論 文 内 容 の 要 旨

This dissertation is about monitoring surface deformation using Interferometric Synthetic Aperture Radar technology. We focused on applying a coherence-based small baseline subset (CB-SBAS) time-series method for retrieving slow-motion deformation. Another objective is solving the existing problems of using InSAR methods due to signal decorrelation. This dissertation is important to understand the ability to capture surface deformation using satellite-based applications and its constraints in various environments as well. The dissertation consists of investigated studies on three different case studies, we applied different methodologies for accurate InSAR measurements. These measurements are based on the type and acquisition of satellite, the surrounding land cover of the study area and available ground-truth data. Although near-surface geophysical surveys have been used to investigate subsurface damage, long-term monitoring is insufficient, expensive, and time-consuming. InSAR methods have the ability to elucidate active regions because of landslides, subsidence, and tectonic movement occurrences. There are other applications of using InSAR coherence, these applications have been used to map the surface environmental damages from explosions, and the burnt scars and their severity.

In the first study, the frequently occurring hazardous landslide in the Mila Basin is an ongoing problem. For this reason, insight studies are needed to understand the geometry of the landslides as well as predict their kinematics and major trend of motion. Landslides reactivated after two successive earthquakes of Mw 4.6 and Mw 4.9 recorded with local magnitude, caused destruction, and partial collapsing of some houses. To correctly assess the earthquake source parameters and shed light upon the environmental effects that seem to be behind the extent of damage, we started by focusing on the seismic history of the Mila region looking for similar events in the past that represented a key to assess the damage occurred and predicting the future ground deformation. Recently, satellite observation acquired by the Interferometric Synthetic Aperture Radar (InSAR) technique and particularly those of Multi-Temporal (MT-InSAR) techniques provide a solution to determine the orientation of landslides and its relation to the past surrounding environmental conditions. In this study, we investigated the rate of recent displacement that occurred in the Mila Basin near the areas that showed damage using archived free data of Sentinel-1 (S-1) ascending and descending tracks. The Mila Basin is exposing to extremely dry and wet weather conditions in summer and winter, therefore landslides occurred in both seasons in Mila city. Moreover, the subsurface lithology composed of Mio- Plio- Quaternary sedimentary basin, in addition to borehole information and extensive in-situ laboratory measurements confirmed the presence of a sub-clay layer revealing geotechnical soil problems. 2D displacement decomposition distinctly described the dominant vertical and minor horizontal components of Kharba city's rotational slide. The maximum vertical velocity was observed at the crown of the Kherba landslide (-30 mm/year), while the rock fall that occurred at Grarem Gouga city shows high horizontal velocity displacement and low vertical velocity rate. The horizontal velocity of -60 mm/year was observed at Grarem Gouga city and is commonly found in the translational slide. Monitoring of precipitation derived from the two meteorological stations showed correlated rainfall episodes compared with time series displacement during 2019 and 2020, confirming seasonal rainfall's contribution to the resulting slow rates of displacement. This study is considered a solution to retrieve the ground motion of the landslides at two regions located 12 km apart from each other in Mila Basin. In fact, land cover conditions with low dense vegetation permit the detection of landslide motion along its three parts (crown, body, and toe parts) clearly using the InSAR technique.

Here, we concluded that the sliding was classified into rotational and translational landslides according to the rupture surface, linking the calculated horizontal and vertical displacements with the field observations. We also concluded that the slope morphology and rainfall are some of the reasons that lead to the erosion of the bottom zone (landslide toe and its margins), then finally shallow earthquakes can trigger more easily eroded soil, followed by landslide occurrence. Also, the outputs reveal the relation of landslides to slow motion towards the downward west rather than sudden fall. In this study, 2D decomposition of InSAR outputs indicated slow motion rather than fast movement along the damaged area. In addition, sliding can be categorized depending on its source, mechanism, velocity direction, and rapture surface. Consequently, this study will contribute to landslide hazard identification and risk assessment in Mila Basin.

