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Earthquake damage and related factors associated with the 2016 M_L = 5.8 Gyeongju earthquake, southeast Korea

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ABSTRACT: The Gyeongju area covers the intersection of two major young structural features in Korea: the Yangsan and Ulsan faults. More than 60 Quaternary fault sites have recently been reported along these fault zones, which are thus considered major active tectonic features in southeast Korea. An earthquake of local magnitude M_L = 5.8 struck the Gyeongju area on September 12, 2016; the largest instrumental earthquake recorded in South Korea. We performed detailed investigation for severely damaged buildings and houses in villages around the epicenter, and determined the characteristics and controlling factors of the earthquake damage. The distribution of damaged buildings is relatively scattered around the epicenter, which may be related to the relatively deep focal depth of approximately 13–15 km. The radius of the reported damage area affected by ground motion is approximately 17 km from the epicenter, which is almost equal to the focal depth. Old buildings with traditional styles are more seriously damaged than modern buildings, suggesting that the damage intensity depends on the building structure, material properties, and seismic design. Interestingly, in a small village, the degree of building damage is clearly divided by a small stream. Based on an electrical resistivity survey for the local geological condition, we found that the degree of building damages also strongly depends on the local unconsolidated alluvium thickness. Moreover, the orientation of tilted or damaged buildings is closely related to the general trend of the related faults indicating the propagation direction of ground motion. Although focal depth, building style, and foundation condition are the main controlling factors to the building damages caused during the 2016 Gyeongju earthquake, other minor factors could also be involved. This information will be useful to design proper construction codes for reinforced buildings and for hazard studies against future earthquakes in potential earthquake prone areas.

Key words: Gyeongju earthquake, earthquake damage, focal depth, damaged building, local geological conditions, ground motion propagation

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1. INTRODUCTION

Recently, many large earthquakes have caused major loss-of-life and extensive property damage worldwide, and projected population growth combined with urbanization suggest that this trend will continue (Wisner et al., 2008; Doocy et al., 2013). For example, the 1999 Chi-Chi earthquake (M_W = 7.6), the 2008 Sichuan earthquake (M_W = 7.9), and the Tohoku earthquake (M_W = 9.0) all occurred neighbouring countries of the Korean Peninsula. In particular, the Tohoku earthquake was classified as a megathrust earthquake, this earthquake generated powerful tsunami waves that reached 40.5 m in height, and was recorded as one of the five most powerful earthquakes worldwide since 1900 (Yagi and Fukahata, 2011). Moreover, the Tohoku earthquake caused a serious nuclear accident at the Fukushima Nuclear Power Plant, and significantly affected lives and properties throughout coastal areas.

The Korean Peninsula has historically been considered to be tectonically stable compared with neighbouring countries such as Japan and Taiwan, because it is located within the Eurasian intracontinental region (e.g., Kim et al., 2004). However, more than 60 Quaternary faults have recently been reported along the Yangsan and Ulsan faults, which are major tectonic features in southeast Korea (e.g., Kyung, 1997; KIGAM, 1998; Kyung and Chang, 2001; Lee and Schwarcz, 2001; KOPEC, 2002; Cheong et al., 2003; Choi et al., 2003a, 2003b; Ree et al., 2003; Kim et al.,

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2004; Lee and Yang, 2005; Ree and Kwon, 2005; Kim et al., 2011). Several paleoseismological and structural studies (e.g., KIGAM, 1998; KOPEC, 2002; Choi et al., 2003a, 2003b; Ree et al., 2003; Kim et al., 2004; Kim et al., 2011) have been conducted on these faults, arguing paleoseismological activity. Furthermore, according to historical records, large seismic events have affected Gyeongju and surrounding areas located in the southeastern part of the Korean Peninsula. In particular, the AD 779 earthquake, inferred to be a devastating earthquake of magnitude M = 6.7 (Lee and Na, 1983; Lee and Jin, 1991; Lee, 1998), was well documented in *Samguksagi*, where states the following "*Approximately 100 people were killed and a number of buildings destroyed by the earthquake*". Many other damaging earthquakes were also reported in historical records (e.g., *Samguksagi, Chaljubongi, Mukseojipyeon*). The instrumental record of earthquakes in Korea began in 1905, and approximately 1000 earthquakes of mostly small magnitude (< M_L = 4) have been detected on or near the Korean Peninsula (Lee and Yang, 2006) since then.

On 12 September 2016, however M_L = 5.1 and 5.8 earthquakes (named the "9.12 Gyeongju earthquake") occurred near the Gyeongju City, which was the capital city of Korea for 1000 years during the Silla Dynasty. The depth of the mainshock was approximately 14 km (Kim et al., 2016) and several aftershocks were reported around the area. Although surface ruptures associated with the earthquake have not been reported, buildings were moderately or severely damaged as a result of the sudden ground shaking associated with the earthquake, which was expressed as scattered damaged buildings over a large area.

In this study, we investigated the damage patterns of buildings and houses in Gyeongju area to understand the controlling factors on structural damages associated with the earthquake. We analyzed and compared the relationship between damage distribution and focal depth, the differences in damage patterns between building structures, the link between damage intensity and local soil and geological condition, and the orientation of damages associated with the propagation of seismic waves. Although it is difficult to estimate the quantitative relationship between earthquake damages and particular controlling factors, this study will provide useful information for prevention study against future earthquake damage hazards and anti-earthquake design.

2. STUDY AREA

The study area is located in the Gyeongsang Basin, South Korea, where the basement rocks are comprised of Cretaceous sedimentary rocks intruded by Cretaceous and Paleogene igneous rocks (Fig. 1). The Gyeongju area is located at the junction between the Yangsan and Ulsan faults (Fig. 1), which are predominant tectonic features within the Gyeongsang Basin. The geometry and characteristics of the intersection between the two faults show analogue to the simulated λ-fault (Du and Aydin, 1995) and small-scale λ-fault (Kim et al., 2000; Han et al., 2009). Recently, approximately 60 Quaternary faults were reported near the Yangsan-Ulsan fault systems (Fig. 1; Lee and Jin, 1991; Kyung and Okada, 1995; Chang, 2001; Kim and Jin, 2006; Kim et al., 2011), and the concern and importance of the activity of the fault system is increasing because of the 9.12 Gyeongju earthquake (M_L = 5.8) in 2016.

Gyeongju was the capital city of Korea during the Silla Dynasty (Three Kingdoms Period), which endured for almost 1000 years (57 BC–935 AD) and incorporated many rich cultures. According to historical records, there were many Buddhist temples and other heritage sites in Gyeongju area due to the spread of Buddhism. Hence, it is a suitable area to study not only earthquake damage but also paleoseismology and archaeoseismology.

3. DISTRIBUTION OF 9.12 GYEONGJU EARTHQUAKE DAMAGE

On 12th September 2016, an M_L = 5.8 earthquake (the mainshock), the biggest instrumental earthquake in South Korea, occurred in Gyeongju 48 minutes after an M_L = 5.1 event (foreshock). More than 600 aftershock events continued for approximately six months around the epicenter (Kim et al., 2017). Many buildings and houses were severely damaged in villages around the epicenter (Fig. 2). Moreover, some large cities around Gyeongju (i.e., Pohang and Ulsan) were also affected by the earthquake. Earthquake damage in this area was of great concern because of large industrial facilities distributed throughout the Pohang and Ulsan areas (Fig. 2), along with their proximity to two nuclear power plant sites (i.e., Kori and Weolsung) and a nuclear waste disposal site.

After the earthquake within a couple of weeks, we mainly conducted field investigations on building damages associated with the earthquake. Three villages (Hwangnam, Bandong, Woewa) were selected because of the relatively severe damage and easy accessibility at those locations during the earthquake (Fig. 2), where many buildings and houses were partial or heavily damaged. Here, we describe the characteristics of the earthquake damages in each village and they will be compared.

