances of several hundred kilometers were severely damaged by the 11 March 2011 M9.0 Tohoku-Oki earthquake, causing a peak ground acceleration of 2933 gal in the Miyagi Prefecture of ~75 km away and 163 gal in Tokyo of ~373 km away from the epicenter (Kalkan and Sevilgen, 2011). However, the peak ground amplitudes are highly dependent on the source properties, medium properties along raypaths, and receiver site effects. The influence of each factor contributing to the amplitudes of seismic waves remains unclear. In particular, the seismic amplitudes vary highly by path in regions with complex crustal structures such as continental margins (e.g., Hong et al., 2008; Kennett and Furumura, 2001).

Structural variations in the medium cause discriminative frequency-dependent attenuation of seismic waves (e.g., Der et al., 1986; Flanagan and Wiens, 1998; Sato and Fehler, 1997; Xie et al., 2006). In particular, local and regional seismic phases are strongly influenced by the crustal and lithospheric structures along ray paths. Various attempts with emphasis on description on relative phase amplitudes have been made to understand the seismic wavefields in continental margins (e.g., Kennett and Furumura, 2001). However, it is not clear which properties of waves change and how much the regional phases are affected. Also, the relationship between structural variation and seismic amplitudes has not been fully understood. It remains unclear how seismic waves behave after passing across regions with complex crustal structures in terms of phase regrowth and attenuation.

Comprehension of path effects in complex regions is crucial not only for accessing seismic hazard potentials, but also for precise monitoring of seismic events. Magnitude estimation is a routine process in seismic monitoring, which is however not an easy task in terms of accuracy and promptness. Local and regional body-wave magnitude scales are typically based on single-component records (e.g., Denny et al., 1987; Hong, 2012; Hong and Lee, 2012; Nuttli, 1986; Priestley and Patton, 1997). Since the seismic waves are highly affected by the complex crustal structures in continental margin, it is not clear whether such a conventional approach is still valid for continental margin.

There is difficulty to study the seismic amplification and attenuation along raypaths using seismic waves from natural earthquakes owing to the source radiation effect that is dependent on the azimuth and takeoff angle (Aki and Richards, 2002). Also, large events incorporate rupture propagation, causing source directivity effect that is dependent on the source geometry and dimension. For correct investigation of path effects...
from local and regional waveforms, it may be desirable to use the seismograms for well-constrained moderate-sized events that are recorded in densely-deployed receivers with good azimuthal coverage. In this sense, seismic waveforms from underground nuclear explosion may be useful.

North Korea conducted two underground nuclear explosion (UNE) tests in 2006 and 2009, which are the latest UNE tests. The North Korean UNE tests were performed in the eastern continental margin of Eurasian plate, and were well recorded in South Korea and Japan across the oceanic regions in East Sea (Sea of Japan) (Ford et al., 2009; Hong, 2013; Hong and Rhie, 2009; Hong et al., 2008; Shin et al., 2010). The waveforms for the UNEs provide us a unique opportunity to investigate the seismic wavefields in continental margin.

In this study, we investigate the influence of continental margin on seismic wavefields using the seismic records of the 2009 North Korean UNE. The properties of waveforms and spectral contents of regional phases across the continental margin are studied. The influence of continental margin on the energy partition of regional phases is studied using a horizontal-to-vertical-ratio analysis. Also, the phase regrowth in continental paths after passing across the continental margin is investigated from analysis of quality factors between two stations on common great-circle directions.

2. Geology

The Korean Peninsula is located in the far-eastern Eurasian plate, and was formed during the continental collision between the North and South China blocks in the late Permian to Jurassic (Chough et al., 2000; Oh, 2006). The Japanese islands were rifted away from the eastern Eurasian plate during the Oligocene to mid-Miocene (Chough et al., 2000; Jolivet et al., 1994). The Korean Peninsula and the Yellow Sea display a typical continental crust, whereas the East Sea (Sea of Japan) has a transitional structure between continental and oceanic crusts. The crust in the Korean Peninsula has a mid-crustal discontinuity that is a characteristic feature of a continental crust (He and Hong, 2010).

The crustal thickness of the Korean Peninsula is 29–36 km, which changes abruptly thinner in the East Sea (Chang et al., 2004; Hong et al., 2008). The crustal thickness in the East Sea reaches 8.5–10 km including sedimentary layers with thicknesses of ~2 km on the top (Hirata et al., 1992; Kim et al., 1998). The surface topography in the Korean Peninsula is relatively high in the eastern regions, and low in western regions. The surface topography also varies highly across the east coast with abrupt decrease to 2 km below the sea level in regions off the east coast (Figs. 1 and 2). The continental shelves develop in most regions of Yellow Sea, whereas they are extended to only several tens of kilometers from the coast in the East Sea.

