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Estimating the extent of stress influence by using earthquake triggering groundwater level variations in Taiwan

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ABSTRACT

Groundwater level variations associated with earthquake events may reveal useful information. This study estimates the extent of stress influence, defined as the distance over which an earthquake can induce a step change of the groundwater level, using earthquake-triggering groundwater level variations in Taiwan. Groundwater variations were first characterized based on the dynamics of groundwater level changes dominantly triggered by earthquakes. The step-change data in co-seismic groundwater level variations were used to analyze the extent of stress influence for earthquakes. From the data analysis, the maximum extent of stress influence is 250 km around Taiwan. A two-dimensional approach was adopted to develop two models for estimating the maximum extent of stress influence for earthquakes. From the developed models, the extent of stress influence is proportional to the earthquake magnitude and inversely proportional to the groundwater level change. The model equations can be used to calculate the influence radius of stress from an earthquake by using the observed change of groundwater level and the earthquake magnitude. The models were applied to estimate the area of anomalous stress, defined as the possible areas where the strain energy is accumulated, using the cross areas method. The results show that the estimated area of anomalous stress is close to the epicenter. Complex geological structures and material heterogeneity and anisotropy may explain this disagreement. More data collection and model refinements can improve the proposed model. This study shows the potential of using groundwater level variations for capturing seismic information. The proposed concept of extent of stress influence can be used to estimate the earthquake effect in hydraulic engineering, mining engineering, and carbon dioxide sequestration, etc. This study provides a concept for estimating the possible areas of anomalous stress for a forthcoming earthquake.

1. Introduction

Anomalous groundwater level variations caused by earthquakes have been observed in many places around the world. The responses of groundwater to earthquakes have long been a topic of research interest (Roeloffs, 1988, 1996, 1998; Roeloffs et al., 1989; Roeloffs and Quilty, 1997; Rojstaczer, 1987; Rojstaczer and Wolf, 1992a, 1992b; Rojstaczer et al., 1995; King et al., 2000; Montgomery and Manga, 2003; Matsumoto and Roeloffs, 2003; Matsumoto et al., 2003; Hsu and Tung, 2005; Cutillo and Ge, 2006; Manga and Wang, 2007; Lai et al., 2010). Groundwater responses may appear before an earthquake, acting as a precursor that starts a few minutes to a few days before the earthquake (Roeloffs, 1996; King et al., 2000; Manga and Wang, 2007; Wang and Manga, 2010). Groundwater level variation is a potential phenomenon for earthquake precursor (pre-seismic phenomenon). Since the strain-related variation in the groundwater level is directly related to the status of strain in the Earth's crust, measuring the variations of groundwater level may be an inexpensive method for obtaining strain information (Lee et al., 2002). Using groundwater variations to study earthquake mechanisms is attractive due to its larger spatial domain and lower cost compared to those of traditional strain measurement equipment. The groundwater level observations can be combined with ionosphere, isotope, radon, and other geochemical data to interpret earthquake mechanisms.

Blanchard and Byerly (1935) found that groundwater level variations are associated with earthquakes. Roeloffs (1996) proposed a

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possible mechanism for the groundwater level variations caused by earthquakes using Biot's poroelastic theory (Biot, 1941). Recent research has indicated that poroelastic theory is more suitable than elastic theory in explaining the response of stress change due to an earthquake (Niu et al., 2008). Poroelastic theory describes the interaction of a solid and a fluid by coupling the stress and change in pore water pressure in the governing equations (Wang and Hsu, 2009a, 2009b, 2013). The deformation of a soil body follows the elastic behavior and the fluid movement is governed by Darcy's law. Pore water pressure and stress are related through the concept of effective stress, which states that the total stress is the sum of effective stress and the change of pore water pressure. Due to its versatility, poroelastic theory has been applied to many fields, such as soil mechanics, hydrogeology, civil engineering, and seismology.

The groundwater level variations triggered by earthquakes contain useful information. A step change implies a change of permanent strain whereas an oscillatory change implies the propagation of an elastic wave (Lai et al., 2010). The post-seismic decay behavior is related to the media characteristics. It is important to classify the responses of groundwater variation and analyze them. Therefore, this study proposes a classification system of the responses of groundwater variation triggered by earthquakes. Only step-change variation is used in the following analyses to focus on the stress–strain behavior.