3.1. Hwangnam Village

Hwangnam Village is located near the downtown of Gyeongju City, approximately 9 km from the epicenter (Fig. 2), which is near the junction between the Yangsan and Ulsan faults, and very close to the east side of the Yangsan Fault (Fig. 2). The village contains many different types of buildings and houses, including schools, government buildings, and markets. Government buildings

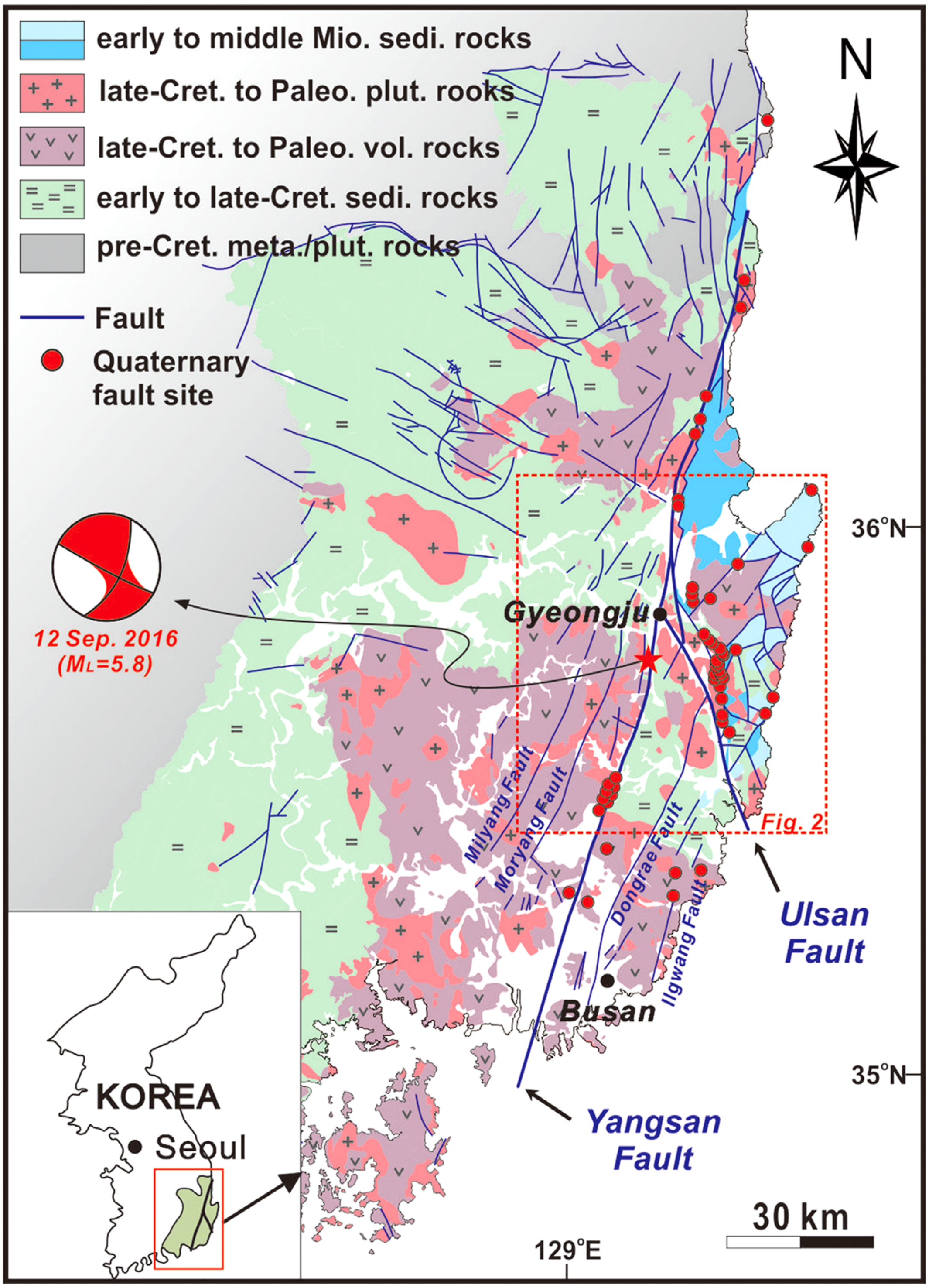

Fig. 1. Geological and structural map of the Gyeongsang Basin (modified from Chough and Sohn, 2010). Red dots indicate Quaternary fault sites. Fault plane solution for the 9.12 Gyeongju earthquake (M_L = 5.8) is constrained by the first-motion solution (Kim et al., 2016).

and schools relative well sustained with low damage from the earthquake, because they were constructed with reinforced concrete frames. However, significant damages occurred in individual houses and buildings, because most residential buildings did not adapt efficient seismic design. In particular, lightweight house roof tiles, masonry walls, and old walls were easily subjected to damage (Fig. 3). Modern walls are built with bricks or blocks joined with cement and relatively strong. However, old walls are relative weak because they are comprised of stones with mud as the adhesive.

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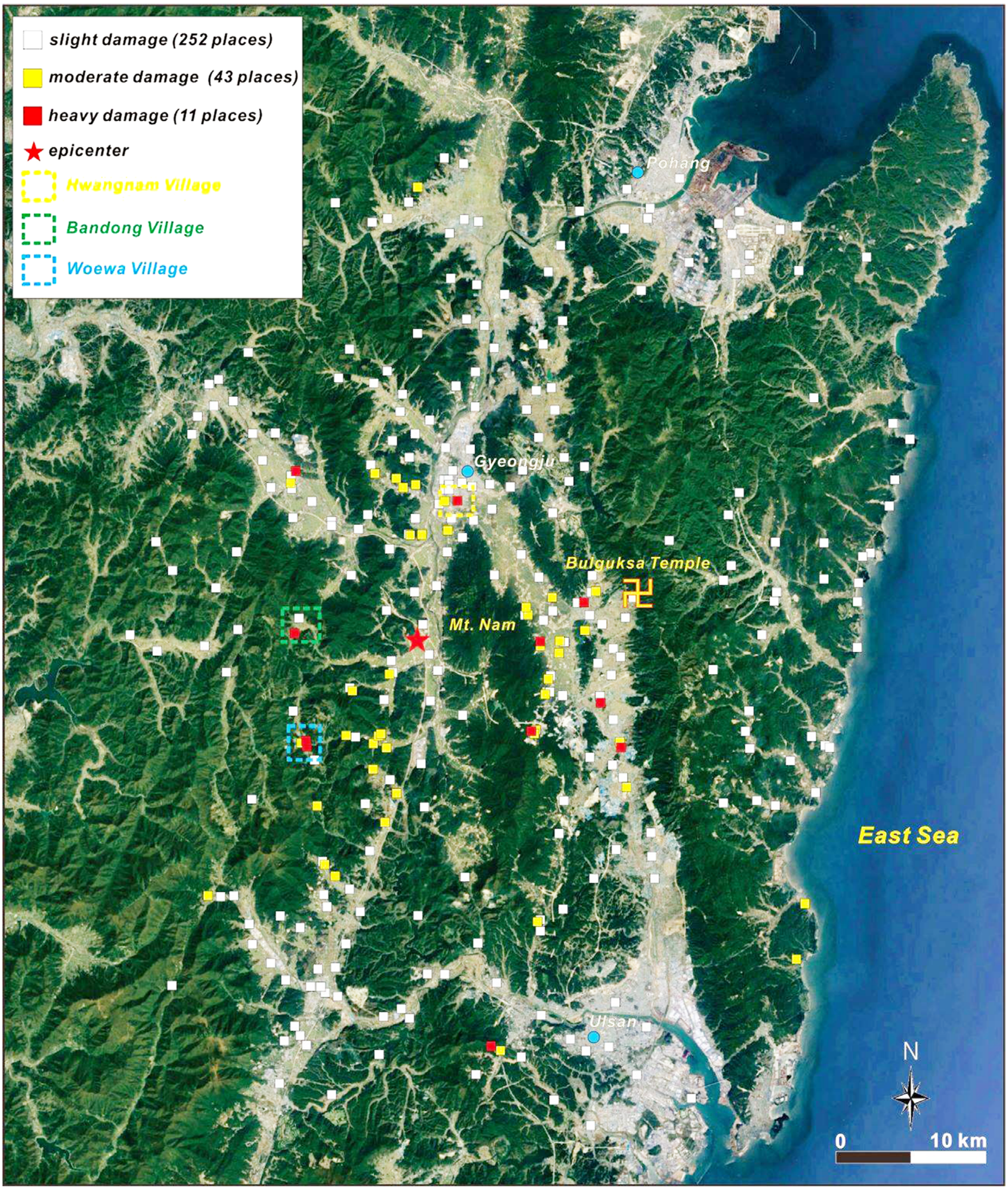

Fig. 2. Distribution map of damaged buildings and houses associated with the 9.12 Gyeongju earthquake (Red star: mainshock, Red square: heavy damage, Yellow square: moderate damage, White square: slight damage). The basic data were provided from Gyeongju City; satellite image from Google Earth.

