Spatial and temporal influence of rainfall on crustal pore pressure changes based on seismic velocity monitoring

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Abstract

Crustal pore pressure, which controls the activities of earthquakes and volcanoes, varies in response to rainfall. The status of pore pressure can be inferred from observed changes in seismic velocity. This study investigated the response of crustal pore pressure to rainfall in southwestern Japan based on time series of seismic velocity derived from ambient noise seismic interferometry. Considering the area heterogeneity, rainfall and seismic velocity obtained at each location were directly compared. We used a band-pass filter to distinguish the rainfall variability from sea level and atmospheric pressure, and then calculated the cross-correlation between rainfall and variations in S-wave velocity (Vs). A strong and mostly negative correlation between rainfall and Vs changes indicates variations in pore pressure (affecting Vs) in the deep formation due to groundwater level fluctuation. The results differ in each location, where most of the observation stations with clear negative cross-correlations were located in areas of granite. On the other hand, we could not observe clear correlations in steep mountain area, maybe because water flows through river without percolation. This finding suggests that geographical features contribute to the effect of rainfall in deep formation pore pressure. The time lag between rainfall and Vs variation constrains the permeability of the near-surface lithology, and hence the mechanism of infiltration, through the relationship of permeability to percolation rate. These analyses explain how fluctuations in the water table cause variations in pore pressure beneath confined formations with low permeability. In areas with high permeability, water percolates deeper and with longer time lags, demonstrating that lithology

contributes to pore pressure changes associated with rainfall. By linking the variations in seismic velocity and crustal pore pressure spatially, this study shows that seismic monitoring may be useful in evaluating earthquake triggering processes or volcanic activity.

Keywords: seismic velocity variation, precipitation, groundwater level, pore pressure, near-surface lithology, monitoring

1. Introduction

Pore pressure has a key role in the occurrence of earthquakes and the activity of volcanoes (Albino et al. 2018; Ellsworth 2013). Under conditions of critical stress and high pore pressure, small changes in pore pressure can trigger seismicity. Therefore, monitoring the status of pore pressure is a vital part of evaluating dynamic crustal activities. Because pore pressure affects seismic velocity, the state of pore pressure can be assessed by seismic velocity monitoring (Chaves and Schwartz 2016; Ikeda and Tsuji 2018; Nimiya et al. 2017; Rivet et al. 2015; Tsuji et al. 2008; Wang et al. 2017).

In field observations, changes in seismic velocity can be induced by various environmental perturbations (Wang et al. 2017) because seismic velocity is sensitive to variations in stress and water saturation (Grêt et al. 2006). Such perturbations include ocean tides and solid earth tides (Sens-Schönfelder and Eulenfeld 2019), and seismic velocity in coastal locations is sensitive to tidal ocean loading (Yamamura et al. 2003).

The influence of the ocean is considered in studies of ambient seismic noise (Hillers et al. 2012). Atmospheric pressure influences seismic velocity over large regions (Niu et al. 2008; Silver et al. 2007), and atmospheric temperature likewise generates seasonal variations in seismic velocity through changes in crustal strain (Ben-Zion and Leary 1986; Berger 1975; Prawirodirdjo et al. 2006), especially in arid regions (Hillers et al. 2015; Richter et al. 2014).

Rainfall and snow are well-known hydrological perturbations by which pore pressure induces seismic velocity changes. For example, the interaction of hydrothermal systems and surface loading from precipitation can lead to seismic velocity reductions (Taira and Brenguier 2016). Snow decreases seismic velocity through increased pore pressure resulting from ice infiltration (Mordret et al. 2016) whereas frost increases seismic velocity at shallow depths by increasing the shear modulus of near-surface materials (Gassenmeier et al. 2015; Ikeda et al. 2018). Rainfall decreases seismic velocity through changes in effective stress (Nakata and Snieder 2012; Miao et al. 2018) and groundwater level (Gassenmeier et al. 2015; Meier et al. 2010; Sens-Schönfelder and Wegler 2006; Tsai 2011). Rainfall triggers seismicity through pore pressure changes caused by crustal loading and unloading (Bettinelli et al. 2008) and pore pressure diffusion (Hainzl et al. 2006; Kraft et al. 2006). Because percolation of water through porous rock may be a major influence in pore pressure changes, we investigated the spatial and temporal relationships between seismic velocity changes and rainfall in a well-instrumented region of Japan.