The Korean Peninsula is composed of three Precambrian massif blocks and two intervening fold belts (Chough et al., 2000). The massif block in the southeastern region is covered by Cretaceous volcanic sediments. The seismic velocities and geophysical properties in the crust and lithospheric mantle are correlated with the geological structures on the surface (Hong, 2010a; Hong and Kang, 2009; Jo and Hong, 2013; Kang and Shin, 2006). The \( V_p/V_s \) ratios in massif regions are as low as 1.64–1.72, while those in volcanic or basaltic regions are as high as 1.73–1.91 due to difference in rock composition (Jo and Hong, 2013).

A solidified underplated magma repository that may be resulted by the paleo-rifting during East Sea opening is identified in the lower crust off the southeastern coast by magnetic anomalies (Cho et al., 2004). Pn traveltime tomography (Hong and Kang, 2009), and Lg Q tomography (Hong, 2010a). The paleo-rifting structures have been seismically activated with reverse-faulting sense by the ambient compressional stress field (Choi et al., 2012). Also, the collision boundary between the North and South China blocks appears to be placed in the central Yellow Sea that may be stretched to the central Korean Peninsula (Hong and Choi, 2012). Series of normal-faulting earthquakes with E–W directional strikes occur in the paleo-collision structures that were activated by lithospheric delamination (Hong and Choi, 2012). The Korea Peninsula belongs to an intraplate region with a mild seismicity rate. There are relatively high density seismicity regions in the Korean Peninsula, which include the paleo-rifting region off the southeastern coast, the paleo-collision region in the central Yellow Sea and northwestern peninsula, and the south-central peninsula.

3. Data

For investigation of seismic amplitude variation with raypath, it may be desirable to use seismic waves from the sources radiating azimuthally-isotropic energy. Moderate-sized and large explosion sources excite azimuthally-uniform energy, and are recorded well at regional distances. North Korea conducted two UNE tests in 2006 and 2009. The magnitudes \( m_b \) of the nuclear explosions are 4.2 and 4.7, which were well recorded by regional stations in the Korean Peninsula (Hong, 2013; Hong and Rhie, 2009; Hong et al., 2008). Long-period waveform inversions revealed that isotropic component of energy composes the waveforms from the UNEs dominantly (Ford et al., 2009; Hong and Rhie, 2009; Walter et al., 2007).

Seismic records for the 2009 North Korean UNE were collected from stations in the southern Korean Peninsula. The stations were equipped with either broad-band velocity seismometers, short-period velocity seismometers, or accelerometers. Seismic records of six stations in comparable distances of 512.2–523.8 km on the paths with azimuths of 176.2°–226.4° are collected for this study (Fig. 1). Also, I collect seismic waveforms of twenty stations in five selected great-circle directions (4 stations in each direction) (Fig. 2). The azimuths of the selected five great-circle directions are 176.4° (path A), 180.0° (path B), 186.6° (path C), 195.2° (path D), and 205.5° (path E). Path A is placed along the east coast of the peninsula, while path E is designed to cross the suboceanic medium minimally. Paths B to C are placed in the region between paths A and D. The length of suboceanic path decreases gradually from path A to path E.

The collected seismic waveforms are deconvolved for instrument responses, and are converted to displacement waveforms. Major regional phases are well identified in the records (Figs. 1, 2). It is noteworthy that shear waves are observed clearly in the seismograms. It is known that the shear waves are excited from nuclear explosions by various mechanisms including rock cracking, tectonic release, spall, and surface-wave scattering (e.g., Day and McLaughlin, 1991; Hong, 2010b; Hong and Xie, 2005; Massé, 1981; Wallace et al., 1985).

4. Method

The spectral amplitudes of seismic waves, \( A(f) \), can be written as (Sereno et al., 1988; Taylor and Harte, 1998; Xie and Patton, 1999)

\[
A(f) = S(f)G(d)\exp\left(-\frac{\eta fd}{\sqrt{Q(f)}}\right),
\]

where \( f \) is the frequency, \( S(f) \) is the source spectrum, \( d \) is the epicentral distance, \( G(d) \) is the geometrical spreading term, \( Q(f) \) is the quality factor along the raypath, and \( \nu \) is the phase velocity. The quality factor \( Q(f) \) is given as

\[
Q(f) = Q_0 f^\eta,
\]

where \( Q_0 \) is the quality factor at 1 Hz, and \( \eta \) is the power-law frequency dependence. The geometrical spreading term, \( G(d) \), is given as (e.g., Xie and Patton, 1999)

\[
G(d) = \left(\frac{d_0}{d}\right)^3 d_0^{-1},
\]
where $\gamma$ is an exponent controlling the phase decay rate with distance, and $d_0$ is the reference distance. Parameter $d_0$ is set to be 1 km with $\gamma$ to be 1.1 for $Pn$, $Pg$, $Sn$ and $Sg$, and $d_0$ is set to be 100 km with $\gamma$ to be 0.5 for $Lg$ (Hong and Rhee, 2009; Zhu et al., 1991).

