Groundwater level changes on Jeju Island associated with the Kumamoto and Gyeongju earthquakes

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ABSTRACT
Groundwater levels on the monitoring wells on Jeju Island were monitored, which were caused by the M 5.4 earthquake in Gyeongju City area, South Korea, at 11:32:54 on 12 September 2016 (UTC time) and the Kumamoto earthquake, Kyushu, Japan, at 16:25:06 on 16 April 2016 (UTC time). The groundwater levels changed after 2–3 min by the generation of the Gyeongju and Kumamoto earthquakes and exhibited spikes or oscillations depending on the magnitude of the earthquakes. The groundwater level change caused by the Gyeongju earthquake (M 5.4) was mostly larger than that caused by the Kumamoto earthquake (M 5.4). The reason is explained by that the energy of the Kumamoto earthquake with high attenuation could not be effectively transmitted to Jeju Island since the earthquake took place in low Q region whereas a higher energy of the Gyeongju earthquake with low attenuation arrived on Jeju Island because the earthquake occurred in the south-eastern part of the Korean peninsula belonging to the high Q crust. Besides the seismic energy from the Kumamoto earthquake was scattered and reflected on the Tsushima-Goto fault zone between Kyushu and the Korean peninsula, with a strike in the ENE-WSW direction that elongates to the east of Jeju Island.

1. Introduction
A magnitude (M) 5.4 earthquake that occurred in Gyeongju was recorded as the largest earthquake in South Korea since the beginning of instrumental earthquake observation in 1978 (Kim, Rhie, et al. 2016). Over 500 times aftershocks occurred and are still underway (Figure 1). The Gyeongju earthquake took place inside the Yangsan fault zone, which is one of the well-known dextral strike-slip faults in Korean peninsula, with a width of a few hundred meters to 2 km and a length of ~200 km from Yeonghwa in the north to the western part of Busan City in the south. The strike of the fault zone generally extends in the direction of NNE in the south and N-S in the north, with steep dip angles. The Yangsan fault initially moved 45 Ma ago (Eocene) based on radiometric data (Chang et al. 1990) and activated during 42–14 Ma ago (Eocene-Miocene) in relation to the opening of the East Sea (Jolivet et al. 1991).

Earthquakes generate static stress and dynamic stress (or seismic waves), producing hydrological and hydrogeological changes (Rojstaczer et al. 1995; Roeloffs et al. 2003). Stress changes in rocks
caused by an earthquake produce strains that cause fluid pressure changes, which again change the hydrogeological properties such as groundwater level and hydraulic conductivity (Manga and Wang 2007). Seismic waves eliminate micro-cracks and micro-particles in fracture zones and generate chemical changes in initial groundwater by the inflow of new groundwater, the acceleration of water–rock reaction, and fluid-source switching (Skelton et al. 2014). Dynamic strain caused by an earthquake (or seismic wave) can affect groundwater level several thousand kilometres away, and the groundwater level shows a fluctuation pattern similar to the seismic wave along the compression.

Figure 1. The Kumamoto and Gyeongju earthquake epicentres (upper map) with spatial distribution groundwater monitoring wells and changes of groundwater level on Jeju Island (lower map).
and expansion of the seismic wave (Brodsky et al. 2003; Wang et al. 2009; He, Fan, et al. 2016). Besides, the change of groundwater level associated with the Wenchuan earthquake in 2008 was analysed as computing earth tidal and atmospheric pressure coefficients by means of regression methods (He, Singh, et al. 2016).

This study examined the changes in groundwater level on Jeju Volcanic Island caused by the Kumamoto earthquake in Japan: 06, on 16 April 2016 (local time) and the M 5.4 Gyeongju earthquake in Korea on 12 September 2016 (local time).

2. Hydrogeology and monitoring earthquake

Jeju Island, about 140 km south of the Korean peninsula, with a total area of 1828 km², is geographically located west of Japan. The island is a dormant shield volcano with one central mountain peak, Mt. Halla, rising to an elevation of 1950 m (Figure 1). The stratigraphy of the island can be categorized into basement rocks (granite and welded tuff), U-formations (UF, unconsolidated sediments), Seogwipo formations (SGF, conglomeratic sandstone, sandstone, sandy mudstone, and mudstone with abundant bio-clastic shells), and repeated basaltic and trachytic lavas (Yoon 1997).

The seven groundwater monitoring wells have been in operation since 2010. The monitoring system comprises wells from 7.5 to 176.1 m in elevation, from 130 to 323 m in well depth, and from 6.4 to 175.2 m in depth-to-water (DTW). Monitoring wells of the study area were mostly drilled to UF (unconsolidated sediments). Around the monitoring wells, various volcanic units (clinker, scoria, sediments, pyroclastites, hyaloclastites, etc.) exist between volcanic lavas. Accordingly, the groundwater flow is complicated due to various hydrogeological factors (Figure 2).

