MAPPING AQUIFER STORAGE PROPERTIES FROM INTERFEROMETRIC SYNTHETIC APERTURE RADAR AND MICROTREMORS MEASUREMENTS

Abstract

Groundwater is a natural and highly valuable source of water supply, especially in arid and remote areas. The increased demand for groundwater over the last few decades is associated with climate change and the increasing population and industrial activities worldwide. Thus, the exploration and management of groundwater resources are necessary to satisfy the increasing water demand. Knowledge of the hydraulic head and aquifer parameters, such as the storage coefficient, is crucial for developing sustainable, long-term water management strategies. If the storage coefficient is known, the ground water level can be estimated from the surface displacement based on geodetic data, such as that obtained using interferometric synthetic aperture radar (InSAR). However, the storage coefficient is commonly estimated at well locations; thus, the spatial distribution of the storage coefficient cannot be estimated. In this study, I developed a novel approach to estimate the storage coefficient from the seismic velocity derived from surface wave analysis. This dissertation contains the following chapters:

Chapter 1 introduces the research background and the motivation of this dissertation. This chapter describes the importance of groundwater as a vital water resource and outlines previous studies that reported the application of InSAR for detecting and monitoring surface displacement due to groundwater withdrawal and for estimating the hydraulic head and storage properties of a confined aquifer system.

In Chapter 2, an overview of the theoretical background of synthetic aperture radar (SAR), InSAR analysis, aquifer system deformation, and surface wave analysis are described. Surface displacements caused by groundwater overextraction have been detected over developed aquifer systems worldwide using InSAR. This phenomenon is explained by elastic and inelastic deformation of the aquifer system in response to hydraulic head

changes in the underlying confined aquifer systems. The change in aquifer thickness is linearly related to the change in the hydraulic head, and governed by the skeletal storage coefficient *Sk* of an aquifer, a parameter that is related to the skeletal compressibility of an aquifer system. Thus, mapping and characterizing the skeletal *Sk* is vital for understanding the characteristics and monitoring of an aquifer. In this chapter, I further outline the theory of microtremor surveys as well as their acquisition and data processing procedures. Microtremors are weak and random vibrations, generally dominated by surface waves (Rayleigh and Love waves). Therefore, microtremor records can provide information on the subsurface structure by clarifying the shallow S-wave velocity (*Vs*) structures.

In Chapter 3, I describe the methodological details for mapping the *Sk* of a confined aquifer using the time series of InSAR displacement and groundwater level data as well as a three-dimensional (3D) *Vs* model. I observed a negative correlation by plotting the *Vs* and the *Sk* estimated from both InSAR and well data. Based on the exponential fitting curve, I identified an empirical relationship between *Vs* and the *Sk*. The empirical relationship can be used to map the *Sk* from the 3D *Vs* model. From the mapped *Sk*, the spatiotemporal variation in ground water level can be estimated using the InSAR-derived surface displacement.

Chapter 4 outlines the geological and hydrogeological settings of the Kumamoto area and datasets. I employed the time series of InSAR displacement and groundwater level data and the 3D *Vs* structure model to map the *Sk* of the confined aquifer in the study area. The Kumamoto area is covered by volcanic rocks and alluvial plain deposits in the eastern and western portions, respectively, and the study area is rich in groundwater. I first obtained one-dimensional *Vs* depth profiles (676 locations) estimated by surface-wave analysis (centerless circular array (CCA) approach) using a miniature microtremor array with a radius of 0.6 m. I applied 3D empirical Bayesian kriging to create a 3D *Vs* model to characterize its spatial variation. I also used the time series of InSAR-derived surface deformation and groundwater level data at 13 well sites between April 2016 and September 2018 to characterize the *Sk* of the confined aquifer.

Chapter 5 shows the results of this study and their interpretation. From the 3D *Vs* model, I identified the faulted/fractured zones identified as areas with a low *Vs*, indicating the feasibility of using microtremor surveys to detect the faulted/fractured zones. Additionally, the InSAR technique was able to identify low-velocity regions correlated with the surface displacement area associated with the 2016 Kumamoto earthquake sequence. Surface displacements are attributed to groundwater migration through new coseismic ruptures around the Suizenji area and liquefaction in the coastal area. The Sk estimated from both InSAR and well data ranged from ~0.03 to 2×10^{-3}, with an average of 7.23×10^{-3}. These values are typical for semiconfined and confined conditions. The *Sk* and *Vs* around the corresponding well locations showed an empirical relationship, indicating that the compressibility of an aquifer is related to the stiffness or *Vs*. By applying this relationship to the 3D *Vs* model, I mapped *Sk* in the study area, filling spatial gaps in the existing data for aquifer storage properties. Furthermore, the *Sk* estimated using the relationship between *Vs* and *Sk* correlated well with the hydrogeological setting: semiconfined conditions are predicted in the Kumamoto alluvial plain with high *Sk*.

In Chapter 6, I report the applicability of the proposed approach for predicting the *Sk* at a high spatial resolution. I then discuss, in general, the uncertainty of the estimated *Sk*. Finally, I applied a statistical method called repeated holdout cross-validation to validate the *Sk*–*Vs* relationship. The low root mean square error (RMSE) (averaged RMSE = 8.1×10^{-3}) indicates that the constructed equation (i.e., *Sk*–*Vs* relationship) can estimate the *Sk* values at unmeasured points with high accuracy.

Chapter 7 summarizes the main findings of this dissertation and suggest avenues for future research. The proposed approach can be used to map the *Sk* of aquifers with a significant spatial resolution from *Vs*, even where limited groundwater level data are available. The map of *Sk* can be used to estimate the spatiotemporal variation of the groundwater-level based on the geodetic data (e.g., InSAR data).