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EDUQUAKES

# Development and Application of a Real-Time Warning System Based on a MEMS Seismic Network and Response Procedure for the Day of the National College Entrance Examination in South Korea

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## ABSTRACT

The largest earthquake in South Korea ($M_L$ 5.8) since modern seismograph network began monitoring in 1978 occurred in Gyeongju on 12 September 2016. Because of the generally low level of seismic activity in the country, Korean citizens had not expected or thought about how to respond to such a large earthquake and its related aftershocks. After the event, Koreans were left feeling a certain level of apprehension. Responding to this situation, a temporary microelectromechanical system (MEMS)-based seismic network was operated at six high-school sites to monitor seismic activity in Gyeongju from 18 October to 18 November 2016. The purpose of this temporary real-time warning system was not only to monitor aftershocks but also to provide an onsite earthquake drill in the event of an earthquake on the day of the College Scholastic Ability Test (which is held in November each year). The national college entrance examination is extremely important in Korea, and the government aims to avoid any interruptions to the exam. An earthquake drill manual was established for the first time for an effective response to possible earthquakes occurring on the day of the exam (17 November) in 2016. The MEMS network detected several aftershocks during the operating period but none on the day of the exam. The real-time MEMS warning system represents a new type of earthquake-monitoring system for South Korea.


*Electronic Supplement:* Response guidelines in the event of an earthquake.

## INTRODUCTION

At 10:44:32 UTC (19:44:32 Korea Standard Time; GMT +9 hrs) and 11:32:55 UTC (20:32:54 Korea Standard Time) on 12 September 2016, two earthquakes with local magnitudes ($M_L$) of 5.1 and 5.8 occurred in the historic city of Gyeongju on the southeastern Korean Peninsula (Fig. 1; Kim, Rhie, *et al.*, 2016). These two events (foreshocks and mainshocks) caused only minor-to-moderate damage in mostly older buildings, including at cultural heritage sites. Despite the lack of deaths and only a few injuries, the country was shocked by the earthquakes, which changed a widely held misconception that Korea is an earthquake-free zone. Several aftershocks, including an $M_L$ 4.5 earthquake on 19 September at 11:33:58 UTC (20:33:58 Korea Standard Time), followed, clustering around the epicenters of the foreshocks and mainshocks (Fig. 1; Kim, Kang, *et al.*, 2016). Prior to these events, seismic activity had been low since 1905, when the first seismic station was installed in South Korea.

However, historical records document high seismic activity in the Gyeongju region in the fifteenth to eighteenth centuries (Kim, Rhie, *et al.*, 2016). At least 10 earthquakes of modified Mercalli intensity (MMI) ≥ VIII are considered to have occurred in Gyeongju (Lee and Jin, 1991). A major earthquake (and possibly the largest-magnitude event in the region over the past 2000 years; Lee and Jin, 1991) occurred in 779, claiming the lives of at least 100 people, according to *Samguksagi*, the oldest surviving chronicle of Korean history.

After the September 2016 earthquakes, residents in Gyeongju and nearby regions continued to experience small-to-moderate tremors, not knowing when they would cease. The Korea Meteorological Administration (KMA) determines the location and size of all earthquakes that occur on the Korean Peninsula and its surrounding regions and disseminates this information to national and international agencies, key relevant facilities, and the general public. However, it does not provide aftershock forecasts for significant earthquakes in Korea, whereas the U.S. Geological Survey (USGS) releases aftershock forecasts following large global earthquakes on an *ad hoc* basis (Page *et al.*, 2016). For example, the USGS issued a series of aftershock forecasts following the $M_w$ 7.8 Gorkha, Nepal, earthquake on 25 April 2015. The regional earthquake catalog provided by the KMA reported that, after the origin time of the $M_L$ 5.8 earthquake, 76 aftershocks with an $M_L$

