Jour. Korean Earth Science Society, v. 29, no. 7, p. 559–566, December 2008

Large Ground Motion Related to Crustal Structure in Korea

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한반도 지각 구조로 인한 이상 강진동 관측 및 해석

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Abstract: Ground shaking recorded during the January 20, 2007, M_L 4.8 Odaesan earthquake (Korea) were used to investigate the role of the crustal structure in producing a strong ground motion, which includes the identification of the phases responsible for the strong ground motion and their implications for seismic hazard assessment. Analyses of strong-motion data together with waveform simulation revealed that critical and post-critical reflections from the crust–mantle boundary are responsible for the abnormal ground motions. This result demonstrates that the crustal structure should be taken into consideration in studies of seismic hazard mitigation even in the areas of relatively low seismicity.

Keywords: Odaesan earthquake, enhanced ground motion, seismic hazards, SmS, crustal structure

요 약: 2007년 1월 20일 규모 4.8의 오대산 지진 관측기록을 사용하여 강진동 발생에 있어서 지각구조의 영향을 조사하였다. 이를 위하여 강진동을 발생시키는 위상을 규명하였으며, 지진위험성 평가에 있어서의 의미를 고찰하였다. 관측자료와 파형모사 분석 결과, 지각-맨틀 경계에서 반사된 파가 예상보다 큰 지진동을 발생시킴을 확인하였다. 본 연구는 우리나라와 같은 지진활동이 많지 않은 지역에서도 지진위험저감 연구에서 지각구조를 고려하여야 함을 보여주고 있다.

주요어: 오대산지진, 지반운동, 지진위험성, SmS, 지각구조

Introduction

Seismic waves attenuate with distance from the source, which causes a corresponding decrease in seismic hazard potential. Because of this, the damage caused by an earthquake is usually limited to radius of a few tens of kilometers from its source. Occasionally, however, regions at a considerable distance from the epicenter experience strong shaking and severe damage, although effects at intermediate distances are comparatively insignificant. For example, on March 31, 2002, the Taipei metropolitan area in Taiwan underwent a major damage due to a M_L 6.8 earthquake about 110 km away, while minor damage occurred in the nearby city of Hualien, 35 km from the earthquake source (Chen, 2003). Both amplifications within the underlying sedimentary basin and the critically reflected S-wave from the Moho (SmS) were indicated as the cause of the strong ground motion and resultant damage in Taipei. Recent studies in other

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regions have also shown that SmS can be the reason for pronounced ground motions (Somerville and Yoshimura, 1990; McGarr et al., 1991; Catchings and Kohler, 1996; Boztepe-Güney and Horasan, 2002).

Predicting the characteristics of seismic energy attenuation (Atkinson and Boore, 1997; Campbell, 1997; Toro et al., 1997) has been increasingly important in an effort to protect from potential strong shaking, especially in regions such as the Korean Peninsula where larger earthquakes are deceptively infrequent. In this study, we examined high-quality strong-motion data recently obtained from a moderate-size earthquake in Korea. At some stations, ground motion was larger than that predicted by attenuation relations suggested previously. We investigate potential causes for the increased ground motion; the implications for the crustal structure and corresponding seismic hazard in Korea are discussed.

Data and Methods

Odaesan Earthquake

The Korean Peninsula, characterized by NE-trending mountain ranges, holds important clues to the tectonics of northeast Asia and the relationship between eastern China and the Japan Islands. The peninsula consists of Precambrian cratonic blocks separated by NE-SW trended fold belts: the Nangrim Massif, the Imjingang Belt, the Kyonggi Massif, the Okcheon Fold Belt, and the Youngnam Massif. Sedimentary basins are also present including the Paleozoic Pyongnam and Taebaeksan basins, the