During the field investigations, we measured the orientation and crack widths of tilted and displaced structures. Most of the collapsed lightweight roof tiles were scattered with no consistent direction, because of their weak construction style and materials. Most damaged structures were old style houses and walls including roof tiles. The cracks in the walls were mainly several centimeters in width (Fig. 3). Interestingly, the tilted and displaced walls showed some preferred orientation, and most of them were oriented in NNE-SSW (Fig. 3). This orientation is similar to the general strike of the Yangsan fault, which may indicate some relationship between damaged structures and horizontal ground motions along the fault as indicated in some previous studies (e.g., Hough, 2018).

Fig. 3. Photographs of damages in Hwangnam Village. (a–d) Displaced and tilted walls generated by the earthquake and the orientation of tilted and displaced structures. (e) Distribution map of the degree of building damage. (f) A rose diagram for the orientation of tilted and displaced buildings in Hwangnam Village. It show NNE-SSW trend of tilting and displacement, indicating the direction of ground shaking.

3.2. Bandong Village

Bandong Village is located approximately 7 km to the west from the epicenter, and on the west side of the Yangsan Fault (Fig. 2). This village is one of the most seriously damaged areas by the 9.12 Gyeongju earthquake. Most buildings in the village

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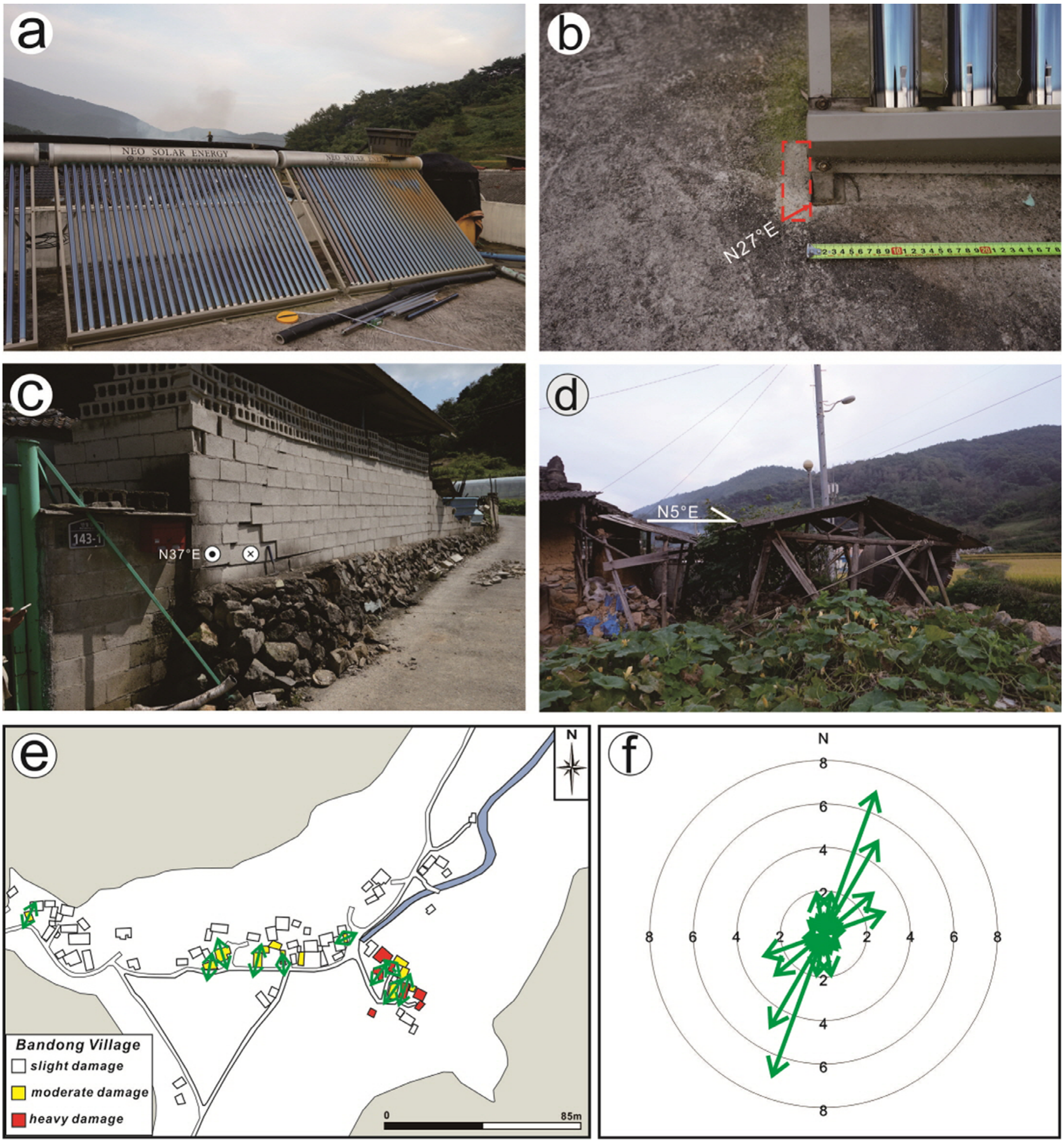

Fig. 4. Photographs of damages in Bandong Village. (a and b) Displaced solar panels on the roofs of residential houses. (c) Displaced masonry blocks in a wall. (d) Inclined farmhouse. (e) Distribution map of the degree of building damages. (f) A rose diagram for the orientation of tilted and displaced buildings in Bandong Village. It shows NNE-SSW and NE-SW trends of tilting and displacement, indicating the direction of ground shaking.

are farmhouses and residential houses, having no efficient seismic design (Fig. 4). Many lightweight roof tiles, masonry walls, old walls joined with stone and mud, and unfixed solar panels were seriously destroyed or damaged by the earthquake (Fig. 4).

In the field, we measured the orientation of tilted and displaced walls, the inclination of farmhouse, and the direction of solar panel movement on roofs to understand the shaking pattern induced by the earthquake (Fig. 4). We found that the solar panels were moved approximately 3–5 cm in the NE-SW direction (Fig. 4b), and masonry blocks of farmhouses were displaced approximately 3–4 cm in the NE-SW direction (Fig. 4c). An old farmhouse was inclined approximately 20° toward NNE-SSW