In the second case study, Kochi Prefecture is located in an active zone of Japan that is frequently subjected to landslides due to heavy precipitation in typhoon seasons. Slow-moving landslides have been reported by both the local prefecture authorities and the National Government of Japan. We observed landslide movement at Otoyo town using ground- and satellite-based tools. Despite the high cost of establishing a borehole inclinometer survey to obtain accurate ground-based measurements, no previous InSAR study has been conducted at Otoyo Town, and the capacity for regional discrimination between active and inactive slow-moving landslides using these tools remains unclear. Since 1949, ground anchors have been installed in unstable slopes in Japan. However, sometimes, especially with unpredicted high precipitation rates, the anchor lost its efficiency causing displacement. For ground-based measurements, after precipitation events in July 2018, the bearing capacity of the ground anchors exceeded their limits, this is the reason for anchor displacement and the need for anchor maintenance. We monitored displacement over 5 years, from 2016 to 2021, in addition to observing factors triggering landslides. Ground-truth data confirmed two reasons for displacement; cumulative precipitation and anchor displacement. Satellite-based monitoring of ground-anchor efficiency may be possible in combination with ground-based inclinometer surveys. After decomposing the Line of sight (LoS) displacement vector component to east-west component and up-down component across the whole of Otoyo town, the 2D decomposition showed a clear horizontal displacement of velocity -21.4 mm/year, while the vertical component was almost diminished. There is another challenge faced using the InSAR application in Otoyo Town, as there are three types of land cover present in the study area---urban, field, and forests---so we selected the random forest (RF) model a supervised machine-learning tool to extract low-coherence pixels using optical (the MODerate-resolution Imaging Spectroradiometer (MODIS) and Sentinel-2) and radar satellite sensors. There are previous studies that proved landslides in forest and field areas can decrease normalised difference vegetation index (NDVI) values, for this reason, we selected S-1 mean interferometric coherence data, S-2 mean NDVI values, and the long-term time series correlation relation of MODIS NDVI and mean interferometric coherence. These three features were used to identify important features and precisely remove pixels causing decorrelation. Ultimately, the RF model can be applied as a low-coherence mask to mitigate the decorrelation effect associated with vegetation activity. We validate the RF classification results, this can be conducted by extracting matrices using a confusion matrix. The confusion matrix of the implemented RF model had an overall accuracy of 0.94. Furthermore, when the RF model was used and continued running the CB-SBAS approach, low root mean square (RMS) from SBAS linear regression with 30% was observed.

In conclusion, long-term monitoring results from ground-based surveys, including inclinometer (boreholes) and anchor tension distribution data, were compared with synthetic radar using coherence-based small baseline subset (CB-SBAS) measurements. This comparison showed a consistent time-series displacement correlation, which was strengthened after introducing the RF mask into the analysis procedure. We also observed the steady-state of ground after anchor maintenance using InSAR technology. Our research will help to mitigate landslide impacts in Otoyo Town and its surroundings, in addition to saving time, and cost, and investigating regional areas after introducing InSAR technology.

In the third case study, land deformation due to natural and anthropogenic impacts is considered a challenging environmental problem in the Aswan area located in the southern part of Egypt. Specifically, we applied multi-spectral analysis in order to record the slow rate of subsidence with a high spatial resolution of COSMO-SkyMed (X-band) and Sentinel-1 TOPSAR (C-band) scenes. We proposed multi-temporal DInSAR and SBAS data analysis of the two satellite sensors by means of ascending and descending orbit tracks during the recent time period of 2012-2021. The stacked DInSAR results from 2012 to 2017 reported the occurrence of land subsidence of -3 mm/yr in active urban areas, while after applying the CB-SBAS approach in the following years from 2018-2021 observed a high rate of displacement of -6 mm/yr and also uplift pattern. In conclusion, a strong correlation between the locations of field observation and the estimated Line of Sight (LOS) displacement time series values, assuming the ground deformation is controlled by seasonal surface water loading, lithological units, and subsurface water activity. Furthermore, land subsidence due to groundwater withdrawal was shown after increasing the time interval of investigation at the north and northeast of the study area, due to the regression of the water table and increased pumping rates from 2013 to 2017, which caused a noticeable land deformation at the urban area located in the depression cone of the groundwater flow direction. On the contrary, borehole investigation showed a sudden increase in the groundwater level that reached the surface during the time period from 2017 to 2020. The detection of seasonal displacement highlights the priority of groundwater management plans in the affected urban areas.

In the future study, regarding the third study at Aswan city, we focus on determining a long temporal baseline for CB-SBAS (2014-2022) using S-1 and Cosmo-skymed radar sensors for monitoring slow-movement of subsidence or uplift accurately. In the second study, we also will continue our investigations at Otoyo Town, as slow-moving landslides are still existing at high rates, especially in vegetated areas. We can use a different type of satellite sensor, which is ALOS-2 with an L-band that may capture landslides in forests. If we install corner reflectors in landslide regions lacking strong reflectors (such as buildings) and fully covered with a highly active canopy, we will observe more stable InSAR phases. In addition, multi-sensor analysis can be used with different L-band satellite sensors that may launch in the near future such as ALOS-4 or NISAR, and these new satellite sensors have improved performance and functionality to observe slow-moving landslides.

As we already show a consistent correlation between ground measurements (inclinometer and pressure distribution data) and downslope movement derived from satellite-based analysis, we can investigate the possibility to apply Landslide Early Warning Criteria (LEWC) using InSAR observations. The LEWC may present initial deformation derived from InSAR analysis that can be used to predict deformation patterns in the future.