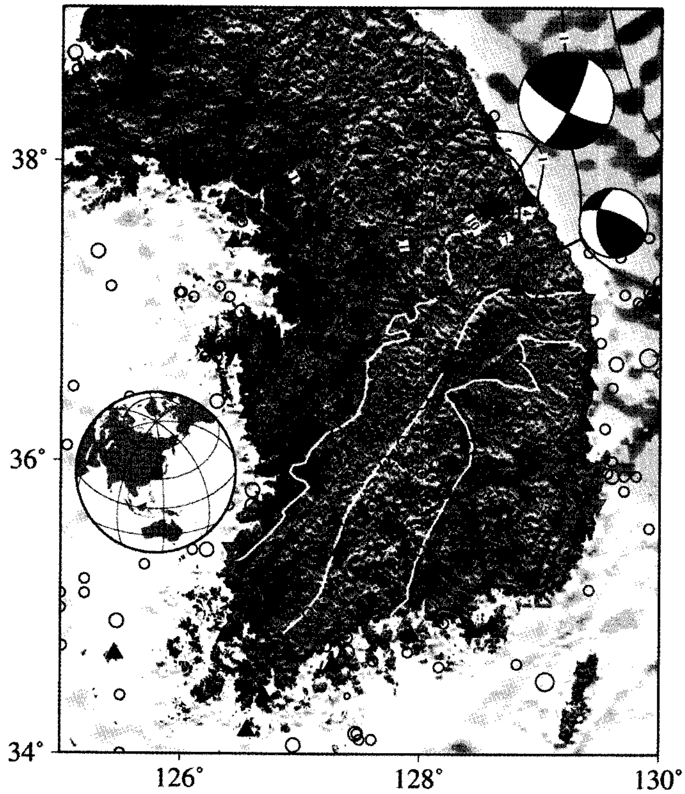

Fig. 1. Contours of horizontal PGA (in %g) during the Odaesan earthquake. The Odaesan earthquake is shown by the red star along with its focal mechanism solution. Red, blue, and inverted purple triangles are locations of strong-motion stations operated by the KMA, KIGAM, and KEPRI, respectively. Open circles are earthquake locations occurring between 2001 and 2007. Location of the Yeongwol earthquake occurred in 1996 is also presented along with its focal mechanism. Tectonic boundaries are shown as white lines and crustal zones are denoted as follows: GM=Gyeonggi massif; OFB=Okcheon fold belt; YM=Yeongnam massif; and GB=Gyeongsang basin.

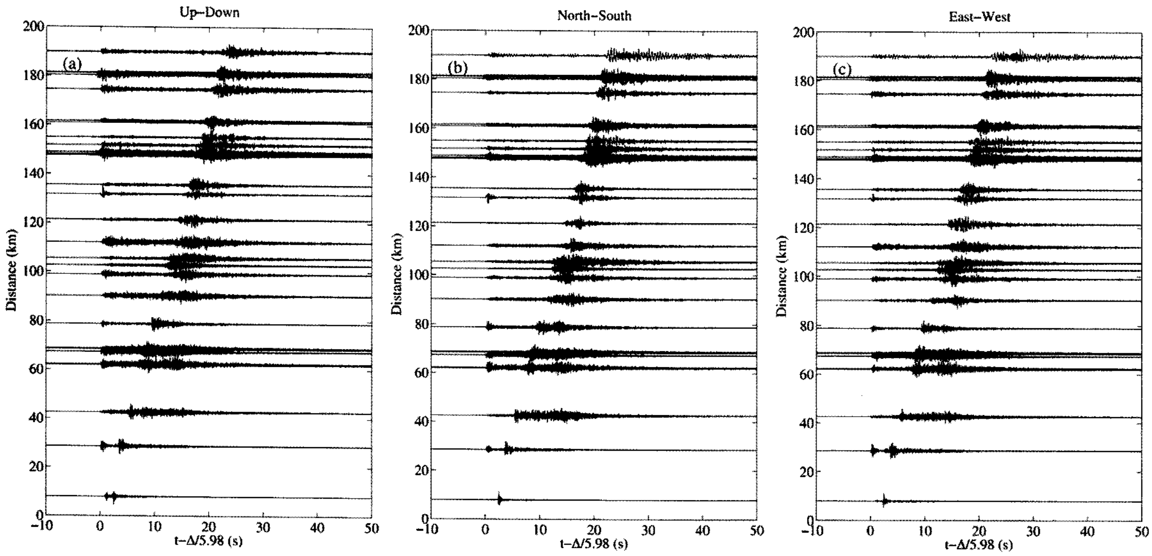

Fig. 2. Acceleration seismograms for the 2007 Odaesan earthquake recorded by Korean seismic networks operated by the KMA, KIGAM, and KEPRI.

Cretaceous Kyongsang basin, and the Miocene Pohang basin.