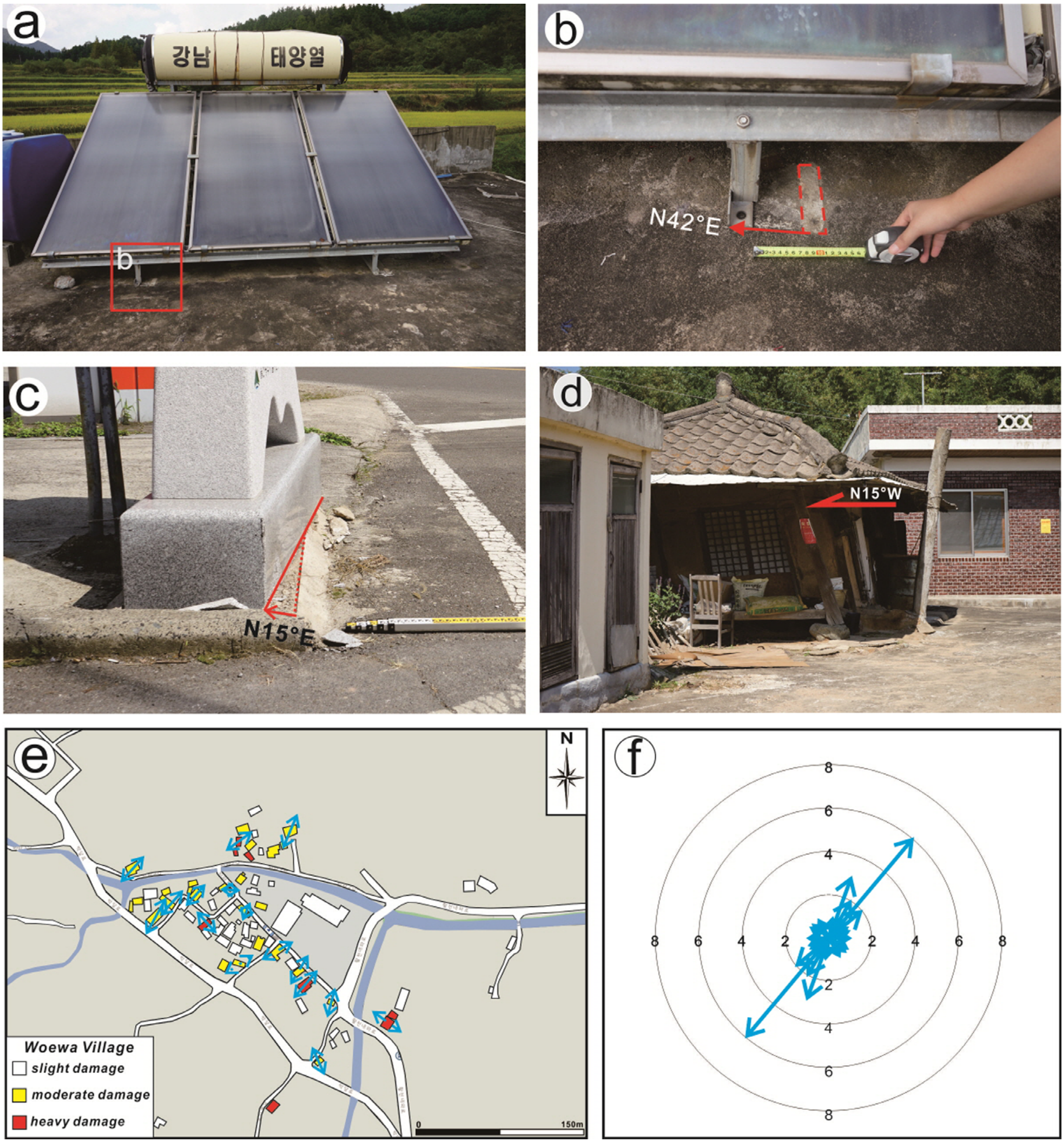

Fig. 5. Photographs of damages in Woewa Village. (a and b) Displaced solar panels on the roofs of residential houses. (c) Tilted stone post at the entrance of the village. (d) Old house severely inclined approximately 15° to the west. (e) Distribution map of the degree of building damage. (f) A rose diagram of orientation based on tilted and displaced buildings in Woewa Village, showing the NE-SW and NNE-SSW trends of tilt and displacement due to ground shaking.

direction (Fig. 4d). Many solar panels, which were not fixed with anchors or bolts, experienced shaking with a similar direction with NNE-SSW and NE-SW trends (Figs. 4a and b). Most damaged buildings measured in the village were oriented NNE-SSW to NE-SW (Fig. 4), and inclined or tilted to the SW or SSW, this indicate ground movement direction.

3.3. Woewa Village

Woewa Village is located approximately 9 km southwest from the epicenter and on the west side of the Yangsan Fault (Fig. 2). This village was also seriously damaged indicating strong ground motion. Many farmhouses and residential houses were seriously

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destroyed, suffering moderate to heavy damage due to a complete lack of aseismic design. Many lightweight roof tiles, masonry walls, old stone and mud walls, and solar panels were destroyed or severely damaged (Fig. 5). A solar panel was moved approximately 10 cm in the NE-SW direction (Fig. 5b). Even the very heavy stone post of the village located at the entrance of the village was severely damaged, and was rotated approximately 10° in the NNE direction (Fig. 5c). An old house was found to be inclined approximately 25° in the NNW direction (Fig. 5d). We measured the orientation of the tilted and displaced walls, the inclined houses and the movement direction of unfixed solar panels (Fig. 5). The damaged buildings were oriented in NE-SW to NNE-SSW (Fig. 5), and the predominant orientation of damaged structures was SW or SSW, indicating a similar trend with those of other villages.

Ground motions in the near-fault zone are affected by the rupture mechanism and slip direction (Bray and Rodriguez-Marek, 2004). Furthermore, it was reported that earthquake seismic waves have been affected by surface topography (Geli et al., 1988; Ma et al., 2007) and geologic structures such as fault and basin geometries (Shani-Kadmiel, 2012; Hough, 2018). We observed remarkable directivity from damage structures in the three villages based on our field investigation. Although some damage structures show scattered orientations, the dominant direction of damage structures is clearly indicating NNE-SSW trend. It coincides with the general trend of the two major faults related with the earthquake (Kim et al., 2017). Therefore, we suggest that there might be some relationship between the orientation of damaged structures and the propagation of horizontal ground motions along the faults associated with the earthquake.

4. MAJOR CONTROLLING FACTORS ON BUILDING DAMAGE ASSOCIATED WITH THE 9.12 GYEONGJU EARTHQUAKE

Several factors can control differences in earthquake damage patterns and intensities (Page et al., 1975). However, it is not easy to decipher the exact controlling factors, because many different factors are related with each earthquake, such as seismic waves, fault type, magnitude, focal depth and distance from epicenter, foundation condition including liquefaction, building style and age, and applied aseismic design. Furthermore, if the earthquake magnitude is too large, very serious shaking occurs and almost all buildings are severely damaged. In such cases, it is very difficult to analyze the damage patterns and decipher both the controlling factors and the contribution of each factor.

However, the 9.12 Gyeongju earthquake was a medium-scale ($M_L = 5.8$) earthquake; thus, the damages were not extremely severe and the damage patterns were clearly recognized. As a result, this kind of earthquakes is much more useful to obtain information on the relationship between controlling factors and building damages. Therefore, based on the building damage patterns, we inferred three major controlling factors; focal depth, building style, and local soil and geological conditions. These factors mainly contributed to the building damage associated with the 9.12 Gyeongju earthquake.

However, the damage effects from differences of building styles can be solved based on the analysis of damage patterns depending on building types and throughout the anti-earthquake design. However, it is difficult to predict the timing, location and magnitude of future earthquakes, and we cannot control other factors. Nevertheless, because most of the accumulated stresses are released along active faults during large earthquakes, producing surface ruptures and strong ground motions. Thus, if we can identify the geological characteristics throughout detailed geological, geophysical and paleoseismological studies, we can greatly reduce earthquake damages. Therefore, this kind of study must be very important and useful for prevention against earthquake hazards in earthquake prone areas.

4.1. Relationship between Damage Distribution and Focal Depth

Focal depth affects the amount of shaking (Keller and DeVecchio, 2016) due to attenuation of the seismic waves. Seismic waves generated from a deep focus must travel farther to the surface, losing energy along the way. Therefore, shallow focused earthquakes more intense and cause more serious damages, while deeper earthquakes are attenuated but more widely felt (Keller and DeVecchio, 2016).

For example, substantial energy loss occurred during the 2011 Nisqually Earthquake (M = 6.8) along the Cascadia subduction zone at a depth of 52 km, while the 1994 Northridge Earthquake (M = 6.7) with similar magnitude at a depth of 19 km less attenuated and stronger shaking was transferred to the surface. Also, the M = 6.2 earthquake with a depth between 4.0 and 9.6 km occurred in Pescara del Tronto, Italy in 2016, killed many people and destroyed a number of buildings and houses (Masi et al., 2016). In contrast, the much larger Bagan, Myanmar earthquake (M = 6.8) in 2016 focused at depth of 85 km killed only a few people and destroyed some ancient Buddhist pagodas (Zaw et al., 2017). However, this earthquake was widely felt not only in Myanmar, but also even in Bangkok, 1000 km away from the epicenter (Zaw et al., 2017).