Crustal deformation in Japan can be evaluated with abundant data from seismic and geodetic observation stations. The crust is affected by perturbations from volcanic and seismic activities (Ueda et al. 2013) and surface loads (Heki 2004), including non-tidal ocean loading (Sato et al. 2001). Recent studies have shown that observed seismic velocity changes reflect volcanic activity (Takano et al. 2017; Yukutake et al. 2016) and earthquake activity (Nimiya et al. 2017). Furthermore, seasonal spatial patterns of seismic velocity change throughout Japan can be explained by seasonal variations in rainfall, snow, and sea level (Wang et al. 2017).

This study relied on records of seismic velocity estimated from ambient noise monitoring in the Chugoku and Shikoku regions of southwest Japan. This area receives high rainfall from the summer monsoon (Aizen et al. 2001) and is relatively unaffected by volcanic activity and snowfall, although we still found it necessary to distinguish rainfall perturbations from sea-level changes. We sought to identify stations at which seismic velocity changes are strongly associated with rainfall by calculating the cross-correlation between precipitation and seismic velocity changes (e.g., Bièvre et al. 2018). The time delay between precipitation events and velocity changes helps constrain near-surface conditions that could be related to lithology-related permeability. From these results we sought to estimate the contribution of lithology to the crustal pore pressure changes associated with rainfall.

Well-quantified monitoring results may be useful information for evaluation of earthquake triggering mechanisms. In CO_2 geological storage projects and geothermal developments, furthermore, earthquakes induced by fluid injection are a notable public concern. Accurate knowledge of natural pore pressure variations can help in distinguishing whether an earthquake is a natural event triggered by environmental variations or remote earthquakes or an induced event triggered by fluid management.

2. Data preparation

The Chugoku and Shikoku region is located in southwest Japan (Fig. 1). The Chugoku region is characterized by mountainous topography with gently sloping, while the slopes of the mountains in Shikoku island are mostly steep (Fig. 1b). Figure 1c shows the rock types of the Chugoku and Shikoku region from the geological map (Geological Survey of Japan AIST, 2015). The Chugoku region is abundant with Cretaceous volcanic and granitic rocks, along with Paleocene to Early Eocene granitic rocks and Late Pleistocene to Holocene sediments at the northern Chugoku. As for the Shikoku region, Late Cretaceous granite can be found in the northern Shikoku, with Sanbagawa metamorphic rocks are widely distributed across the centre of the Shikoku. Sandstone of Cretaceous – Oligocene accretionary complexes is mainly located in the southern Shikoku island (steep mountain).

We collected data on seismic velocity changes, precipitation, atmospheric pressure, and sea-level change for the period 2015–2017 in the Chugoku and Shikoku regions. The meteorological data was obtained from the Japan Meteorological Agency (JMA) and we used seismic data from 98 seismometers operated by the National Research Institute for Earth Science and Disaster Resilience (NIED). We estimated seismic velocity changes on the basis of ambient-noise coda wave interferometry (Hutapea et al. 2020; Nimiya et al. 2017).

To obtain virtual seismograms propagating between pairs of stations, the power-normalized cross-correlation (cross-coherence) was applied in the frequency domain between seismometers at sites A and B (e.g., Nakata et al. 2011, 2015) by

$$CC_{\mathrm{AB}}(f) = \frac{F_{\mathrm{A}}(f)\, F_{\mathrm{B}}^{*}(f)}{|F_{\mathrm{A}}(f)||F_{\mathrm{B}}(f)|}, \quad (1)$$

where F_A and F_B are the seismic waveforms in the frequency domain (f) recorded at seismometers A and B and the asterisk (*) denotes a complex conjugate.