In the evening of January 20, 2007, a moderate M_L 4.8 earthquake occurred in the central eastern Korean Peninsula, which was reported by Korea Meteorological Administration (KMA, 2007) (Figs. 1 and 2). Although the earthquake was not destructive, it provided an impetus to better understand the seismic hazards inherent to the Korean Peninsula. Fortunately, the earthquake was remote and caused no damage but did provide high-quality seismic data since it was the largest inland earthquake ever recorded after the installation of the Korea National Seismic Network. KMA named the event as the Odaesan earthquake (also known as the Woljeongsa earthquake). Within several minutes of the earthquake, KMA had announced the event through TV and radio broadcastings, and communication services such as faxes and mobile phone short message services. Soon after a detailed analysis of the seismic data, reliable source parameters and the focal mechanism were identified. Although the analysis indicated the strike–slip focal mechanism (Jo and Baag, 2007; KIGAM, 2007; Kyung et al., 2007), it is not possible yet to determine which nodal plane was the rupture surface, because both the local geology and the historical seismicity patterns of the source area are not adequate.

The KMA and the Korea Institute of Geoscience and Mineral Resources (KIGAM) routinely monitor the seismic activity in the Korean Peninsula; the Korea Electronic Power Research Institute (KEPRI) and the Korea Institute of Nuclear Safety (KINS) also have an interest in monitoring strong earthquakes. All seismic stations in Korea were fully operational during the Odaesan earthquake. Figures 1 and 2 show the locations of strong motion stations and acceleration data recorded at the stations. Horizontal-component peak ground accelerations (PGA's) are indicated as contours superimposed on a topography map (Fig. 1). At the station closest to the epicenter (~8 km), 0.065, 0.132, and 0.156 g were registered on the vertical, east-west, and north-south components, respectively (KIGAM, 2007).

The Odaesan earthquake was preceded by a foreshock and followed by at least four aftershocks M <2.0 (KMA, 2007). Kyung et al. (2007) studied the details of the focal mechanisms for the main event and two large aftershocks. Their results suggested that the aftershocks were produced by reverse faulting, which was different from the strike-slip motion of the

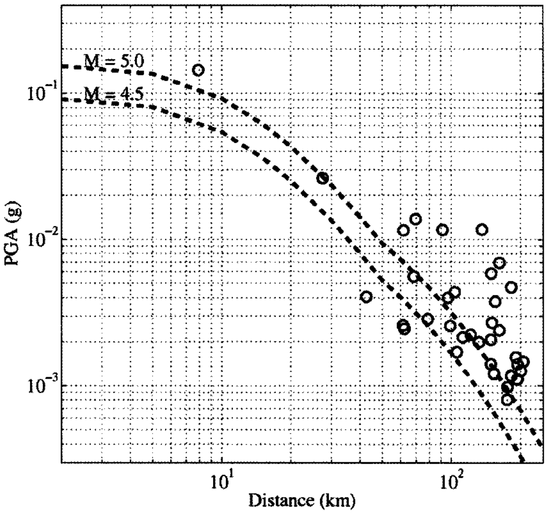

Fig. 3. Peak horizontal acceleration as a function of distance. Dotted lines show the expected values for magnitude 4.5 and 5.0 proposed by Yun et al. (2005). Observed peak accelerations at some stations were significantly larger than expected, causing a flat trend in the attenuation relation at the distance range from about 80 to 180 km.

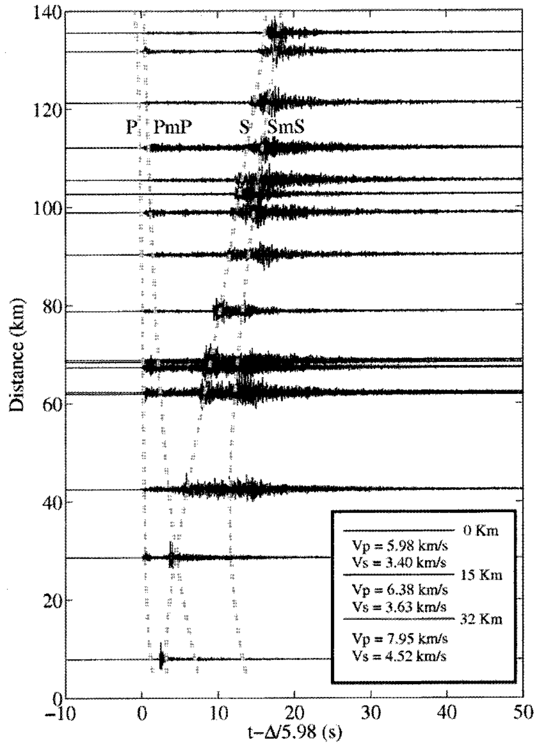

Fig. 4. Transverse components of acceleration records for the Odaesan earthquake. Arrival times for major crustal phases are shown as dashed lines. The legend gives the velocity model of Kim and Kim (1983) used for the calculation of expected arrival times.