The main shock of the 9.12 Gyeongju earthquake ($M_L = 5.8$; Kim et al., 2016) ruptured the fault plane with a strike of 24° (or 115°), a dip of 78° (or 86°), and a rake of 176° (or 12°). The depth of the 9.12 Gyeongju earthquake was approximately 14 km based

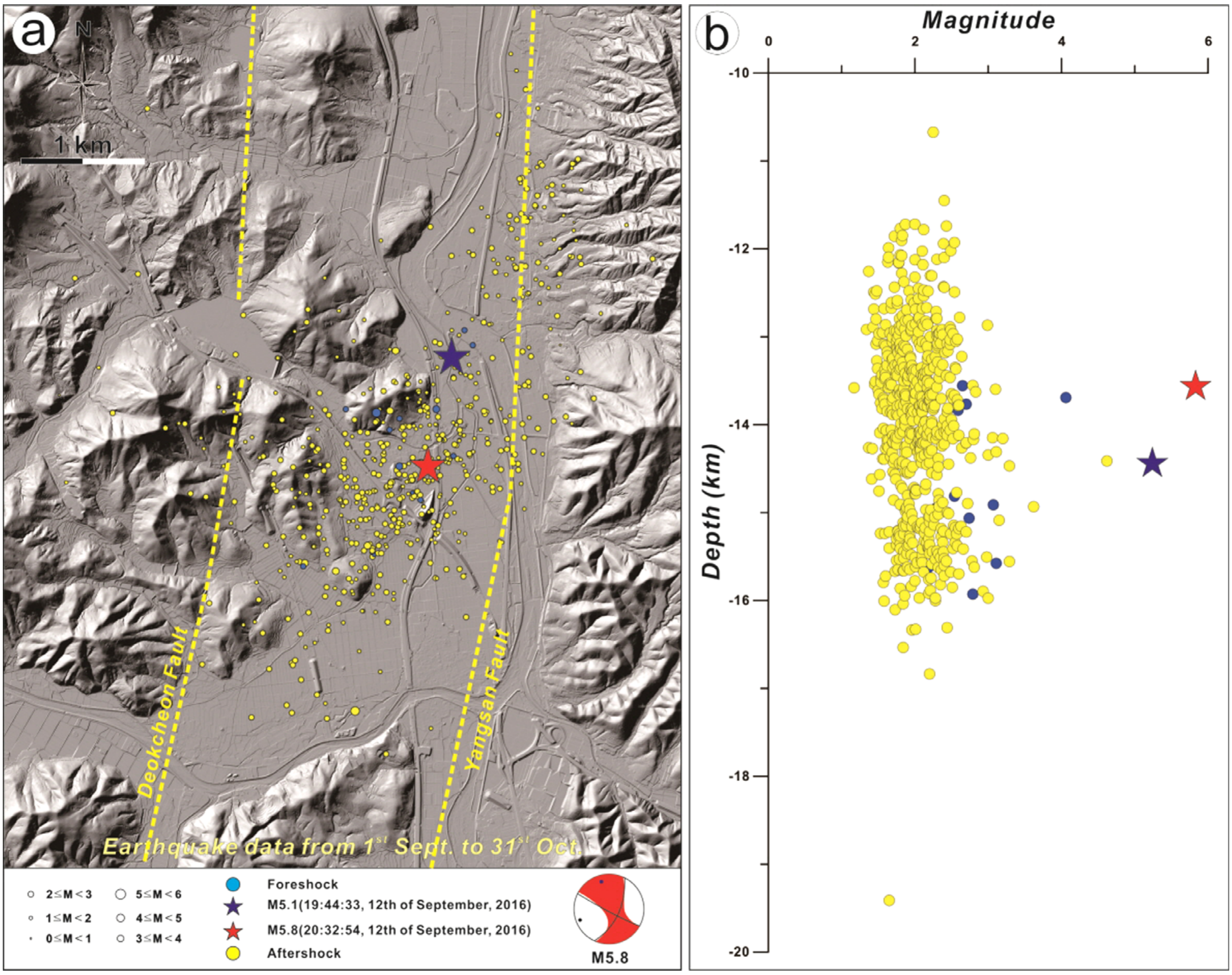

Fig. 6. Horizontal and vertical distribution of seismic events associated with the 9.12 Gyeongju earthquake (modified from Kim et al., 2017). (a) Distribution of seismic events (Blue circle: foreshocks, Dark blue star: the largest foreshock (M_L = 5.1), Red star: mainshock (M_L = 5.8), Yellow circle: aftershocks). Seismic data were collected from the 1st to 31st of October in 2016. Note that 98% of events are concentrated between the Yangsan and Deokcheon faults. (b) A depth-magnitude relationship for the 2016 Gyeongju earthquake. Note that the seismic events occurred at depths of 12–16 km.

on focal mechanisms (Fig. 6; Kim et al., 2016). The aftershocks of the earthquake occurred at depths around 12 to 16 km for more than two months (Fig. 6). The foreshocks, mainshock and aftershocks were concentrated in a small area between two faults (Yangsan and Deokcheon faults) indicating a close relationship with the linking damage zone (Kim et al., 2017).

However, the distribution of damaged buildings was not concentrated around the epicenter, but it was instead relatively scattered over a 17 km radius, almost the same distance as the focal depth (Fig. 2). Furthermore, according to media reports, the earthquake was felt throughout South Korea and even in China and Japan. Therefore, we suggest that the broad distribution of damage and shaking associated with the 9.12 Gyeongju earthquake is related to the relatively deep focal depth. This indicates that the focal depth is closely related to the distribution area of the building damage, which is completely different from the damage patterns from the 2017 Pohang earthquake with similar magnitude (M_W = 5.4). The focal depth of the Pohang earthquake was 3–4 km and the damages by the earthquake, such as buildings, houses, roads, bridges and walls, are mainly concentrated near the epicenter.

4.2. Influence of Building Style on Damage Patterns

Gyeongju was the ancient capital city of the Silla Dynasty for 1000 years; thus, many structures are heritage buildings of various ages. Specifically, many Buddhist related structures were constructed during the Silla Dynasty, such as temples, stone Buddha statues and stone pagodas (Jin et al., 2011). For this reason, modern and old buildings co-exist in Gyeongju, and the city is currently one of the most famous tourist cities in South Korea.

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Official seismic design regulations for buildings were introduced to Korea in 1988 (Ministry of Construction and Transportation, 1997). The first national seismic design code was applied to buildings with six or more floors or areas of more than 10,000 m^2. Recently, revised seismic design codes have extended into the buildings of three or more floors or areas of more than 500 m^2 (Ministry of Construction and Transportation, 1997); thus, only approximately 30% of the existing buildings in Korea were built according to seismic design standards, all of which are within major cities. Thus, most buildings and houses in Gyeongju were

