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Delineation and interpretation of spatial coseismic response of groundwater levels in shallow and deep parts of an alluvial plain to different earthquakes: A case study of the Kumamoto City area, southwest Japan

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ABSTRACT

Coseismic changes in groundwater levels have been investigated throughout the world, but most studies have focused on the effects of one large earthquake. The aim of this study was to elucidate the spatial patterns of level changes in response to several earthquakes, and the relationship of the patterns to shallow and deep groundwater in the same area. We selected the Kumamoto City area in southwest Japan, a region with one of the richest groundwater resources in Japan, as our study site. Data from hourly measurements of groundwater levels in 54 wells were used to characterize the coseismic responses to four earthquakes that occurred in 2000, 2001, 2005, and 2008. Although the distance to the hypocenter (12–2573 km), and seismic energy ($M_w = 5.0–8.0$) of these earthquakes varied, systematic groundwater level changes were observed in the range of 0.01–0.67 m. Spatial patters of the level changes were clarified by interpolating the point data by a spline method. The zones where coseismic rises were observed were generally wider for deep groundwater than for shallow groundwater, probably as a result of an increase in compressive stress. General trends in the changes in groundwater levels, and calculated pressure changes, were clarified to be consistent in the deep groundwater, but the coseismic increases or decreases in compressive stress in the shallow groundwater were variable, depending on the distance to the earthquake epicenter. We developed a conceptual model of the mechanism underlying this phenomenon by assuming permeability enhancement induced by elastic strain and pore-pressure change over the depth range. In addition, the importance of local geology was identified, because levels in the area of Togawa lava (a porous andesite) tended to change more in magnitude, and more quickly, with a shorter recovery time, than levels measured in the area outside the lava.

1. Introduction

Groundwater levels are influenced by barometric pressure, precipitation, earth tide, and earthquakes. The effect of earthquakes has been a focus of research because the correlation between groundwater level fluctuations and earthquakes can contribute to elucidate the signatures of the crustal responses to tectonic deformation (e.g., Davis et al., 2001). Understanding the origin of the correlation can provide new insights into the spatio-temporal variability of hydrological properties and processes at pore to continent scales (Montgomery and Manga, 2003; Wang and Manga, 2010). Moreover, it is significant from a groundwater resource management perspective, because water-level changes can affect water supplies (Chen and Wang, 2009) and decrease water quality by causing water turbid. Groundwater levels respond rapidly to an earthquake, particularly in seismically active areas, and begin to change during ground shaking (coseismic), and continue to change after ground shaking ceases (post-seismic). These immediate and delayed responses are caused by different mechanisms including proximity to the epicenter, geological structure, and hydraulic properties (Montgomery and Manga, 2003). This study focuses on coseismic changes because they are generally much larger than post-seismic changes and easier to identify and characterize.

The coseismic groundwater level changes in wells are typically classified into three types by Roeloffs (1998): step-like change for the near field of epicenter, gradual and persistent changes for hours to weeks for the intermediate field, and only transient

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oscillations in the far field (Manga et al., 2012). Redistribution of static stress or the strain field induced by fault displacement is probably associated with the generation of persistent coseismic changes in the near field (Roeloffs, 1996; Chia et al., 2008). Strain changes fluid pressure and alters hydrogeological properties such as permeability (Manga and Wang, 2007). Change of permeability has been of particular interest as a common cause for affecting various hydrological systems (Elkhoury et al., 2006; Manga et al., 2012).

Various mechanisms have been proposed to explain groundwater level changes in wells during earthquakes including permeability changes at the site as shown in Fig. 1 (e.g., Montgomery and Manga, 2003; Manga and Wang, 2007). Most studies have focused on level changes at several wells in a study area or for one large earthquake. For the groundwater resource management, detailed pattern of level changes in response to multiple earthquakes in a watershed using closely located monitoring wells is needed to be clarified. Also the patterns may differ with proximity to the epicenter, local geological setting, and magnitude of earthquake. Such clarification is the most important in areas that rely on groundwater. For this problem, we investigated the detailed spatial distribution of coseismic groundwater level changes over an unconsolidated sedimentary basin rich in groundwater resources. One new approach of this study was to compare the level changes between shallow and deep groundwater. Previous studies on clarifying the difference of groundwater level changes with location are Lee et al. (2002), Wang et al. (2001, 2004), Manga and Wang (2007), and Chia et al. (2008) by selecting a large alluvial fan in Taiwan for the Chi-Chi earthquake in 1999. Our improvement is to map level changes more in detail by considering the aquifer depth and using an interpolation technique. Another was to construct a conceptual model for the mechanism of groundwater level changes by integrating the coseismic responses to multiple earthquakes.