main event. We note the moderate-size Yeongwol earthquake (M 4.5) also occurred in this region on December 13, 1996. The Yeongwol event took place on the southern boundary of the Okcheon fold belt, whereas the 2007 Odaesan event occurred along the northern boundary of the Taekbaeksan basin. The strike–slip faulting and the direction of the compressional axis for the two events were similar. These two events are probably the most important earthquakes that have occurred in the southern Korean Peninsula during the last several decades.

Elevated Ground Accelerations

PGA's for the Odaesan earthquake versus epicentral distance are shown in Fig. 3, along with the expected ground-motion decay for magnitude 4.5 and 5.0 events (Yun et al., 2005). Although the ground motion during the Odaesan earthquake follows the exponential decay trend proposed by Yun et al. (2005), some ground motions at 100 km distance are several times larger than expected. To explain such a phenomenon, it is necessary to examine which phase, or wave type, is mainly responsible for the peak ground motion.

Since the shape of transverse waveforms, obtained by rotating the two horizontal seismograms, does not depend on azimuthal takeoff angle for pure strike-slip mechanisms (Mori and Helmberger, 1996), the transverse components from the strike-slip Odaesan earthquake are suitable for examination. Each trace is normalized (Fig. 4) to illustrate the relative variation of different phases with distance and their effects on PGA. Figure 4 also shows expected arrival times for seismic phases P, PmP, S, and SmS, which were estimated using the velocity model (shown in the inset) proposed by Kim and Kim (1983).

The transverse component of acceleration waveforms at distance ranges of 95 to 125 km clearly identify SmS (Fig. 5a). Since we are interested in the effects of strong shakings on seismic hazard, the waveforms (Fig. 5b) were processed by a shaping filter used by Japan Meteorological Administration (Yamamoto et

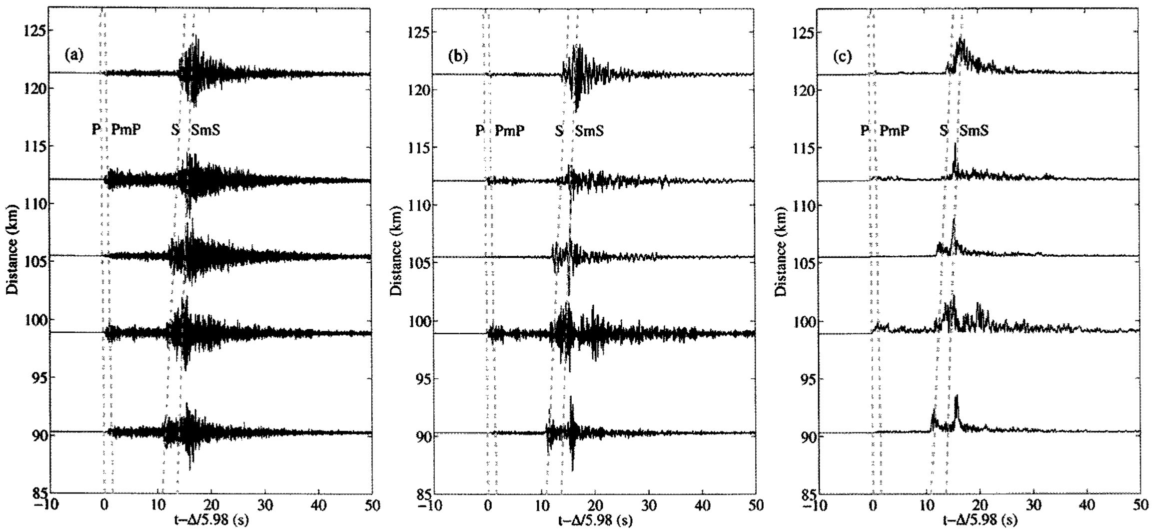

Fig. 5. (a) Transverse component acceleration records for seismic stations with epicentral distances between 90 and 125 km. (b) Band-pass-filtered traces and (c) their envelope functions. Expected arrival times for major crustal phases are indicated by thick gray dotted lines. SmS phases arriving 2-3 s after the S-wave produce the enhanced ground shaking at a given distance range.

al., 2007). The shaping filter is a tuned band-pass filter that is used to isolate the seismic energy in a bandwidth that is especially damaging to buildings and structures. To better characterize the amplitude and arrival time of energy extremes, the envelope functions of the filtered transverse component traces were estimated (Fig. 5c). At this distance range, the SmS phases arrive 2-3 s after the S-wave, and their amplitudes are three to five times larger than the S-wave, resulting in larger PGA's than expected. Some arrival times do not match the estimated arrival times, probably because the velocity model lacks details of the subsurface structure, especially for the S-wave.