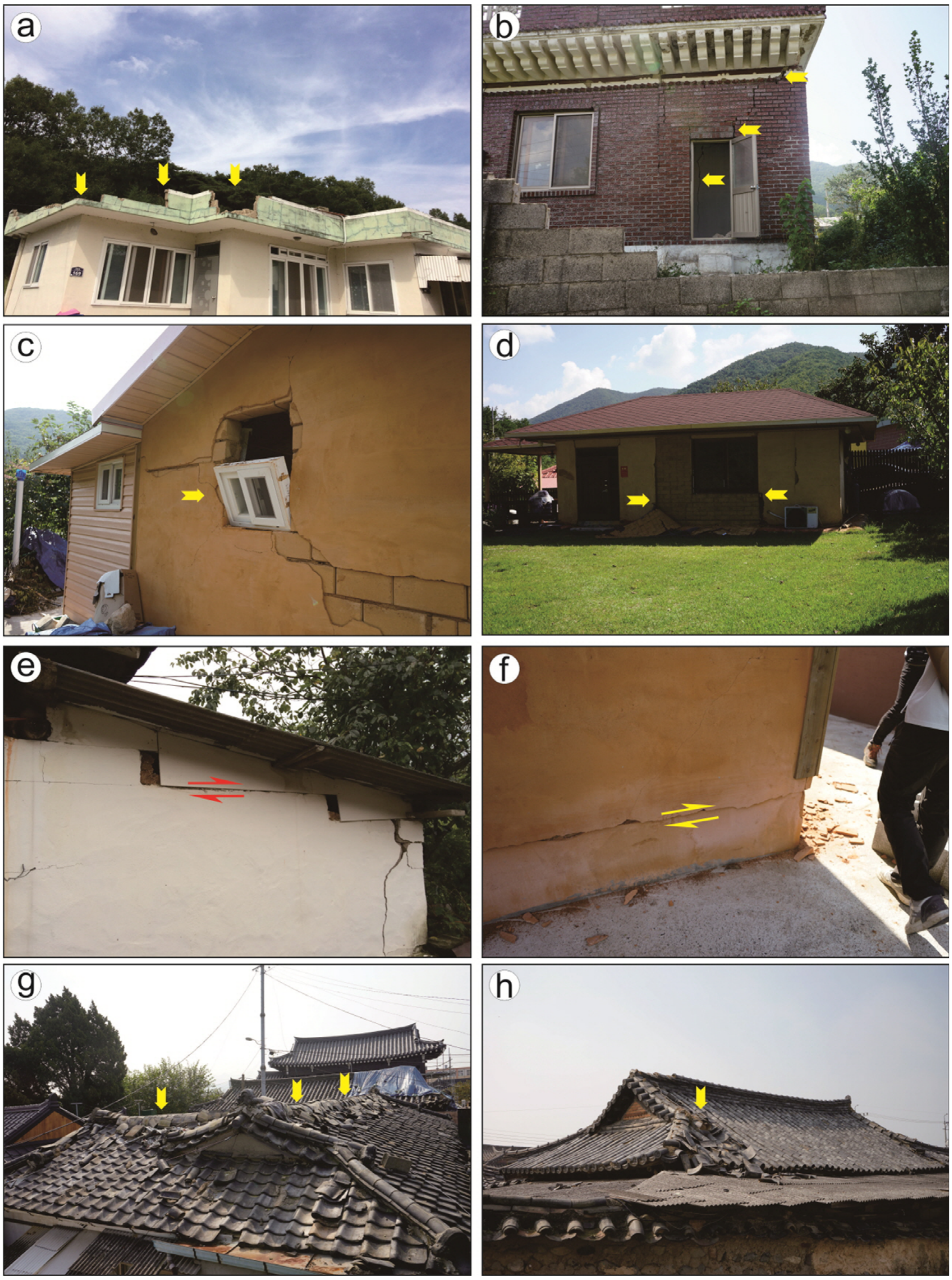

Fig. 7. Photographs of damages with various styles of building and house associated with the 2016 Gyeongju earthquake. (a) Collapsed soft bricks unreinforced and unconfined on the roof of reinforced concrete houses. (b) Cracks and distortions in infill walls with clay bricks between reinforced concrete pillars, showing no damage to reinforced concrete pillars. (c) Destroyed window and wall of an old house. (d) Damaged wall built of traditional dry grass and clay. (e and f) Photographs of cracks between roofs and walls in unreinforced and unconfined masonry of old houses. These cracks between walls and roofs are similar to shear fractures. (g and h) Photographs of collapsed lightweight roof tiles of old houses. These lightweight roof tiles exhibit very weak resistance to earthquake shaking because clay was used as the adhesive.

not built according to seismic design standards, except for recently constructed buildings, schools, government buildings and hospitals.

Field investigation for earthquake-damaged buildings is one of the most basic and important prevention strategies against earthquake hazards (Okada and Takai, 2000), and is performed throughout the world after large earthquakes. Thus, we also performed a detailed field investigation for destroyed buildings and houses around the epicenter of the Gyeongju earthquake (Fig. 7). Firstly, we classified building styles in damaged areas based on their structures as follows: 1) reinforced concrete frame buildings; 2) reinforced concrete confined masonry; 3) unreinforced and unconfined masonry; and 4) vernacular and historical constructions.

Reinforced concrete frame buildings exhibited minimal damages by the earthquake, indicating sufficiently strong against this level of intensity. Note that reinforced concrete frame buildings are the most common construction type for recently built public and commercial buildings, including schools, hospitals, government buildings, hotels and business buildings.

Reinforced concrete confined masonry buildings and houses were slightly damaged during the earthquake. Some cracks and distortions occurred within infill walls, which were built with clay bricks between reinforced concrete pillars (Figs. 7a and b). However, many walls with soft concrete bricks of the unreinforced and unconfined masonry were heavily damaged (Figs. 7c and d). These structures consist of soft concrete bricks, wooden columns, and concrete pillars without iron rebar. The material comprising infilled walls is a mixture of dry grass and red clay, which is a traditional housing material in Korea (Figs. 7c and d). These structures including plastered walls were severely inclined or collapsed by the earthquake (Figs. 7c and d). In addition, many cracks were found on masonry walls with windows and on mud floors.

Interestingly, many cracks were observed between the roofs and walls because there were no strong linkages between their different structures (Figs. 7e and f). These cracks show very similar patterns to natural shear fractures (Riedel shear style) (Figs. 7e and f). It indicates the shear movement between the ground and building was accommodated between roofs and walls, because different structures behaviour differently to seismic waves.

The most common traditional building structures are wooden frames with lightweight roof tiles and clay. In particular, roofs with lightweight roof tiles are very weak against earthquake shaking, because they are weakly attached with clay. Thus, many roof tiles in the affected areas collapsed by of the earthquake-induced shaking (Figs. 8g and h).

One of the most common types of earthquake damage was wall damage (Figs. 3a–d). There are two types of wall in the study area; traditional and modern. The traditional walls were built with rocks and clay (Fig. 3b), but the modern walls were built with soft concrete bricks cemented with concrete plaster (Figs. 3a, c and d). The damaged walls showed different damage patterns depending on their material and construction methods. The traditional walls were completely collapsed or severely inclined (Fig. 3b), but the modern walls were only slightly damaged with minor cracks or slight distortions (Figs. 3a, c and d).

This indicates that stone walls bonded with clay are more prone to collapse against shaking, because the adhesion of clay is greatly reduced if it dries. Hence, earthquake damage intensities and patterns are entirely dependent on building styles, materials and seismic design, as well as the earthquake intensity. This means that appropriate improvements in construction materials or styles and aseismic design codes could greatly reduce earthquake hazards as already reported from several previous earthquakes (e.g., Zhao et al., 2009). However, these design codes should be carefully developed, considering the tectonic setting, distance from active fault, foundation, building style and seismic activity for safety and economic feasibility.

4.3. Influence of Local Soil and Geological Condition on Building Damage

Local soil and geological condition can also contribute to the amplitude, spectral content, and duration of strong ground motion involving soil liquefaction, and ultimately alter the resulting damage patterns to man-made structures (Trifunac, 2016). During field investigations on damage patterns of buildings associated with the 9.12 Gyeongju earthquake, we found highly distinct damage intensities depending on location within a small village (Bandong Village), located approximately 8 km away from the epicenter to the west (Fig. 8). Although the buildings had similar structures and materials, the damage intensity was very different in the northern part (Figs. 8a, c and e) and in the southern part (Figs. 8b, d and f) of the village. That is, houses located in the southern part of the village were more severely damaged than those in the northern part (Fig. 8).

Electrical resistivity method is a useful tool to image the subsurface structures, especially related with faults in various environments (Choudhury et al., 2001; Gourry et al., 2003; Sass, 2007; Hsu et al., 2010). 2D electrical resistivity survey has a good advantage, because it can rapidly analyze the geological conditions of broad areas compared with drilling or trench. The electrical resistivity for underground media is affected by various factors such as the rock-forming minerals, porosity, conductivity of pore water, saturation, and clay content (Archie, 1942; Keller and Frischknecht, 1966). In particular, resistivity survey is strongly influenced by porosity and saturation (moisture content), because