Changes in seismic velocity between pairs of seismometers were estimated by the stretching interpolation method (Hadziioannou et al. 2009; Hutapea et al. 2020; Minato et al. 2012; Nimiya et al. 2017). This method elongates the time axis and looks for the trace most similar to the reference trace by means of the correlation coefficient $CC(\varepsilon)$ between the reference trace and the current trace:

$$CC(\varepsilon)=\frac{\int f_{\varepsilon}^{cur}(t) f^{ref}(t)dt}{(\int (f_{\varepsilon}^{cur}(t))^2 dt \int (f^{ref}(t))^2 dt)^{1/2}}, \quad (2)$$

$$f_{\varepsilon}^{cur}(t) = f^{cur}(t(1+\varepsilon)), \quad (3)$$

where f^{ref} is the reference trace, f^{cur} is the current trace, and t is time. The ε term is the stretching parameter associated with relative time-shift ($\Delta t/t$) and velocity change ($\Delta v/v$) from

$$\varepsilon = \Delta t/t = -(\Delta v/v). \tag{4}$$

Although we used three years of seismic data, seismic velocity change was estimated independently for each individual year by defining the 1-year stack of the coda of cross-correlation data as the reference trace f^{ref} and the 10-day stack of the coda of cross-correlation data as the current trace f^{cur}. Because we focused only on comparing the short-term variability of seismic velocity with short-period rainfall, we could combine the estimated seismic velocity changes for each year into a 3-year record. To stabilize the monitoring results over the 3-year term, we used the Sliding Reference Method to define the reference trace (see Hutapea et al. 2020). The daily velocity change was considered to represent the velocity change in the middle of the 10-day window of the current trace. The frequency range of the seismic data was restricted to 0.1 to 0.9 Hz, which reflects the sensitivity of surface waves to S-wave velocity between depths of 0 and 8 km (e.g., Nimiya et al. 2017). To obtain seismic velocity changes for each station (Fig. 1d), we applied spatial averaging within a radius of 40 km.

To obtain precipitation data for each seismic station, we averaged the data from all precipitation gauges within a distance of less than 40 km from the seismic stations (Fig.

1e). Atmospheric pressure and sea-level changes were obtained from the tidal gauge closest to the seismic station (Fig. 1f) and the daily sea-level change was estimated by averaging data for the most recent 24-h period.

3. Correlation analysis of band-pass filtered data

We investigated the power spectra of seismic velocity changes, precipitation, sea-level changes, and atmospheric pressure changes (additional file 1: Fig S1a). Whereas the power spectrum of seismic velocity changes decreased toward a frequency of 0.1 cycle/day, those of precipitation, sea-level, and atmospheric pressure change showed similar peaks at 0.0018–0.0036 cycle/day, a frequency band close to a 365-day or one year (additional file 1: Fig. S1b). The similarity of these three peaks meant that the long-term estimated seismic velocity changes could be affected not only by precipitation, but also by sea-level and atmospheric pressure changes. We excluded frequencies below 0.0036 cycle/day to remove the annual seasonal influence of sea-level and atmospheric pressure changes, and we excluded frequencies above 0.05 cycle/day to eliminate the neap and spring tides of sea-level change and the decreasing spectrum of seismic velocity change. We then searched for the frequency band where precipitation could best be distinguished from sea-level change and atmospheric pressure change, as indicated by weak correlations between precipitation and the other two variables. We applied a band-pass filter for periods between 20 and 137 days (0.05 to 0.0073 cycle/day; additional file 1: Fig. S1c and S1d) and sought minima in the correlation coefficients between precipitation and sea-level change and between precipitation and atmospheric pressure change, based on the data for all stations. The correlation coefficients were based on the Pearson correlation

$$\rho(A,B) = \frac{cov(A,B)}{\sigma A\ \sigma B}, \tag{5}$$

where $cov(A,B)$ is the covariance of time series A and B and σA and σB are the standard deviations of time series A and B.

Figure 2 shows an example of the unfiltered and filtered data for one station. Because the Pearson correlation value between rainfall and sea level is very small (Fig. 2e), we can use band-pass filtering to separate the imprint of precipitation and sea level. At the selected period band, variations in precipitation are likely to dominate seismic velocity change, considering that the dominant annual cycles of sea level and atmospheric pressure have already been removed (additional file 1: Fig S1). The correlation coefficients between band-pass filtered precipitation and sea-level and atmospheric pressure change, respectively, are shown in Fig. 3 for all stations. The small correlation coefficients indicate that rainfall is more readily distinguishable from sea-level and atmospheric pressure changes.