Numerical Modeling

In order to demonstrate that the anomalies associated with the M_L 4.8 Odaesan earthquake were caused by Moho reflections, it is needed to examine the effects of the Moho discontinuity on seismograms at different distances from the source. To do so, waveform simulation was carried out based on the 2-D cell-based finite-difference method suggested by Min et al. (2004), which correctly describes Rayleigh waves as well as P and S waves. A relatively simple one-dimensional layered velocity model (Kim and Kim, 1983) was used. Since duplicating various phase arrivals is beyond the scope of this study, it was not attempted.

Caution is required when we compare synthetic waveforms generated from an explosive source with observed earthquake waveforms. Most explosions are point sources located on the surface or at very shallow depths, whereas most earthquakes are spatially complicated and much deeper. An earthquake produces both P- and S-waves, but an explosive source mainly generates compressional waves with limited S-waves. This study assumes an explosive point source to be excited at the depth of 13 km and examines the compressional components of the simulated waveform. We expect that the general features of P wave arrivals may be applicable to the S-phases, albeit with the understanding that the source effects are different. In other words, the radiation patterns are not identical, but the propagation paths of P- and S-waves are generally similar (Catchings and Kohler, 1996). Under this assumption, the generation of the strong ground motion by the S-wave components can be inferred.

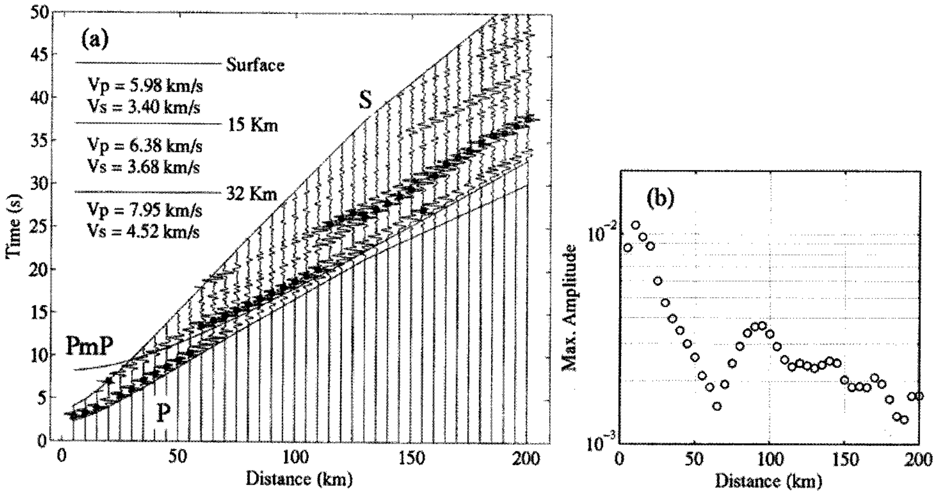

Fig. 6. (a) Synthetic P-wave seismograms for the one-dimensional velocity structure in Korea (inset) using an explosive source 13 km deep. S-wave and later arrivals have been excluded to highlight the small energy arrivals that precede S arrivals. Theoretical arrival times of P, S, and PmP are shown as solid lines. Arrivals of the largest amplitude in each trace are shown as red circles. (b) Maximum amplitudes of each simulated trace against distance show logarithmic decay of amplitude at shorter distances. Enhanced ground motions near 100 km are caused by critical or post-critical reflections from the Moho discontin.

Results

Results of simulations with an explosive source at 13 km depth are presented in Fig. 6(a). Receivers are located at the distances from 5 to 200 km from the source with the spacing of 5 km. Theoretically computed arrival times of P, S, and PmP are shown as solid lines and the waveforms are self-scaled to emphasize the arrival times of the different phases and the relative importance of the P-wave components. Direct P-wave arrival is the predominant feature at shorter distances; as distance from the epicenter increases to 60 km or more, later arrivals emerge as major features. The figure also shows the time for the largest amplitude to develop in each simulated trace as a red circle. At distances between 60 and 120 km, the maximum amplitude occurs when PmP phases arrive. Absolute values of the maximum amplitude for individual traces are presented as a function of distance in (b). The figure shows a logarithmic decay with distance, which is mainly due to the attenuation of the amplitude of the initial P-waves. It also shows increased maximum amplitudes near epicentral distances of 100 km, which are the result of critical reflections from the Moho discontinuity.