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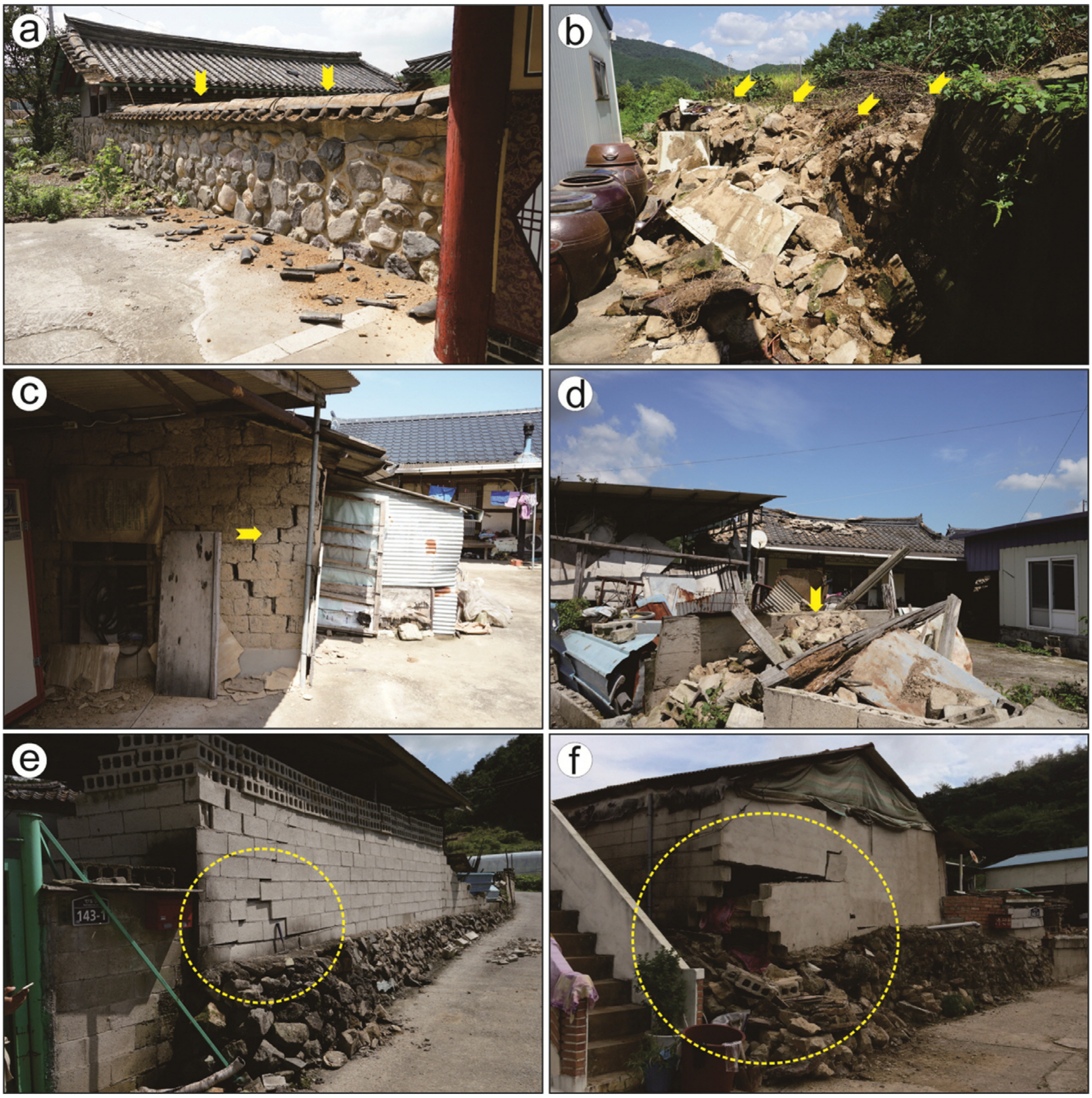

Fig. 8. Photographs of damaged buildings associated with the 9.12 Gyeongju earthquake in Bandong Village; approximately 8 km away from the epicenter to the west. (a), (c), and (e) Damages in the northern part of the village. (b), (d) and (f) Damages in the southern part of the village, showing a completely different damage intensity even for similar building structures and materials.

the current is injected into the ground flows through pore fluid as an electrolyte. Generally, alluvial sediments consist of clay, silt, sand and gravel, and have lower resistivity than the bedrock below the groundwater table because of the high porosity and moisture content. In this study, we estimated the thicknesses of the alluvial sediments in the study area based on the characteristics electrical resistivity.

To identify the damage effect of alluvium thickness as a controlling factor, we performed a 2D electrical resistivity survey across the Bandong Village in April 2017. Two lines (Line A and Line B) with a length of 275 m were established in the northern and southern areas, respectively (Fig. 9a). The 2D resistivity survey lines were designed with one survey line perpendicular to the slope from the valley and the other perpendicular to the exposed ground (Fig. 9a).

A modified pole-pole configuration was adopted for the survey lines. To enhance the quality of the results, data were acquired using a combination of double electrode spacings (5 and 10 m). Advanced Geosciences Inc. (AGI) SuperSting R8 multi-channel system was used for data collection, which was connected to an external switching box that controlled the flow of current along the 56-electrode cable. The maximum current

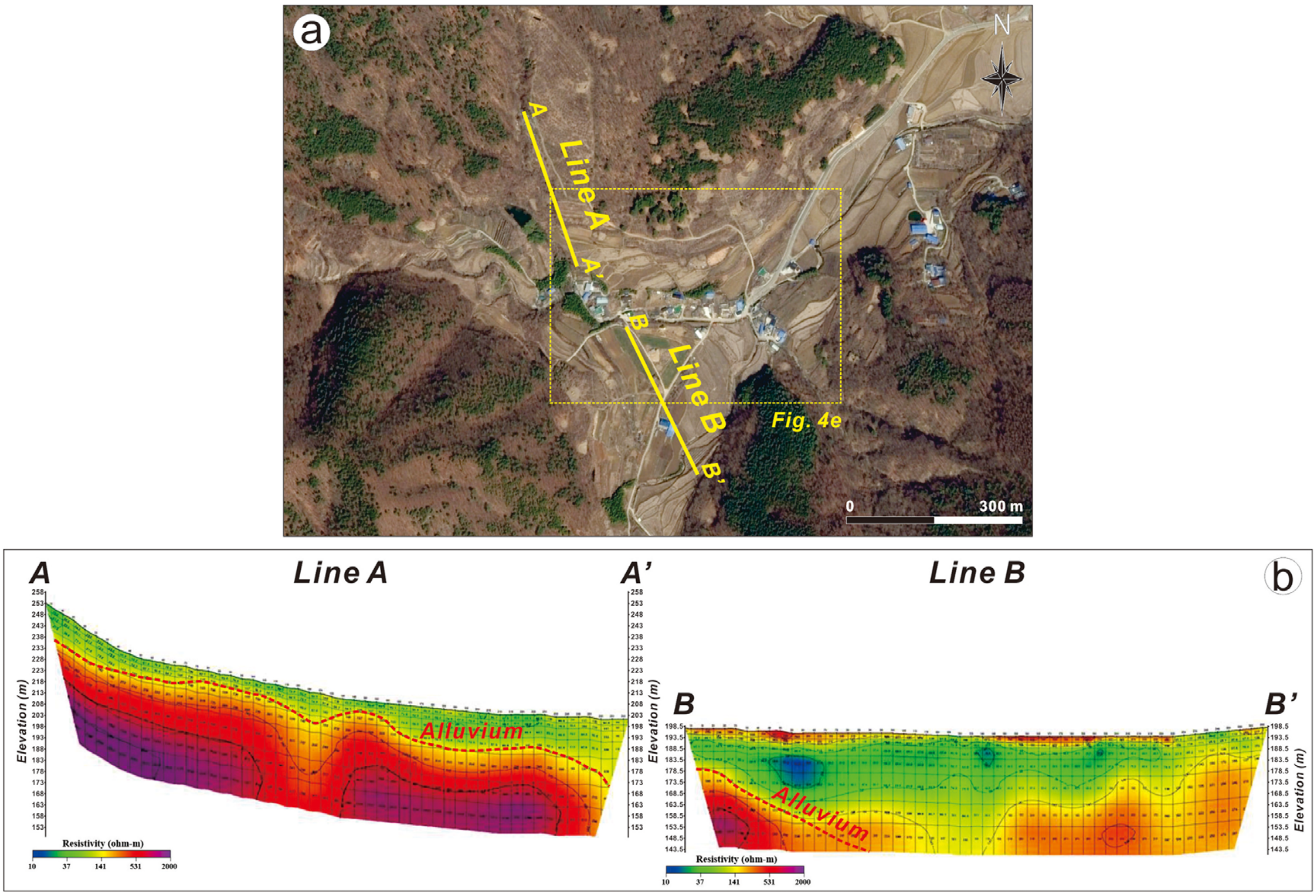

Fig. 9. (a) Design map for 2D electrical resistivity survey on alluvium in Bandong Village. (b) Survey results of Line A and B, showing the difference in alluvial thickness between northern and southern areas. Line A shows the 2D inversion results for the modified pole-pole data acquired at Line A. The rms misfit is approximately 2.2%. The overall resistivity distribution of Line-1 is approximately 40–2500 ohm-m, and has a four-layer structure. The boundary of the alluvial layer for Line 1 and 2 was estimated to be a relatively low resistivity layer (< 141 ohm-m). The thickness of the alluvial layer is approximately 5–20 m, and becomes deeper downstream of the mountain. Line B shows an electrical resistivity distribution of approximately 10–2000 ohm-m. The rms misfit is approximately 2.9%. The alluvial thickness is approximately 15–50 m, and becomes shallower toward the end of the survey line.

injection was set at 200 mA and the repeat measurement error was fixed until the threshold was less than 5%. An automatic resistivity instrument with eight channels was used for data collection. The collected data were inverted by the 2D inversion program, DIPROWin software version 4.0, which adopts a well-known iterative least-squares method based on finite element modeling. The 2D inversion program used in this study adopts a smoothness constraint algorithm with the Active Constraint Balancing technique (Yi et al., 2003).