From Eq. (1), the amplitude ratio of a phase between two stations on a common great-circle path can be written as

$$\ln \left( \frac{A_1(f)}{A_2(f)} \right)^\gamma = \frac{nf_2}{v} \frac{l}{Q(f)},$$

where $A_i$ ($i = 1, 2$) is the spectral amplitude at station $i$, $d_i$ ($i = 1, 2$) is the epicentral distance from the source to station $i$, $l$ is the inter-station distance (i.e., $l = d_2 - d_1$), and $Q_0$ is the quality factor for the inter-station path. The quality factor along the inter-station path ($Q$) allows us to infer the medium properties, and also enables us to assess the influence of medium on phase development.

For sources radiating azimuthally-uniform energy, the amplitude ratio between two stations at a common distance can be expressed as

$$\ln \left( \frac{A_1(f)}{A_2(f)} \right)^\gamma = \frac{nf_2}{v} \frac{l}{Q(f)} \left( \frac{1}{Q_2(f)} - \frac{1}{Q_1(f)} \right),$$

where $Q^{-1}$ is the $Q^{-1}$ difference between the paths, presenting difference in seismic attenuation between the paths. Relative $Q^{-1}$ differences ($\Delta Q^{-1}$) among various paths at a certain distance are calculated using Eq. (5). The reference spectra for the given distance are calculated by stacking the spectra of all paths, and are used for $A_2(f)$ to calculate the $\Delta Q^{-1}$ of the path. The $\Delta Q^{-1}$ of regional phases for every path is

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**Fig. 1.** (a) Map of 6 stations in comparable distances of 512–524 km from the 2009 North Korean underground nuclear explosion (UNE), (b) Surface topography and (c) crustal thicknesses along the great-circle paths from the UNE to stations. Regional displacement waveforms in (d) vertical, (e) radial and (f) tangential components at the stations are presented with epicentral distances and azimuths. The waveforms are bandpass filtered between 0.8 and 17 Hz. Major regional phases ($Pn$, $Pg$, $Sn$, $Sg$, $Lg$) are indicated, and their peak amplitudes in the unit of $10^{-3}$ m are presented. Stations close to the east coast have long oceanic paths, while those near to the west coast have long continental paths. The regional phases vary significantly by path.
notated on each seismogram. The locations of stations are marked on the surface topography and crustal thickness models. The waveforms are band-pass stations on (d) paths A, (e) B, (f) C, (g) D, and (h) E. (i) Displacement waveforms in radial components of stations on path E are presented. The epicentral distance and azimuth are annotated on each seismogram. The locations of stations are marked on the surface topography and crustal thickness models. The waveforms are band-pass filtered between 0.8 and 17 Hz.

Analysis based on horizontal-to-vertical (H/V) spectral ratios was performed to present the relative attenuation or amplification in media beneath receivers. The H/V ratios allow us to estimate the

$$F_{ij} = \left| \Delta Q^{-1}(i) - \Delta Q^{-1}(j) \right|,$$

where $i$ and $j$ indicate the components analyzed ($i, j = R, T, Z$). Note that absolute values of $\Delta Q^{-1}$ are used for calculation of $F_{ij}$ to present the relative attenuation or amplification.

Analysis based on horizontal-to-vertical (H/V) spectral ratios was proposed by Nakamura (1989) to account for seismic amplification in media beneath receivers. The H/V ratios allow us to estimate the
fundamental resonance frequency and shear-wave velocity structures of the shallow subsurface layers, which is crucial information for seismic hazard mitigation (e.g., Arai and Tokimatsu, 2004; Fäh et al., 2003; Picuzzi et al., 2005). The H/V ratio analysis was originally based on ambient noises (microtremors) (Nakamura, 1989). The H/V ratio analysis was expanded to implement seismic signals such as seismic coda, teleseismic waves, and local aftershock waveforms (e.g., Bonilla et al., 1997; Ferretti et al., 2007; Oth et al., 2009; Parolai et al., 2004).

It was reported that the fundamental resonance frequencies are determined to be similar between ambient-noise-based H/V analysis and seismic-signal-based H/V analysis (Ferretti et al., 2007). However, the H/V ratios from ambient noise analysis are lower than those from seismic signal analysis. This may be because ambient noises and seismic signals have their own propagation properties, and each composing wavelet responds to subsurface structures differently depending on its raypath and incidence angle (Ferretti et al., 2007). Lermo and Chávez-García (1993) have their own propagation properties, and each composing wavelet responds to subsurface structures differently depending on its raypath and incidence angle (Ferretti et al., 2007). Lermo and Chávez-García (1993).

The H/V ratios of regional phases are results of combined effects of site response and path properties. The site response in the shallow subsurface structure beneath station can be quantified using the H/V ratios of ambient noise. To distinguish the path effect in the waveforms, the H/V ratios of regional phases are divided by the H/V ratios of ambient noise. To distinguish the path effect in the waveforms, the H/V ratios of regional phases are divided by the H/V ratios of ambient noise. Regional waveforms in the radial–tangential–vertical (R–T–Z) axis system are analyzed to understand the variation of H/V ratios with direction. In this study, radial-to-vertical (R/Z) ratios and tangential-to-vertical (T/Z) ratios are calculated.