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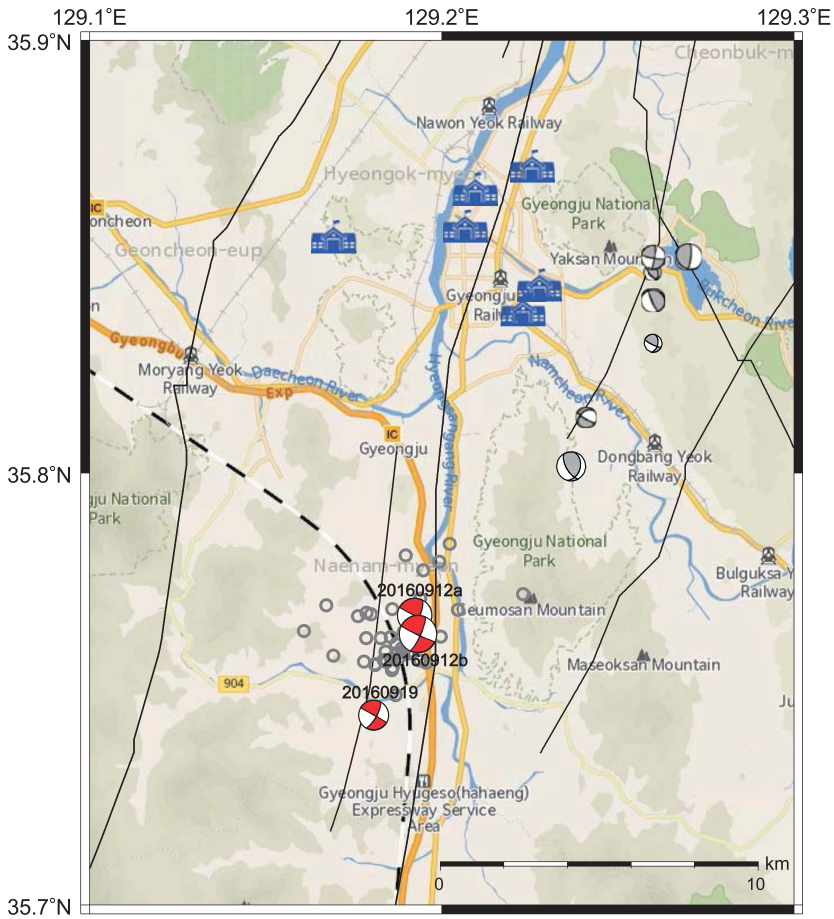



▲ **Figure 1.** Map showing the location of exam centers in Gyeongju, the 2016 Gyeongju earthquakes, and previous seismic events. Thin black lines denote lineaments and faults. Red focal mechanisms with a date show the source mechanisms of the 2016 Gyeongju events (20160912a for an $M_L$ 5.1 earthquake, 20160912b for an $M_L$ 5.8 earthquake, and 20160919 for an $M_L$ 4.5 earthquake) (Kim, Rhie, *et al.*, 2016). Gray focal mechanisms indicate past earthquakes in the region (Chung and Kim, 2000; Jo and Baag, 2003; Park *et al.*, 2007; Chang *et al.*, 2010). Circles mark the locations of aftershock events. The background image is from Google Maps.

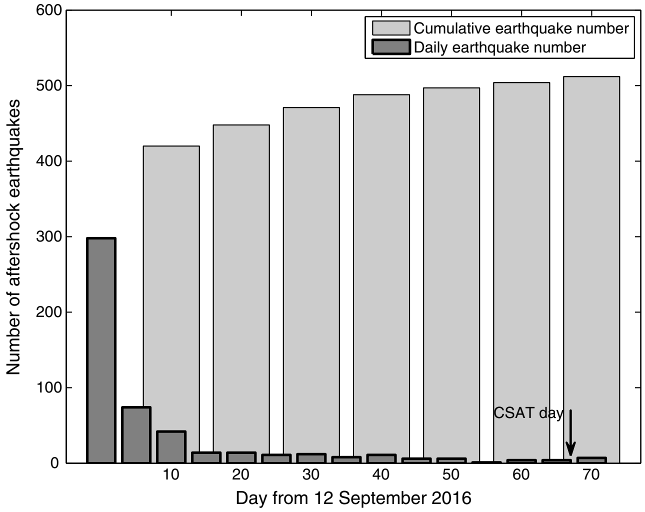
greater than 1.5 occurred on 12 September 2016. The total number of aftershocks had exceeded 500 by early November (Fig. 2). Accordingly, there was growing concern about aftershocks in Gyeongju on the day of the national college entrance examination (the College Scholastic Ability Test [CSAT]; *Suneung* in Korean).

The CSAT is an important event for high-school students, parents, and educators in South Korea because the results are the determining factor in college admission, and the exam is offered only once a year in November. Some 600,000 college applicants took the exam on 17 November 2016. On the day of the CSAT, there is increased use of public transportation services, such as buses and metro trains; public organizations adjust their work hours (the starting time is delayed by 1 hr to 10 a.m.); and the stock market opens 1 hr late. Even takeoff and landing of aircraft (except for emergencies) are banned for a period of 25 min during the listening comprehension section of the English exam.