Figure 9b shows the 2D inversion results of the Line A and Line B. The rms misfit of the inversion results are about 2.4% and 3.8% respectively. The survey results show very different alluvium depths in the northern and southern parts of the village (Fig. 9b). The alluvium depth is approximately 5–20 m along Line A, and approximately 15–50 m along Line B (Fig. 9b). Thus, the alluvium along Line B is two times deep compared with that along Line A (Fig. 9b). This indicates that the deep alluvium amplified the seismic wave in the southern part of the village causing more serious damage to man-made structures. This suggests that soft sediment as a superficial material causes even greater damage to structures than hard rock. Thus, information on the local geological and foundation conditions and appropriate location of important structures could neutralize from serious hazards or greatly reduce earthquake-related damages.

5. DISCUSSION

The foreshocks, mainshock, and aftershocks were concentrated in a small area between the NNE-SSW trending Yangsan and Deokcheon strike-slip faults within the Yangsan Fault Zone (Fig. 6). The focal mechanisms of the 9.12 Gyeongju earthquake indicate predominantly right-lateral strike-slip movement along the NE-SW trending fault, indicating a connecting fault within the linking damage zone of the two faults (Fig. 6a; Kim et al., 2017).

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We observed dominant directivities of the damaged walls in three villages. The strain accommodation of a wall depends on its foundation, the sizes of the bricks or blocks within the wall, the presence of adhesive among the bricks or blocks, and the presence of bolts or anchors (Rodríguez-Pascua et al., 2011). The dominant movement direction of wall in Hwangnam Village was NNE-SSW. Deformation patterns of folds, rotated blocks, bricks and fractures in walls depend on the orientation of the wall to the main horizontal component of the seismic waves (Korjenkov and Kaiser, 2003; Korjenkov et al., 2003). In particular, tilted and displaced walls in NNE-SSW trends occurred for E-W trending walls in Hwangnam Village (Fig. 3). In addition, unfixed solar panels, village post, old-style houses, and farmhouses in the Bandong and Woewa villages exhibited NNE-SSW and NE-SW movement (Figs. 4 and 5). The dominant orientation of tilted, inclined and collapsed structures in the Bandong and Woewa villages was NE-SW or NNE-SSW. Tilted and displaced walls are typically caused by horizontal ground movement probably due to propagation of ground motion, which affects wall foundation (Rodríguez-Pascua et al., 2011). Hence, the dominant orientation of the damaged walls and structures was most likely affected by the propagation of the ground motion generated by the strike-slip faulting during the earthquake, which is almost parallel to the related faults indicating fault controlled wave propagation (Shani-Kadmiel, 2012; Hough, 2018).

Ground shaking of an earthquake near the causative fault is much stronger than it was previously believed, suggesting that many buildings and houses do not fully resist to ground shaking (Page et al., 1975). Although previous studies (e.g., KIGAM, 1998; KOPEC, 2002; Choi et al., 2003a, 2003b; Ree et al., 2003; Kim et al., 2004; Jin et al., 2011; Kim et al., 2011), including paleoseismological and structural analyses, have reported more than 60 Quaternary faults along the Yangsan and Ulsan fault zones, and also historical records reported large earthquakes around the Gyeongju area and neighbouring cities, the linkage between these large historical earthquakes and surface ruptures or active faults has not been solved until now. Therefore, more intensive paleoseismological investigation on the active faults, potentially related with the large historical earthquakes and the 9.12 Gyeongju earthquake should be performed in and around the Gyeongju area.

Historical earthquake records in Korea can be divided into three historic time periods: Three Kingdoms (18 BC–918 AD), Koryeo Dynasty (918–1392 AD) and Choseon Dynasty (1392–1922 AD). In the Three Kingdoms period (Kogooryeo, Baekjae, and Silla), 105 earthquakes were recorded, most of which were concentrated in the capital cites of the Three Kingdoms. This result may be partly due to a more systematic reporting and recording system for the areas around the old capital cities. Even considering this factor, however, Gyeongju has many historical earthquake records. This area has experienced many large earthquakes resulting in extensive damages to historical and heritage buildings from the Silla Dynasty. Recently, a unique archaeoseismological study on a damaged Buddha Statue in Gyeongju City was reported (Jin et al., 2009, 2011), which interpreted the damage as being related to a historical earthquake. Thus, additional archaeoseismic studies based on historical structures are necessary to obtain more information on historical earthquakes.

Anti-earthquake structural design and construction in ancient buildings can provide clear evidence for previous strong seismic events occurring in a region (Michetti et al., 2007; Rodríguez-Pascua et al., 2011). According to well-documented historical records, such as the ancient texts of *Samguksagi*, *Chaljubongi* and *Mukseojipyeon*, the Gyeongju area has been significantly affected by multiple large earthquakes. In particular, stone stairs, stone bridges and two pagodas of the Bulguksa Temple (a representative temple of the Silla Dynasty) were destroyed several times by large earthquakes. However, many historical buildings in the area already employed excellent anti-earthquake designs to minimize earthquake damage. Some notable construction techniques have been applied in the Bulguksa Temple and other large stone structures, such as Grengee, Chuduseok and Gyeolgoo techniques, which was originally used for wooden-style structures (Hwang, 2007).

In addition, the reconstruction and repair of earthquake-related damage is a secondary evidence of EAE (Earthquake Archaeological Effects) (Michetti et al., 2007; Rodríguez-Pascua et al., 2011). According to the *Chaljubongi*, the Hwangryongsa nine-story wooden pagoda was repaired six times after earthquakes during the 8th and 9th centuries (Jin et al., 2011). The famous Seokga pagoda, built in the Bulguksa Temple, was also repaired twice; in 1024 AD and 1038 AD, after three large earthquake events in Gyeongju, based on the *Mukseojipyeon* historical record (Jin et al., 2011). Moreover, according to the famous historical book, *Samguksagi*, many Buddhist heritage sites, such as temples, stone Buddha statues, and stone pagodas, were constructed on Mt. Nam, a holy mountain, for praying to prevent earthquakes. These records indicate that the Gyeongju area has suffered from many earthquakes. Although the present earthquake-resistant buildings were constructed in the past, new earthquake code should similarly be applied to new buildings based on evaluation of the causative fault and maximum earthquake magnitude associated with the active fault. These applications will greatly reduce potential damages from future earthquakes.

6. CONCLUSIONS

During the 2016 Gyeongju earthquake (M_L = 5.8, 12th Sept. 2016), many buildings and houses were severely damaged in villages around the epicenter. We analysed the damage patterns of buildings, and inferred the dominant controlling factors affecting damage intensity.

Firstly, we conclude that the dispersion of building damage is likely to relate with the relatively deep focal depth of the earthquake; this indicates that deep focal depth generates a wide hazard area with lower damage. Secondly, the vastly different damage patterns are mainly influenced by building style, materials and seismic design. This means that earthquake hazards can be greatly reduced by promoting appropriate construction materials, styles and aseismic design codes. Thirdly, we confirm that unconsolidated sediments amplified the seismic waves and caused severe damage to man-made structures. Finally, the orientation of damaged buildings closely related to the propagation of ground motion during the earthquake. Thus, selection of optimal structural locations based on geological studies could greatly reduce earthquake-related damages. To conclude, although these three factors are likely to be the dominant controlling factors affecting the building damages occurred during the 9.12 Gyeongju earthquake, other additional minor factors could be involved. These findings will be helpful for future earthquake hazard assessment and anti-earthquake design.

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