Figure 2. Geologic logs of the observation wells. The depth of the groundwater level in the observation wells is mostly similar to the sea level. Each observation well was formed by continuous accumulation of lava flows.
The groundwater levels on the monitoring wells are automatically monitored every minute. The raw groundwater levels were corrected for barometric pressure effect, using atmospheric pressure sensor simultaneously with the pressure transducers. The residual groundwater level was obtained by removing tidal effect through ocean tidal prediction and T_TIDE MATLAB code (Pawlowicz et al. 2002; http://www.iamg.org/CG-Editor/index.htm or http://www.ocgy.ubc.ca/~rich). Finally, the filtered groundwater levels were obtained by having removed long-term tendency using modified moving average method:

\[
X_t^* = X_t - \frac{X_{t-n} + \ldots + X_t + \ldots + X_{t+n}}{2n + 1}
\]

where \(X_t^*\) is the filtered groundwater level, \(X_t\) is the raw groundwater level corrected for atmospheric pressure, and \(n\) is the number of samples in the moving average before and after \(X_t\). In this study, changes in groundwater level caused by earthquakes were evaluated using \(n = 2\) in Equation (1).

3. Results

3.1. Groundwater level change caused by the Kumamoto earthquakes

An earthquake of M 7.0 occurred in Kumamoto prefecture, Kyushu, Japan, at 16:25:06, 15 April 2016 at UTC time (Uchide et al. 2016). Three foreshocks (M 6.2, M 5.4, and M 6.0) occurred in the Kumamoto area two days before the M 7.0 earthquake and many aftershocks have occurred such as the M 5.4 aftershock at local time 03:03:10, on 16 April 2016 (Table 1, Figure 1).

DTW was obtained as correcting raw groundwater level by the atmospheric pressure at the SG1 well from 7 to 24 April 2016. The residual groundwater level was obtained by removing tidal effect from the DTW, and then the filtered water level (FWL) was obtained by eliminating long-term tendency using the modified moving average (Equation 1), as shown in Figure 3. The FWL reacted 2 min following the initiation of the M 7.0 Kumamoto earthquake at a distance of \(\sim 390\) km from the epicentre. Most changes in the groundwater level due to the Kumamoto continuous earthquake at the monitoring wells are of the oscillation type (Brodsky et al. 2003, Figure 4).

The average groundwater level changes by the Kumamoto earthquakes were 1.4 cm for the M 5.4 foreshock (10 km depth), 0.7 cm for the M 5.4 aftershock (4.4 km depth), 1.65 cm for M 6.0, and 3.5 cm for M 6.2, with an average water level change width of 12.5 cm caused by the M 7.0 main earthquake (Table 2, Figure 5). These changes in groundwater level are proportional to the magnitudes of the Kumamoto earthquakes.

3.2. Groundwater level change caused by the Gyeongju M 5.4 earthquake

An M 4.9 earthquake at 10:44:32 UTC time on 12 September 2016, followed by the M 5.4 earthquake at 20:32:54 local time, occurred in Gyeongju City, South Korea (Table 1, Figure 1). The M 5.4

| Earthquake        | Magnitude (M) \(^{a}\) | Depth (km) | Date (local time) | Date (UTC) |
|-------------------|-----------------------|------------|-------------------|------------|
| Kumamoto Foreshock| 6.2                   | 9.0        | 14 April 2016 21:26:35 | 14 April 2016 12:26:35 |
|                   | 5.4                   | 10.0       | 14 April 2016 22:07:35 | 14 April 2016 13:07:35 |
|                   | 6.0                   | 8.0        | 15 April 2016 00:03:47 | 14 April 2016 15:03:47 |
| Main earthquake   | 7.0                   | 10.0       | 16 April 2016 01:25:06 | 15 April 2016 16:25:06 |
| Aftershock        | 5.4                   | 4.4        | 16 April 2016 03:03:10 | 15 April 2016 18:03:10 |
| Gyeongju Main earthquake | 5.4           | 13.0       | 12 September 2016 20:32:55 | 12 September 2016 11:32:55 |

Note: UTC stands for Universal Time Coordinated.  
\(^{a}\) The magnitudes were presented by the United States Geological Survey.
Figure 3. Changes of groundwater level related to the successive Kumamoto earthquakes at well SG1 from 7 to 24 April 2016. The DTW (depth-to-water) means the corrected groundwater level for the atmospheric pressure. The residual groundwater level series mean the result by having removed the tidal effect. The FWL (filtered water level) means the level having removed long-term tendency by the modified moving average method.
The water level change caused by the Gyeongju M 5.4 earthquake in Jeju Island was mostly larger than that caused by the Kumamoto M 5.4 earthquakes. This phenomenon is explained by that the monitoring wells were greatly subjected by tectonic setting more than local hydrogeological
response. In fact, the lower crust of the Japanese island arc is the low Q subduction zone while the Korean peninsula is composed of the Precambrian massif of high Q (Komatsu et al. 2017; Wang et al. 2017). Since earthquake energy is highly attenuated in low Q region, the energy of the Kumamoto earthquake could not effectively transmit to Jeju Island. On the other hand, the earthquake energy is thought to have been effectively detected on Jeju Island because the south-east part of the Korean peninsula where the Gyeongju earthquake occurred is composed of the high Q crust. Also, the seismic energy from the Kumamoto earthquake was scattered and reflected on the large fault zone between Kyushu and the Korean peninsula, the Tsushima-Goto fault zone with a strike in the ENE–WSW direction that elongates to the east of Jeju Island (Kim, Baek, et al. 2016). Additionally,
the local hydrogeological response may have induced different water level changes by the Kumamoto M 5.4 and the Gyeongju M 5.4. Resultantly, the groundwater level change by the earthquakes in the study area is more significantly governed by tectonic setting than local hydrogeology around the monitoring wells. Besides, the groundwater level responses displayed depending on the magnitude of the earthquakes.

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