Because of nationwide concern about earthquakes in Gyeongju, the Korean Ministry of Education (KME) established the Earthquake Preparedness Advisory Committee, charged with developing a response plan for possible earthquakes in Gyeongju on the day of the CSAT, aiming to prevent any interruptions to the exam. The committee has published an onsite earthquake drill manual (Table 1; also see Ⓔ electronic supplement to this article), which guides examination invigilators and exam candidates in how to immediately respond to sudden ground motions and earthquake-related damage, such as cracks in ceilings and walls, and doors and windows that will not open or close. Efforts to develop the manual were featured in the media on the day of the most recent CSAT. Psychologists were stationed at each exam center (high school) in Gyeongju so that, in the event of an earthquake, they could counsel any candidates experiencing anxiety. There were also designated surveyors who inspected the conditions of the buildings at each site. Here, we describe the onsite manual, which outlines three steps for invigilators and exam candidates to follow in the event of an earthquake on the day of the CSAT, as well as describe the temporary microelectromechanical system (MEMS) network developed by seismologists to monitor seismic activities from 18 October to 18 November 2016 at the CSAT exam centers.

## ONSITE EARTHQUAKE DRILL MANUAL

The earthquake early warning (EEW) system of the KMA, which was established in 2005, provides the magnitude, origin time, and epicenter of any earthquake exceeding $M_L$ 5.0 within ~30 s after detecting a $P$ wave from 6 or more of the ~150 seismometers in the country. The accuracy of the epicenter location is within ±10 km, and that of the $M_L$ is ±0.5. On 12 September 2016, the EEW provided such information for the $M_L$ 5.8 earthquake 26 s after its occurrence. However, this would not be particularly useful on the day of the CSAT if the epicenter is near the exam centers. The distance between the exam centers in Gyeongju and the 12 September $M_L$ 5.8 earthquake was only 10–13 km (Fig. 1). Furthermore, depending on the epicenter's vicinity and other factors, such as the conditions of exam centers and the seismic resistance of buildings, people at different centers might respond differently to sudden ground shaking. There were 2600 exam candidates in Gyeongju on 17 November 2016.




▲ **Figure 2.** Histogram of the number of detected earthquakes since the $M_L$ 5.8 earthquake. The catalog is provided by the Korea Meteorological Administration and includes aftershock events with a local magnitude ≥1.5.

Following the September 2016 earthquakes, the advisory committee mentioned above, consisting of seismologists and earthquake engineers, produced the aforementioned earthquake response manual. It has a concise format to minimize any confusion that may arise during an earthquake (Table 1; also see Ⓔ electronic supplement). Invigilators are trained to immediately follow the guidelines, whether or not they receive notification from the KMA. The KME distributed the manual to all 85 exam districts, as well as to the general public on 8 November 2016. On the day of the CSAT, officials from the KME were placed at the National Earthquake and Volcano Center at the KMA to provide information on any earthquake and the levels of response (Table 1; also see Ⓔ electronic supplement) to any such event. In addition, all exam candidates were notified about the manual and informed that they would follow it in the event of an earthquake.

**Table 1**
**Earthquake Response Guidelines in the Event of an Earthquake on the Day of the College Scholastic Ability Test in South Korea**

| Response Level | Response Guidelines |
|---|---|
| Level I | In the event of a minor tremor, invigilators do not stop the exam and continue with normal procedures. |
| | In certain cases, invigilators can stop the exam temporarily and guide the exam candidates to take cover under their desks. |
| Level II | In cases where the tremor is felt but the exam candidates' safety is not compromised, the candidates may temporarily take shelter under their desks then restart the exam once the tremor has stopped. |
| | In cases where broken glass, fallen materials from the ceiling, damaged lights, cracks on walls, and microcracks on columns are witnessed, the room may be evacuated, depending on the circumstances of the exam candidates and/or facility. |
| Level III | In cases where tremors are strong and the exam candidates' safety may be compromised due to structural damage, exam candidates are directed to evacuate the building once the tremors have ended. |
| | If damage to exam site facilities is minor and exam candidates are unaffected, the exam can be resumed. |