To further analyse the dependence of seismic velocity changes on rainfall, we applied various time shifts to the rainfall record and evaluated the resulting cross-correlations with seismic velocity changes, as depicted in Fig. 4. Under the assumption that seismic velocity changes are triggered by precipitation after a time lag, we restricted ourselves to positive time lags (i.e., velocity variation after rain precipitation) and determined the time shift that produced the largest Pearson correlation coefficient.

Figure 5 shows an example of the results of our evaluation at a station near the middle of the study area, starting with a comparison of precipitation and seismic velocity without band-pass filtering (Fig. 5a), then after band-pass filtering (Fig. 5b), and then after shifting the precipitation record by 8 days to fit the respective peaks (Fig. 5c). This 8-day time shift raised the correlation coefficient for the three years' data by more than half, although it was still relatively small at –0.33. However, when we restricted the comparison to the rainy season (in this case, June to July of 2016 and 2017), the correlation coefficient became much greater (–0.7).

We observed negative cross-correlation coefficients between rainfall events and seismic velocity changes at most stations (Figs. 6a, 6b); however, some stations had positive correlations (Fig. 6c). The highest absolute value of these correlations, even after applying the optimum time lag, was approximately 0.3 (Fig. 7). This value is not high because several factors may weaken the correlation between seismic velocity changes and rainfall events. For example, random noise in both of the time series and the time windows decreases the coefficient. In the latter case, a short time window for stacking cross-correlations (10 days in this study) was necessary to analyse the short-term seismic velocity changes induced by precipitation. A longer time window would improve the stability of the velocity change estimate, but would reduce its temporal resolution (Hutapea et al. 2020). Another possibility is that an external factor other than precipitation also influences seismic velocity, such as atmospheric pressure, which can exert effects even at seismogenic depths (Niu et al. 2008).

Figure 7a shows the correlation coefficients between rainfall and seismic velocity for all stations, after applying the optimum time lag for each station. Among these stations, 26 had absolute correlation coefficients smaller than 0.1, 35 stations had absolute correlation coefficients of 0.1 to 0.2, and 37 stations had absolute correlation coefficients greater than 0.2. We selected the third group with high coefficient for further analysis because these stations are clustered and information regarding time lag is reliable only if there is a sufficiently strong correlation. Because most of these stations had a negative correlation between precipitation and seismic velocity, we focused on the stations in this group with negative correlations. These selected stations are shown in Fig. 7b, and their respective time lags are shown in Fig. 7c.

4. Discussion

4.1. Mechanism of variations in seismic velocity

Because the seismic velocity in our analysed frequency range reflects the depth range from the surface to 8 km (Nimiya et al. 2017), it is difficult to specify at which depth spatial variations in seismic velocity changes occur. However, crustal vertical stress could be influenced by variations in surface water mass (e.g., snow, soil moisture, and groundwater; van Dam et al. 2001), which have been reported to affect annual variations in a deep confined aquifer through mechanical loading (van der Kamp and Maathuis 1991). This mechanism implies that velocity fluctuations are mainly due to stress changes instead of deep recharge. Several studies have also reported a rainfall loading effect in confined aquifers within a few hundred meters of the surface (Bardsley and Campbell 2000; Sophocleous et al. 2006).

We suggest that groundwater recharge by rainfall is the cause of spatial variations in seismic velocity changes. An increase in groundwater adds pressure (overburden stress) onto the formation below the water table. Under undrained conditions, the increased overburden stress increases pore pressure. The correlation between rainfall and seismic velocity changes is negative if the deeper formation has low permeability and the fluid filling the pore space cannot escape, resulting in higher pore pressure (Fig. 8a). The correlation may be positive if the formation fluid escapes when the vertical stress is increased; The effective stress increases due to vertical overburden (Fig. 8b). The mechanical load exerted by groundwater depends on a considerable amount of rainfall reaching the water table, which is controlled by the lithology above the water table.

To validate this interpretation, we compared the records of rainfall and groundwater level variations. Figure 9 shows the unfiltered records for an example station and the calculated cross-correlation between band-pass filtered precipitation and groundwater level. As shown in Fig. 9c, it takes 5 days for rainfall to recharge groundwater, whereas Fig. 9d shows that rainfall is most strongly correlated with a decrease in seismic velocity 9 days later. The spatial resolutions of rainfall and groundwater clearly differ, as groundwater is controlled mainly by the local lithology; nevertheless, the groundwater level clearly responds directly to precipitation. The small difference in the time lags between Figs. 9c (5 days) and 9d (9 days) supports our interpretation that the increased groundwater load due to recharge by rainfall causes a subsequent decrease in seismic velocity.