5. Process

Regional phase waveforms were chosen using traveltime curves that are defined to be functions of epicentral distance and phase velocity (e.g., Hong, 2012; Hong and Rhie, 2009; Xie, 2002). The wavetrains in travel times between $(d/7.95 + 1$ and $d/7.0 + 1$ were selected for $Pn$, those between $d/4.3 – 3$ and $d/3.9 – 4$ for $Sn$, those between $d/3.9 – 2 and $d/3.6$ for $Sg$, and those between $d/3.6 + 2$ and $d/2.7$ for $Lg$, where $d$ is the epicentral distance in km. The ambient noises were collected from 10-second-long record sections prior to the $Pn$ arrival.

A 4.5-second-long moving time window with 0.2-second-long cosine tapers at both ends was applied to the waveforms in the prescribed time ranges. The representative phase spectrum was calculated by stacking the spectra of moving time windows. The waveform spectra were estimated in a frequency range of 0.5–8 Hz considering the frequency contents of regional phases (Fig. 3). The representative phase velocities ($V$) are set to be 7.95 km/s for $Pn$, 6.05 km/s for $Pg$, 4.55 km/s for $Sn$, 4.00 km/s for $Sg$, and 3.50 km/s for $Lg$.

6. Regional waveforms

Fig. 1 presents regional waveforms at stations in comparable distances of 512.2–523.8 km on various paths. The presented waveforms are bandpass-filtered between 0.8 and 17 Hz considering the dominant

![Fig. 3. Frequency contents of three-component displacement waveforms for stations DEI and UCN. The distances and azimuths are denoted. The peak amplitudes of waveforms in the unit of $10^{-7}$ m are annotated. Major regional phases ($Pn$, $Pg$, $Sn$, $Sg$, $Lg$) are marked on the seismograms. $P$ energy is observed consistently at least up to 15 Hz, while $S$ energy displays lower frequency contents. The high frequency contents of wavetrains decrease with lapse time. Waveforms in frequencies greater than 10 Hz appear to be highly contaminated by ambient noises.](image-url)
Fig. 4. Three-component displacement spectra of major phases and ambient noises at stations in comparable distances (Fig. 1): (a) Pn, (b) Pg, (c) Sn, (d) Sg, (e) Lg, and (f) ambient noises. The spectral amplitudes vary significantly by station.
Fig. 5. Vertical displacement spectra of regional phases and ambient noises at stations for the five paths in Fig. 2: (a) $P_n$, (b) $P_g$, (c) $S_n$, (d) $S_g$, (e) $L_g$, and (f) ambient noises. Displacement spectra at some stations in far distances display higher amplitudes than those at stations in near distances. The variation of $P_n$ spectra is most complex. $L_g$ phase grows stably along continental path (e.g., path $E$).
Fig. 6. Comparison of normalized H/V ratios of stations in comparable distances for common regional phases (Fig. 1): (a) radial-to-vertical (R/Z) spectral ratios and (b) tangential-to-vertical (T/Z) spectral ratios. The normalized H/V ratios for comparable distances are significantly different by path.
frequency contents of regional phases. Peak amplitudes of phases vary highly by path. Also, the relative amplitude among phases is different by path. Seismic sources radiating azimuthally-uniform energy develop strong P waves on vertical and radial components. However, prominent P waves are observed also in tangential component (e.g., stations ULJ and YCH), suggesting fractional partition of P waves in tangential direction due to structural heterogeneities along path (Fig. 1).

Shear waves are observed at most stations, and their amplitudes vary by path. Shear waves are barely observed at a station (ULJ) near the east coast of the peninsula where crustal structures change abruptly. Crustal-reflection phases develop strongly on pure continental paths (e.g., stations DEI, BAR), while are weak on the suboceanic paths (stations ULJ and YCH). These observations suggest that regional phases are highly affected by the crustal structures along the paths, which is consistent with other studies (e.g., Hong et al., 2008; Kennett and Furumura, 2001).

The regional waveforms on common great-circle directions are compared to understand the evolution of regional phases depending on the change of medium properties along paths (Fig. 2). The variations of peak amplitudes do not appear to be correlated among regional phases on common great-circle paths. For example, phases with a common geometrical-spreading factor (e.g., Pn and Sn) present a different variation of amplitudes along common paths. The observation suggests that each phase experiences unique attenuation or amplification that is different among phases.

Strong Lg waves develop in the continental crust that is present in the paths to stations in the western peninsula. On the other hand, weak Lg waves are observed on oceanic paths to the stations in the east coast. This observation is consistent with previous studies (Kennett, 1986; Zhang and Lay, 1995). It is observed that Lg waves regrow on continental paths after passage of oceanic paths. For instance, weak Lg energy is observed at stations near the continental margin (stations TBA, ADO, YOC on path B, and stations SKC, YOW, GUM on path C). On the other hand, distinctive Lg waves are observed at stations on continental paths in long distances after continental margin (e.g., station BUS on path B, and station JIN on path C).