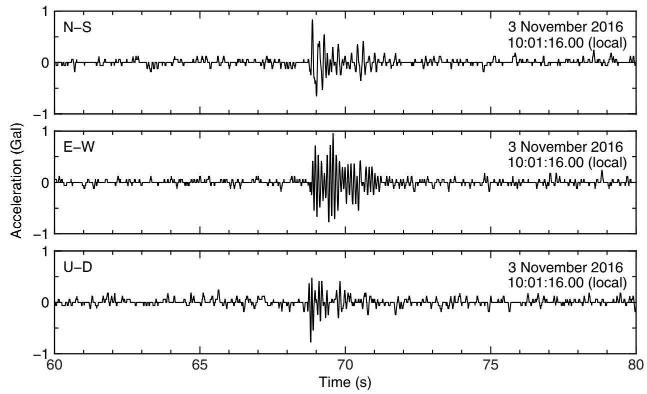
## MEMS-BASED REAL-TIME WARNING SYSTEM AT SIX HIGH SCHOOLS IN GYEONGJU

In addition to the manual, a real-time warning system is needed. We employed a real-time warning system with MEMS for the first time in Gyeongju, encouraged by recent success using an MEMS-sensor network for monitoring earthquakes and issuing early warnings in Taiwan (*P*-alert, *P*-wave Seismic Alarm System; Wu *et al.*, 2013, and references therein).

Each *P*-alert device is equipped with a three-component accelerometer with 16-bit resolution and a dynamic range of 0.1–1960 Gal. The signal from each field station is processed to detect *P*-wave arrivals and is continuously double-integrated into a displacement signal to calculate the vertical peak amplitude of displacement from the *P* waves (Wu and Kanamori, 2005). Once the captured signal exceeds the predefined threshold of 25 Gal, the *P*-alert device sends an alert with a warning signal.

The real-time warning system was established at six exam centers (all were high schools where power and internet connections were available; Fig. 1) on 18 October 2016 to monitor seismic activity. These schools were all north of the 2016 September events (only ~10 km from the mainshock location) (Fig. 1). Each school was equipped with an MEMS sensor on each floor and one monitoring system. On 7 November 2016, the *P*-alert group from Taiwan visited Gyeongju to install sensors at one of the sites. Data were transferred continuously to a central processing station located in the KME building in Gyeongju. Several aftershocks were recorded by the *P*-alert system. Figure 3 shows strong-motion data from one of the *P*-alert stations, located 11 km from the epicenter of the Gyeongju earthquakes (Fig. 1).

On 17 November 2016 (the day of the CSAT), two university students (from Pukyong National University and Seoul National University) were assigned to each high-school exam center to monitor the real-time seismic signals recorded by the MEMS sensors. Three seismologists were present at the central processing station to monitor all signals from the six sites. No earthquake activity was recorded by the MEMS on that day.




▲ **Figure 3.** Seismic waveform recorded at one high-school site by *P*-alert on 3 November 2016.

The monitoring officially started at 8:40 a.m. and ended at either 5:40 p.m. or 10:00 p.m. (the latter time being for exam candidates with disabilities).

Overall, the system was considered a success by both local residents in Gyeongju and the KME. Although there is still room to improve seismic activity monitoring in Gyeongju using MEMS, it can be applied to other intraplate areas where there is a record of historical earthquakes (despite low-seismic activity during the modern monitoring period) or areas where aftershocks are likely on important days, such as the day of the CSAT in South Korea.

## CONCLUDING REMARKS

The 2016 Gyeongju earthquakes (including the $M_L$ 5.8 event, the largest earthquake in Korea since 1978) have changed perceptions of earthquakes among the Korean public. These events have served as forceful reminders that earthquakes have occurred in the past (based on Korean historical records) and can strike the region again at any time. The onsite earthquake drill manual was established to provide a rapid and effective response to possible earthquakes on the day of the CSAT. In addition, a temporary MEMS network was operated at six high-school exam centers in Gyeongju to monitor seismic activity from 18 October to 18 November 2016 and to effectively inform invigilators and exam candidates how to respond to an earthquake on the day of the CSAT (17 November 2016). The MEMS network detected several aftershocks during the one-month operating period but no seismic events on exam day. Our system may be a model for future earthquake monitoring systems in South Korea. It can be used in other intraplate regions and regions where aftershocks are likely.

## DATA AND RESOURCES

The data recorded by the microelectromechanical system (MEMS) sensors used in this study are available from the authors upon request. The regional earthquake catalog was provided by the Korea Meteorological Administration (KMA). Plots were generated using Generic Mapping Tools, v.5.3.0 (gmt.soest.hawaii.edu, last accessed May 2017; Wessel *et al.*, 2013).

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