4.2 Consideration of near-surface lithology

The seismic velocity change associated with rainfall is presumably related to surface and near-surface conditions, which influence water percolation and modulate the vertical load imposed upon the deep formation by groundwater. Several studies have linked spatial variations in seismic velocity change to groundwater level fluctuations (e.g., Gassenmeier et al. 2015; Sens-Schönfelder and Wegler 2006). The time lag between rainfall events and seismic velocity changes may represent the time needed for percolating rainfall to reach the water table of an unconfined aquifer. Percolation through the unsaturated zone is likely determined by the permeability of the near-surface layers and the surface geologic and geographic conditions at the seismic station. For example, in mountain regions with high permeability, water derived from the surrounding mountains percolates into intermountain basins. The comparison of our result with the geological and topological map of Japan (Figs. 1b, 1c) shows that stations with negative correlations are mostly located in granite areas with gently sloping (Fig. 1b; pink in Fig. 1c). On the other hand, we cannot identify clear negative correlation in sedimentary rock with steep slope area in the southern Shikoku (Fig. 1b; green in Fig. 1c), maybe because water flows through the surface river without percolation into deep formation.

Because the unsaturated zone in humid climates is generally less than 10-m thick (Phillips and Castro 2003), we assumed the unsaturated zone in our humid study area to be shallower than 10 m. Borehole logs from the sites where our seismometers are deployed classify the shallow formation as high-permeability materials, low-permeability materials, and weathered igneous rocks (Obara et al. 2005). Under the assumption that S-wave velocity may be related to permeability, we examined plots of time lag versus S-wave velocity (Fig. 10) to evaluate the relationship between lithology and time lag. Although the relationships are unclear, we identified some features for each formation.

Clay and hard rocks (e.g., schist, slate, and intact granite) are grouped as low-permeability materials. These materials show a negative trend between S-wave velocity and time lag (Fig. 10a), such that higher S-wave velocity indicates more compact, lower permeability material. The association of decreasing time lag with increasing S-wave velocity may suggest that the depth of the saturated zone is smaller in area with more-compact material.

High-permeability material such as sandy soil, silt, and gravel shows a positive trend in which the time lag increases with increasing S-wave velocity (Fig. 10b). Because seismic velocity varies inversely with porosity, this relationship implies that percolation could be faster in more porous materials and slower where porosity is lower.

In weathered igneous rocks, which consist mostly of granite, the time lag and S-wave velocity show a relatively negative trend (Fig. 10c). This trend may be connected to the spatial concentration of fractures in these rocks. Although fractures in crystalline rocks generally decrease with increasing depth, at depths shallower than 10 m in plutonic and crystalline metamorphic rocks, fractures are the primary determinant of permeability (Freeze and Cherry 1979). As is the case for low-permeability material, the decreasing time lag with increasing S-wave velocity implies that the water table is shallower in the less-fractured igneous rocks whereas brittle, more-fractured igneous rocks allow rainfall to percolate to greater depths, resulting in longer lag times for water to reach the saturated zone.

We conclude that local lithology, both above the groundwater table and in the deep formation, contributes to the pore pressure changes associated with seasonal rainfall. The interpretations we describe here are simple ones. In real hydrogeological systems, however, there are many other complex mechanisms that affect the time lag (e.g., flow path influenced by geographical features).

5. Conclusion

Our results show that monitoring of seismic velocity changes can be used to evaluate both spatial and temporal changes in pore pressure due to rainfall perturbations. By considering the delay of the rainfall, we obtained a strong relationship between seismic velocity change and rainfall. For rainfall to influence seismic velocity, the near-surface layer must be permeable, allowing rainfall to percolate to the water table. The near-surface layer’s permeability differs depending on location. As rainfall recharges the unconfined aquifer, it increases the mechanical load from the groundwater, causing temporal variations in pore pressure.