It is observed that the high frequency content in the regional waveforms decreases with lapse time gradually (Fig. 3). In addition, the frequency content is different by phase. The P phases have broad frequency contents that are rich up to 10 Hz or higher. On the other hand, Lg wave is composed of low-frequency energy that is rich up to 6 Hz. Shear waves present intermediate frequency contents between P and Lg waves. This observation suggests that each phase responds to a common crustal structure differently due to difference in phase properties such as wavelength, incidence angle and raypath. The ambient noises are comparable to the regional phases at frequencies equal to or greater than 10 Hz. The regional phases are analyzed at frequencies of 8 Hz or below in this study.

7. Spectral properties

The influence of paths on regional waves is investigated from comparison of spectra of regional phases among stations in comparable distances (Fig. 4). The spectra present characteristic features of regional waves. The corner frequencies of P waves are higher than those of S waves. The Lg waves present the lowest corner frequencies (Fig. 4). This feature is consistent with the observation of decreasing high-frequency content in regional wavetrains with lapse time (Fig. 3).

Strong overshooting at frequency of ~4 Hz is observed in the Pn spectra of most stations. The overshooting feature is weak in shearwave spectra. The spectral overshooting is a feature associated with explosion (Hong, 2013; Hong and Rhie, 2009; Xie, 2002; Xie and Patton, 1999). It is observed that the overshooting strengths of Pn spectra are different by path. This observation suggests that the regional-phase spectra vary by the crustal properties along paths. It is observed that the overall shapes of spectra are similar among stations on various
Fig. 8. Normalized H/V ratios of regional phases (Pn, Pg, Sn, Sg, Lg) among stations on path D in Fig. 2: (a) radial-to-vertical (R/Z) spectral ratios and (b) tangential-to-vertical (T/Z) spectral ratios. The shapes of normalized H/V ratios are different among stations, suggesting the influence of inter-station paths on waveforms.
paths in comparable distances. Here, the levels of spectra are different among the stations, which may be due to discriminative path-dependent attenuation. The high variation in spectral amplitudes at different stations in comparable distances suggests that the regional body-wave magnitude estimates can vary by path in continental margin.

The influence of continental margin on regional-phase spectra is studied by comparison of spectra of regional phases from stations in common great-circle directions (Fig. 5). The spectra of ambient noises are also presented for comparison. The spectra of mantle-lid waves \( (Pn, Sn) \) are highly different among stations in common great-circle directions, which is particularly apparent at stations placed near to continental margin. On the other hand, crustal reflection waves \( (Pg, Sg) \) and crustally-guided shear waves \( (Lg) \) display similar shapes of spectra among stations in common great-circle directions. However, the spectral-amplitude levels of some phases do not appear to decrease with distance; spectral amplitudes of far-distance stations are larger than those of near-distance stations (e.g., \( Sg \) and \( Lg \) phases of station PHA on path A, station ADO on path B, and station GUM on path C in

![Fig. 9](image-url). Comparisons of normalized H/V ratios among regional phases at common stations on path D: (a) radial-to-vertical \( (R/Z) \) spectral ratios and (b) tangential-to-vertical \( (T/Z) \) spectral ratios. The normalized H/V ratios are determined to be similar among different phases at common stations. The shapes of \( R/Z \) ratios are different from those of \( T/Z \) ratios, suggesting directional energy partition depending on crustal structures.
Mantle-lid waves are highly affected by the Moho structures along raypaths. Also, the mantle-lid waves interfere with the shallow crustal structures beneath stations. The high modulation in spectra of mantle-lid waves may be associated with complex Moho topography across the continental margin and shallow crustal structures beneath stations. The spectral contents of regional waves, particularly mantle-lid waves, at frequencies equal to or greater than 2 Hz appear to be similar to those of ambient noises (e.g., station YCH in Fig. 4). It is known that ambient noises at frequencies equal to or greater than 1 Hz are mainly composed of wavelets from local sources associated with natural or human activities. The wavelets from local sources are amplified by shallow crustal structures beneath stations (Bonnefoy-Claudet et al., 2006).

The similar high-frequency spectral feature between regional phases and ambient noises suggests that the modulation of high-frequency spectra of regional waves may be partly affected by the shallow crustal structures. On the other hand, low-frequency energy is relatively little affected by the shallow crustal structures. Thus, the low-frequency spectra may be useful to constrain the path effects on the regional waves. The increase of spectral amplitudes with distance in common great-circle directions suggests amplification of regional waves during propagation that may be due to interaction of waves with crustal structures.