Discussion

In the preceding sections we show the large amplitude observed during the moderate earthquake in Korea can be generated by the crust-mantle boundary, or Moho discontinuity. In this section we discuss other possible effects that may contribute to the formation of large amplitude: local geological conditions or site responses that amplify waves in thick sedimentary basins (Hough et al., 1990), directivity resulting from rupture processes (Ammon et al., 2005; Ni et al., 2005), simple crustal structure (Mori and Helmberger, 1996), and dipping crustal structures (Catchings and Kohler, 1996), among others. The most frequently cited cause for wave amplification is a thick sedimentary basin (Beck and Hall, 1986). Although details of site conditions for stations shown in Fig. 5 are not provided, three of them are located on hard rock, which acts to minimize amplification effects. Directivity caused by rupture propagation is expected to be negligible because the magnitude of the Odaesan earthquake was less than 5. The effects of the focal mechanism should be minor because the transverse components are analyzed, which are not sensitive to the azimuthal take-off angle for strike-slip mechanisms (Mori and Helmberger, 1996).

Reliable three-dimensional velocity models for the Korean Peninsula are not yet available. A map of the peninsula (Fig. 1) shows that the Odaesan event took place in the middle of mountainous region at a relatively high elevation. If isostatic equilibrium is assumed, then a relatively thick crust may exist beneath this NS-trending mountain region, which thins to the west. Radiated waves will therefore encounter a Moho discontinuity that gets shallower as they travel westward. This may result in the focusing of seismic energy at some distance, producing unusually large amplitudes. Chi et al. (2007) documented azimuthal variation of PGA during the Odaesan earthquake that could be the effect of different subsurface structures on ray propagation.

Cho et al. (2006) used explosive sources to image the crustal structure beneath the Korean Peninsula. They analyzed a NW-trending, 300-km-long seismic refraction profile, and found the deepest Moho discontinuity beneath the Okcheon fold belt and the Yeongnam massif, in the southeastern part of Korea. They also noticed a strong mid-crustal discontinuity, presumably the Conrad discontinuity, at a depth of 15 $\pm$1 km beneath the Gyeonggi massif and the Okcheon fold belt, but found that the mid-crustal discontinuity was missing beneath the Yeongnam massif and the Gyeongsang basin. Although the implication of a simple crustal structure lacking the Conrad discontinuity is not used here, it should be considered and will be the focus of future studies.

Conclusions

The Korean Peninsula is a part of the stable Eurasian continent, and only a few moderate earthquakes have occurred during the last few decades. Compared to the high seismicity of surrounding nations, the Korean Peninsula is generally considered to be safe from earthquake hazards. Historical documents, however, may suggest otherwise; although inferred magnitudes and epicenters of historic events are disputed, the peninsula has clearly experienced large destructive earthquakes (Chiu and Kim, 2004; Lee and Yang, 2006).

Anomalously large PGA's were examined and their potential causes were investigated. Moho-reflected S-waves (SmS) are proposed as the cause of large amplitudes recorded at strong-motion stations at distances of 80 to 180 km from the epicenter. Empirical PGA predictions in previous studies may have underestimated strong ground motions at this distance range. Although this study did not incorporate site-specific amplification mechanisms such as basin configuration, in which such phenomena are important, ground motion will be further enhanced because a basin will amplify the elevated ground motion caused by SmS. Moho reflections may dominate the strong ground motion at a distance of approximately 100 km from earthquake sources, and thus should be taken into consideration in the prediction of the strong ground motion and the assessment of seismic hazards.

Acknowledgments

We thank the KMA, KIGAM, KEPRI, and KINS staffs for providing the data used in this study. The generic mapping tool GMT (Wessel and Smith, 1991) was used for plotting Fig. 1. The authors also thank the reviews by two anonymous reviewers and Dr. Paul Rydelek. This study was funded by the Korea Meteorological Administration Research and Development Program under Grant CATER2006-5101.

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Manuscript received: July 30, 2008
Revised manuscript received: November 25, 2008
Manuscript accepted: December 4, 2008