Being part of the circum-Pacific seismic belt, Japan is one of the most seismically active regions in the world. Therefore, groundwater levels in Japan would be expected to change frequently in response to earthquakes. The Kumamoto City in central Kyushu, southwest Japan (Fig. 2) is one of the best sites to conduct research on the spatial distribution of groundwater level changes, because all drinking water, and water used for agriculture and industry by the population of 700,000, are sourced from local groundwater. The systematic measurement of groundwater levels has been implemented at many wells to monitor the groundwater resource. We therefore selected the Kumamoto City area as our study site.

2. Physical and mathematical model for coseismic change

2.1. Poroelastic theory for pressure change

Poroelasticity is a continuum theory for the analysis of a porous media consisting of an elastic matrix and interconnected fluid-saturated pores. Since the pores are fluid-filled, the presence of the fluid acts as a stiffener of the material and further, results in the flow of the pore fluid (diffusion) between the regions of higher and lower pore pressure (e.g., Cederbaum et al., 2000). According to the poroelastic theory (Biot, 1941; Roeloffs, 1996), stress, strain, pore pressure, and water content are related to each other. Based on these relationships, Montgomery and Manga (2003) proposed two main causes for earthquake-related groundwater level changes: static volumetric strain changes, and ground shaking, with the later including dynamic volumetric strain changes (see Fig. 1).

Hydrologic responses to crustal strain can be described quantitatively using the theory of linear poroelasticity (e.g., Roeloffs, 1996). The volumetric stress–strain relation for a porous elastic material is

$$\Delta\varepsilon_{ij} = \frac{1}{2G_u}\left[\Delta\sigma_{ij} - \frac{\gamma_u}{1+\gamma_u}\Delta\sigma_{kk}\delta_{ij}\right], \tag{1}$$

where $\Delta\varepsilon_{ij}$ is the difference in the strain tensor, G_u is the shear modulus (Pa), σ_{ij} and σ_{kk} are components of the stress tensor (Pa), γ_u is the Poisson's ratio, and δ_{ij} is the Kronecker delta ($\delta_{ij} = 1$ at $i = j$ or 0 at $i \neq j$). The G_u and γ_u are the values under undrained condition, because the stress in the crust by an earthquake in a relatively short time can be induced under this condition (Roeloffs, 1996; Wang, 2000). In this study we used typical values for rocks, 2.3×10^4 MPa for G_u (Jaeger, 1969), and 0.25 for γ_u (Detournay and Cheng, 1993), and simplified the stress tensor as $\sigma_{ij} = \sigma_{kk}$, which allowed consideration of only one component, as a scalar. This simplification was adopted because it was difficult to correctly define the anisotropic behavior of the stress–strain field within an arbitrary study area.

The change in volume strain is accompanied by a change in the volume of solid material and fluid pressures. This can be described

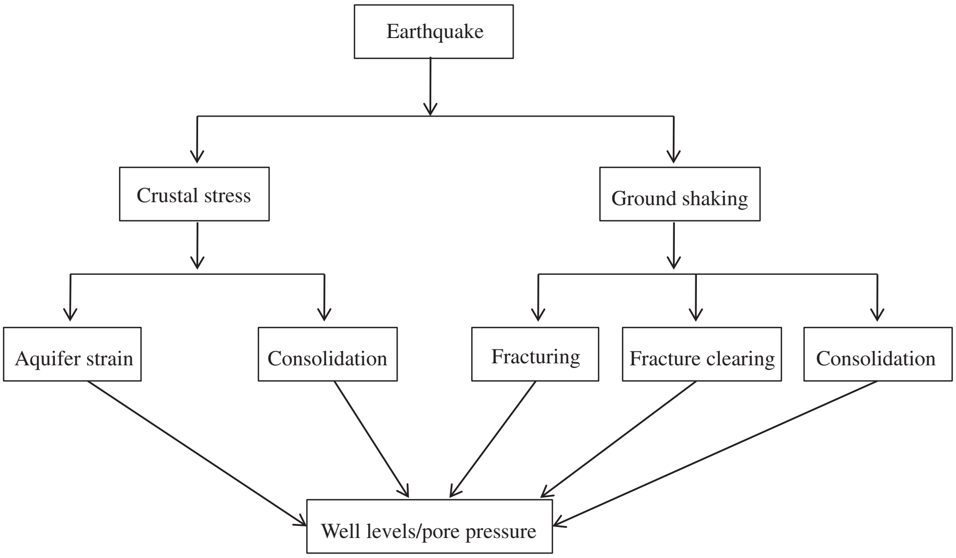

Fig. 1. Interactions between earthquakes and hydrological processes according to Montgomery and Manga (2003).