8. Energy partition in continental margin

The influences of crustal structures on the regional waves are examined using horizontal-to-vertical (H/V) spectral ratios of regional waves. The influence of shallow crustal structures beneath stations is dominantly reflected in high-frequency H/V ratios. On the other hand, low-frequency H/V ratios may be primarily affected by large-scale medium structures along raypaths. Here, the H/V ratios are also dependent on the vertical incidence angle to the surface (e.g., Lermo and Chávez-García, 1993). Note that the vertical incidence angles of mantle-lid phases (Pn, Sn) are smaller than those of crustal reflection phases (Pg, Sg). The crustally-guided shear waves (Lg) have the largest incidence angle.

In this study, the regional-phase H/V ratios are normalized by ambient-noise H/V ratios. These normalized H/V ratios represent the spectral ratios corrected for the shallow-crustal structure effects. The normalized H/V ratios in comparable distances are compared among various paths (Fig. 6). The normalized H/V ratios at similar distances are observed highly different among stations. However, the normalized H/V ratios display high correlation in shape among various phases at each station (Fig. 7). The peak H/V ratios are observed in similar frequencies among different phases at each station. The levels of S-wave H/V ratios appear to be higher than those of P-wave H/V ratios. The frequency for peak H/V ratio is the fundamental resonance frequency associated with the velocity structure beneath the station (e.g., Satoh et al., 2001). The consistent peak frequencies among various phases suggest that regional phases are highly influenced by the shallow crustal structures.

The normalized H/V ratios are compared among stations in common great-circle directions to examine possible influence of continental margin. The normalized H/V ratios of common regional phases at stations on path D are presented in Fig. 8. The appearances of normalized H/V ratios of common regional phases are highly different among the stations. However, the normalized H/V ratios are observed similar among different regional phases at common stations (Fig. 9), which is consistent with the observation in Fig. 7. These observations confirm that the H/V ratios are primarily dependent on the shallow crustal structures beneath the stations.

The levels of H/V ratios are observed different between two horizontal components. The radial-to-vertical ratios are generally observed to be greater than the tangential-to-vertical ratios for P phases (Pn, Pg) (Figs. 6–9). This unequal distribution of energy between two horizontal components is much clear in average H/V ratios for all stations (Fig. 10). For Pn, the radial-to-vertical ratios are about 1.3 to 1.9 times greater than the tangential-to-vertical ratios. For Pg, the radial-to-vertical ratios...
Fig. 11. Inverse quality factors \( (\frac{1}{Q}) \) of regional phases \((\text{Pn, Pg, Sn, Sg, Lg})\) on inter-station paths for (a) 1.0-Hz vertical waveforms, (b) 1.0-Hz radial waveforms, (c) 5.0-Hz vertical waveforms, and (d) 5.0-Hz radial waveforms. The inverse quality factors for vertical and horizontal waveforms are estimated negative or near zero on some inter-station paths near the east coast in all frequencies, suggesting seismic amplification during propagation. The seismic amplification feature is particularly strong on oceanic paths (paths A, B and C), whereas weak on a continental path (path E).
are about 1.0 to 1.5 times greater than the tangential-to-vertical ratios (Fig. 10(c)). The larger energy in radial component than tangential component is caused by the typical polarization of P energy in radial direction.

On the other hand, for S phases in frequencies equal to or greater than 5 Hz, the levels of radial-to-vertical ratios appear to be comparable to those of the tangential-to-vertical ratios. However, the radial-to-vertical and tangential-to-vertical ratios vary much by the station in low frequencies (≤3 Hz). This may be because high frequency energy is highly affected by small-scale crustal heterogeneities (Sato and Fehler, 2009). High-frequency shear waves are scattered by randomly-oriented small-scale heterogeneities, developing both SV and SH waves with comparable strengths (Hong, 2004; Hong and Kennett, 2003; Sato and Fehler, 2009). Note that scattered energy develops strongly when the wavelengths of incident waves are comparable to the sizes of heterogeneities (e.g., Hong, 2004; Hong et al., 2005; Sato and Fehler, 1997). On the other hand, low-frequency shear waves are dominantly affected by large-scale crustal structures that may be different by region.

The average H/V ratios of regional waves display characteristic levels of amplitudes that differ by phase (Fig. 10). Note that regional waves are incident to the surface near vertically. Also, P waves are polarized in the radial directions, whereas S waves are polarized in the tangential directions. Thus, the H/V ratios of P phases (Pn, Pg) are observed to be smaller than those of S phases (Sn, Sg, Lg), which is more distinct in the tangential-to-vertical spectral ratios than in the radial-to-vertical spectral ratios. It is observed that the Pg H/V ratios are larger than the Pn H/V ratios. Also, the levels of average H/V ratios are observed comparable among S phases.