The status of pore pressure associated with seasonal rainfall can be evaluated by monitoring seismic velocity. By determining the correlation coefficient between rainfall and velocity changes and the time lag between rainfall and velocity changes, we can assess the influence of rainfall on seismic velocity changes. Our primary conclusions are these: (1) Rainfall causes seasonal variations in seismic velocity through mechanical loading by groundwater. (2) The lithology both above the water table and in the deep formation contributes to crustal pore pressure changes associated with seasonal rainfall. (3) A negative correlation between rainfall and seismic velocity indicates high pore pressures within low-permeability material. (4) Time-lag information represents the rate at which rainfall influences seismic velocity changes, which depends on the permeability of the near-surface layer.

Declarations

Availability of data and materials

Seismic data required to evaluate the conclusions in the paper are available from NIED (http://www.hinet.bosai.go.jp/about_data/?LANG=en). The meteorological data were obtained from JMA (https://www.jma.go.jp/jma/index.html).

Competing interests

The authors declare that they have no competing interest.

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Authors' contributions

RDA drafted the initial manuscript. TT proposed this study. TT, RS, and TI suggested the method for the interpretation, and revised the manuscript. All authors read and approved the final manuscript.

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Figures Legends

Figure 1. (a) Location map of Japan showing the study area in the Chugoku-Shikoku region. (b) Topological and (c) geological maps of Chugoku and Shikoku region (modified from Geological Survey of Japan AIST, 2015). The dots on the geological map represent the location of seismic stations. The colour of dots in panels (b) and (c) indicates the time lag shown in Fig7c. Maps of the study area showing (d) seismic stations, (e) precipitation gauges, and (f) ocean tidal stations, pressure gauges, and groundwater level (GWL) stations. The red circle in (d-f) indicates the seismic station for which the correlations in Figs. 2 and 5 are computed. The yellow circles in (d) represent the station pairs and (e) precipitation gauges within 40 km from the selected seismic station, respectively.

Figure 2. Example of band-pass filtered (a) seismic velocity changes, (b) precipitation, (c) sea level, and (d) atmospheric pressure during the study period at the station shown in Fig. 1f. (e,f) Comparisons of precipitation with changes in sea level and atmospheric pressure, respectively, at the station shown in Fig. 1f. Signals are normalized.

Figure 3. Pearson correlation coefficients between band-pass filtered (a) precipitation and sea-level change and (b) precipitation and atmospheric pressure change at stations in the study area.

Figure 4. Schematic figure of cross-correlation analysis between seismic velocity changes (reference) and precipitation (shifted time series): (a) positive time lag with negative correlation and (b) positive time lag with positive correlation. The delay between the peaks of precipitation and seismic velocity change is represented by Δt.

Figure 5. Cross-correlation analysis between seismic velocity changes and precipitation at the seismic station shown as red dots in Fig. 1f: (a) unfiltered signals, (b) band-pass filtered signals (normalized), and (c) band-pass filtered signals with precipitation shifted 8 days later.

Figure 6. (a–c) Cross-correlation between seismic velocity change and precipitation at the stations in the map at left, showing the estimated delay from positive time lag (solid magenta line).

Figure 7. Maps of the study area showing (a) correlation coefficients between seismic velocity change and precipitation at all stations after time shifting, (b) stations in (a) with negative correlation coefficients < –0.2, and (c) time delays at stations in (b). The time lag in panel (c) is also shown in Fig. 1c.

Figure 8. Schematic diagrams showing the mechanisms of changes in crustal pore pressure associated with seasonal rainfall. (a) In low-permeability rocks, cracks open as pore pressure increases with the increasing groundwater load (large black arrow). (b)

In high-permeability rocks, cracks close as fluid escapes in response to the increasing groundwater load (curved blue arrows).

Figure 9. Cross-correlations at the station shown in Fig. 1f: (a) unfiltered precipitation and groundwater level (GWL), (b) band-pass filtered precipitation and GWL, (c) band-pass filtered precipitation and GWL with precipitation shifted earlier by 5 days, and (d) band-pass filtered precipitation and seismic velocity change (normalized) with precipitation shifted earlier by 9 days.

Figure 10. S-wave velocity versus time delays of precipitation in (a) low-permeability materials, (b) high-permeability materials, and (c) weathered igneous rocks.