The earthquake focal area is usually in an area with anomalous stress (Stein, 1999; Parsons et al., 2008). Dobrovolsky et al. (1979) proposed an empirical relationship between the earthquake magnitude and the maximum influence distance for a given strain. Niu (2000) used the sudden changes of crust deformation at various stations to predict the location of the epicenter of an earthquake in China. Chen et al. (2015a, 2015b) using momentary high-conductivity materials to estimate the hypocenter for earthquakes in Taiwan. The concept stated above expresses that the stress (or strain) caused by earthquakes should be related to the earthquake magnitude and epicentral distance. The signal of the stress (or strain) can be detected by groundwater variations. Therefore, this study used a multivariable equation from an analytical solution based on poroelastic theory to construct the model for evaluating the extent of stress influence by using earthquake magnitude, epicentral distance, and magnitude of groundwater level variation. The extent of stress influence is defined as the distance over which an earthquake can induce a step change of the groundwater level.

The main concept of this study is to estimate the extent of stress influence by using the observed groundwater level variations and a given earthquake magnitude. The developed model was applied to estimate the area of anomalous stress using the intersection method from several observation stations. The extent of stress influence facilitates the investigations on anomalous stress caused by earthquakes. The proposed model can be used to estimate the hazard potential of a reservoir dam or an underground structure under the earthquake effect. The method also provides a concept for estimating the possible areas of anomalous stress for a forthcoming earthquake.

2. Groundwater level observation wells for earthquakes

The Taiwan Water Resources Agency (TWRA) has built a high-resolution earthquake groundwater data collection system in the plain area of Taiwan to monitor groundwater level variations (Lai et al., 2010). Different from the existing groundwater resource monitoring network that focuses on the availability of groundwater in aquifers, the earthquake groundwater monitoring wells were installed by considering geological structure, geographical location, pumping activity, leakage of precipitation, and seismic sensitivity. Thus, the groundwater levels in the monitoring wells are sensitive to stress/strain due to the installation requirements of the monitoring well. The screens of the monitoring wells are opened at various depths in the range of 84–294 m beneath ground surface. A 2-min sampling rate is adopted for the earthquake groundwater monitoring system, which is much faster than the 1-h sampling rate for the groundwater resource monitoring wells in Taiwan. The accuracy for groundwater measurement is up to 0.2 mm. A total of 18 wells were constructed around Taiwan initially. They started to operate in 2003, at which point their capability of detecting groundwater level anomalies triggered by earthquakes was tested. The durations of observation data vary with station due to the differences in the completion times of the well installations. Locations of the observation wells are shown in Fig. 1. More detailed information of the earthquake monitoring wells is shown in the study of Lai et al. (2010).

Among the 18 monitoring wells, eight observation wells were adopted in the analysis due to their high sensitivity to earthquakes. From the monitoring data, the groundwater level variations triggered by earthquakes can be detected only for earthquakes with magnitudes greater than 4.0. Therefore, a total of 21 earthquake events with Richter scale magnitudes greater than 4.0 that occurred from 2003 to 2004 were collected and analyzed. The earthquake events are shown in Table 1. The earthquake times are the local times in Taiwan (GMT + 8). The earthquake magnitudes used in this paper are Richter scale magnitudes (local earthquake magnitude, M_L) provided by the Taiwan Central Weather Bureau (TCWB). The locations of the eight wells and the epicenters of the 21 earthquake events are shown in Fig. 2. Twenty of the earthquakes occurred in the eastern region of Taiwan or in the sea and one occurred in the western part of Taiwan. This distribution is due to Taiwan being west of the Pacific Ring of Fire, with the plate boundary in the eastern part of Taiwan.

3. Classification of anomalous groundwater variations and data analysis

Many factors cause the groundwater level to change, such as tides, earth tides, atmospheric pressure, earthquakes, pumping activity, and recharge. The type of groundwater response depends on the driving force. Some driving forces, like atmospheric pressure and earth tides, act periodically such that their effects on the groundwater variations can be traced. Pumping activity and recharge are closely related to human activity and natural precipitation, respectively. Earthquake-triggered groundwater variations occur stochastically and thus their connection to earthquakes is more difficult to determine. The two major types of groundwater level variation triggered by earthquakes are step and oscillatory changes, respectively. Oscillatory changes may reflect the energy propagated by seismic waves, whereas step changes are believed to be more closely related to the crust deformation caused by anomalous stress. Usually, step changes occur within a limited distance from the slipping fault. However, a step change in groundwater levels may be observed for a distant earthquake. For example, step changes in the groundwater levels in Taiwan were observed in six of the installed monitoring wells for the 2008 *M*7.9 Wen-Chuan Earthquake in China, whose epicenter was about 1900 km away from Taiwan. This was the only earthquake event for which a step change was observed in the Taiwan area whose epicentral distance was farther than 1000 km. The mechanism for this event is still unclear and the epicenter location was far away from Taiwan, so the data were not included in our analysis. The detectable distance of the oscillatory change of groundwater can be very large, on the order of thousands of kilometers, if the

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