The phase-dependent vertical incidence angles cause frequency-independent changes in levels of H/V ratios. The radial-to-vertical ratios are larger by constant times than the tangential-to-vertical ratios in the frequencies between 0.5 and 8 Hz for P waves, and in frequencies between 5 and 8 Hz for S waves (Fig. 10). The constant differences between radial-to-vertical ratios and tangential-to-vertical ratios suggest that the energy is partitioned constantly into three orthogonal components during propagation along raypaths. For S waves, the difference between the tangential-to-vertical ratios and radial-to-vertical ratios decreases gradually with frequency between 0.5 and 5 Hz. The gradual decreases in differences between radial-to-vertical ratios and tangential-to-vertical ratios suggest that the S energy partition among three components is different by frequency. These observations suggest that SH waves appear to develop strongly compared to SV waves in low frequencies (≤5 Hz), which decreases in high frequencies.

9. Phase regrowth in suboceanic-and-continental paths

The regional phase development in continental margin is investigated from the quality factors of inter-station paths. Regional waveforms are highly modulated by complex crustal structures in the passive margin off the east coast (Fig. 2). Regional phases appear to be significantly attenuated after passing through the continental shelf. However, regional phases that were highly attenuated in the continental margin are observed to redevelop on continental paths. The attenuation and growth of regional phases on inter-station paths are investigated in terms of quality factor from Eq. (4).

Fig. 11 presents the inter-station attenuation of major phases in vertical and radial components at frequencies of 1 and 5 Hz. The lateral variation of quality factors appears to be similar among different phases. The Q−1 estimates of inter-station regions along a continental path (path E) present typical values. On the other hand, regional phases from inter-station paths in about 50–100 km after the continental margin on paths A, B, and C present negative or near-zero Q−1 estimates. Such negative or near-zero Q−1 estimates are consistently observed in the wide frequencies (Fig. 11). Note that the negative or near-zero Q−1 estimates mean increasing or near-invariable amplitudes with distance.

The high modulation of regional waveforms in inter-station regions of paths A, B, and C is significantly affected by the lateral variation of crustal structures (Fig. 2). Regional phases are highly attenuated after passage of continental margin in which crustal structures change abruptly. The regional waves are attenuated in distances of about 50 km or greater after the continental margin. These regional waves are stabilized in distances of about 50–100 km along continental paths, and grow gradually with distance. In this distance regime, the phase growth rate is stronger than the inherent attenuation rate. The regional wavefields are fully rebuilt in distances of about 100 km after the continental margin. In distances of ~100 km or greater, regional waves are attenuated along the continental paths.

10. Path-dependent attenuation

Regional waveforms display path-dependent variations. Also, the regional phases grow on continental paths after passage across the continental shelf. The path-dependent phase attenuation is investigated from relative Q−1 differences, ΔQ−1, among paths. The relative Q−1 differences were calculated from seismic waveforms in Fig. 1 using Eq. (5). The stacked spectra of all records are used for the reference spectra, A2, in Eq. (5). The reference distance, d, is set to be 51.6 km.

The relative Q−1 differences of regional phases are presented in Fig. 12. Positive ΔQ−1 estimates indicate large amplitudes relative to the reference amplitudes, whereas negative estimates suggest relatively small amplitudes. The ΔQ−1 estimates of horizontal components are slightly larger than those of vertical components, in general. The ΔQ−1 estimates decrease with frequency. The ΔQ−1 estimates reach to 0.001 or less in 8 Hz. This observation suggests that low-frequency waves are affected more than high-frequency waves. The frequency-dependent ΔQ−1 estimates suggest frequency-dependent responses of regional waves to the crustal structures and heterogeneities along paths.

The lengths of oceanic paths decrease with the azimuth from the source (Fig. 1). It is observed that the Lg ΔQ−1 estimates increase generally with azimuth. The Lg ΔQ−1 estimates present that the Lg attenuation is consistent with previous studies that present high attenuation of Lg in oceanic and laterally-inhomogeneous crusts (Kennett and Furumura, 2001; Zhang and Lay, 1995). The path-dependent Lg ΔQ−1 estimates suggest the difference in the crustal structures along the paths. The Lg phase is highly affected by the crustal thickness and lateral crustal structure. The Lg ΔQ−1 estimates suggest that the Lg attenuations are primarily controlled by the lengths of oceanic paths in continental margin environment. Also, low frequency Lg waves appear to be dissipated much effectively compared to high frequency Lg in thin crusts.

The ΔQ−1 estimates of Pg, Sn and Sg display weaker correlation with azimuth than those of Lg. The weak correlation of ΔQ−1 estimates with azimuth suggests that the mantle lid S waves (Sn) and crustal reflection waves (Pg, Sg) are affected not only by the lateral variation of crustal structures along paths, but also by other factors including shallow crustal structures beneath stations.

The Pn ΔQ−1 estimates display azimuth-independent variations. Large differences in Pn ΔQ−1 estimates between two nearby paths are observed. Stations MGY and CEA on two adjacent paths are placed in comparable distances from the source (Fig. 1). Station MGY displays...
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large negative Pn ΔQ\(^{-1}\), whereas station CEA presents large positive Pn ΔQ\(^{-1}\) in low frequencies. The Pn ΔQ\(^{-1}\) estimates for continental path (station BAR) are observed to be close to zero. On the other hand, large Pn ΔQ\(^{-1}\) estimates are observed on paths across substantial oceanic regions. The observation suggests that the Pn phase grows stably on continental paths, while it is developed in various forms on oceanic paths.

The observed Pn features are associated with the Pn nature. The Pn waves are not influenced only by the Moho topography along raypaths, but also by the crustal structure beneath station (e.g., Bhatthacharya et al., 1996; Cormier, 1987). The Moho topography causes the focusing-and-defocusing effect on Pn. The focusing effect amplifies the Pn waves, while the defocusing effect causes apparent attenuation of Pn waves. The high variation of Pn amplitudes between two nearby stations suggests that the Pn amplitudes are highly affected by the shallow crustal structures beneath stations.

The differences of ΔQ\(^{-1}\) among three components (Fij) are calculated from Eq. (6) to investigate the strengths of directional amplification and energy partition (Fig. 13). Three combinations of components are considered (radial–vertical, tangential–vertical, radial–tangential). The differences of ΔQ\(^{-1}\) present that the ΔQ\(^{-1}\) estimates of two horizontal components (radial and tangential) are similar. The absolute ΔQ\(^{-1}\) estimates from horizontal components are larger than those from vertical components in frequencies equal to or less than 3 Hz in most regional phases but Pg. However, the ΔQ\(^{-1}\) estimates of horizontal and vertical components are comparable in high frequencies (3 Hz or larger). The observations suggest that most regional phases except Pg experience strong attenuation or amplification in the horizontal directions relative to the vertical directions. Also, large scale variations in crustal structures may be responsible for such discriminative amplification or attenuation of energy in low frequencies.

11. Discussion and conclusions

Large earthquakes can cause seismic damages to regions in regional distances. It is crucial to understand the nature of the regional seismic waves for regional seismic hazard mitigation. In this study, the path effect around the continental margin was investigated using regional seismic waves from the 2009 North Korean UNE test. The spectra, horizontal-to-vertical (H/V) spectral ratios and quality factors for stations on various paths were calculated. The waveforms and spectral contents of regional phases vary significantly by path. The attenuations of regional phases were generally observed to increase with the length of oceanic path. It was found that regional phases are dependent not only on the crustal thickness, but also on lateral variation of crustal structures. In particular, crustally-guided shear waves (Lg) are highly attenuated along oceanic paths due to continuous leakage of energy into the mantle during propagation. The path-dependent seismic attenuation is strong in low frequencies (≤3 Hz), while weak in high frequencies (>3 Hz).

It was observed that regional waves are highly attenuated in continental margin. The regional waves regrow along continental paths. The regrowth rates are strong over the inherent attenuation along paths, causing increase of amplitudes of regional phases. The H/V ratios of regional phases were observed to be different among stations in common great-circle directions. However, the H/V ratios were observed similar among regional phases at common stations. The observations suggest that the regional phases are affected by the shallow crustal structures beneath stations. The vertical incidence angle of regional phase affects the levels of H/V ratios. The levels of H/V ratios are different between two horizontal components, suggesting directional partition of seismic waves by crustal structures.

It was observed that seismic amplification is stronger in horizontal components than vertical components, suggesting that horizontal seismic motion is a crucial factor to be considered for assessment of regional seismic hazards. Also, strong shear waves with tangential motion were excited from complex crustal structures in continental margin. The observation suggests that P-to-S wavetype coupling may be another factor to be considered for seismic hazard assessment.

Event magnitude along with event location composes vital information. Also, correct estimation of event magnitude is crucial for seismic hazard analysis. However, regional seismic waves are highly influenced by the crustal structures along raypaths. Thus, complex crustal structures around continental margins make it difficult to estimate event magnitudes correctly. In addition, the wave propagation effects including the focusing-defocusing and wavefront healing cause a significant variation in regional waveforms. It was found that large-scale structure variation in the crust affects low frequency waves primarily. On the other hand, small-scale perturbations cause attenuation of high-frequency waves. The frequency-dependent influences of heterogeneities cause complex variation in regional waveforms, from which source and path effects are difficult to be separated. However, it was observed that Lg waves are primarily dependent on the crustal thickness along the path. Thus, Lg attenuation may be useful for investigation of lateral variation of crustal thickness.

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Fig. 13. Differences of ΔQ\(^{-1}\) among three components: (a) Pn, (b) Pg, (c) Sn, (d) Sg, and (e) Lg. Three combinations of components are considered for calculation of differences of ΔQ\(^{-1}\). The variations of differences of ΔQ\(^{-1}\) are large in low frequencies compared to high frequencies. Crustal reflection phases (Pg, Sg) present small differences between radial and tangential components, suggesting equal energy partition during reflection. Mantle-lid phases (Pn, Sn) display fluctuations deviated from zero-base lines at some component combinations. Lg phase presents consistent energy partition among components.


