Land subsidence at the Kujukuri Plain in Chiba Prefecture, Japan: evaluation and monitoring environmental impacts

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Abstract The impacts of land subsidence on surface environmental changes were analysed for the Kujukuri Plain, Japan, where subsurface brine has been abstracted for more than 50 years. Reconstruction of past landforms using airborne laser scanning and existing levelling data showed that the geomorphological setting of the whole region, such as beach ridges and backmarshes, has been retained during the recent 40 years. Apparent and simple relationships between shoreline retreat and land subsidence were not recognized, and the spatio-temporal distribution of shoreline change seems to be mainly controlled by coastal constructions. In addition, a method to measure long-term deformation by combining InSAR and time series analysis was proposed to improve our ability for monitoring land subsidence. The local uplifts and subsidence detected by the proposed method were quite consistent with those obtained from levelling data, suggesting that our method was applicable to the detailed monitoring. By combining and integrating the approaches presented in this paper with numerical modelling of deformation/fluid flow processes, scientifically sound recommendations for the sustainable development of the subsurface resources can be proposed for society.

Key words land subsidence; environmental impact; monitoring; InSAR; GIS; Kujukuri Plain, Japan

INTRODUCTION

Land subsidence causes various types of damage to civil society and it may result in the permanent deterioration of environmental conditions due to the irreducible nature of the subsidence phenomena in general (Deming, 2002). Because of the industrial withdrawals of subsurface fluid resources, such as dissolved methane and groundwater, land subsidence has occurred at many places in Japan (Environmental Management Bureau, Ministry of the Environment, 2009). The Kujukuri Plain, Chiba Prefecture (Fig. 1), is one of the places where heavy subsidence, with a maximum value of accumulated subsidence of 100.7 cm, was observed during the period from 1969 to 2007 (Environmental and Community Affairs Department, Chiba Prefecture, 1970–2007). This coastal plain is composed of alternating beach ridges and backmarshes (Moriwaki, 1979); (Fig. 1). Most of the area is situated below 10 m elevation, therefore it is of concern that continuous land subsidence by abstraction of subsurface brine and possible future sea-level rise due to global warming may increase the risks of flood disaster and coastal erosion. However, our understanding of the surface environmental changes caused by subsidence are not yet sufficient to predict the extent of the environmental impacts and to propose efficient countermeasures against these influences. This paper presents our activities to tackle the problems through two different approaches, i.e. (1) to better understand the surface environmental changes caused by land subsidence, and (2) to further improve the Interferometric Synthetic Aperture Radar (InSAR) method to achieve a high resolution monitoring technique for surface movement. We also present the importance of integrating these approaches to achieve the sustainable development of subsurface resources.
ANALYSING CHANGES OF THE SURFACE ENVIRONMENT

Reconstructing past landforms
We conducted an airborne laser scanning survey in December 2008 to obtain high accuracy and high resolution digital elevation model (DEM) (Fig. 2). The study area includes Mobara City, Shirako Town and Chosei Village on the southern Kujukuri Plain. The DEM has an area of 224 km² (14 km × 16 km), 1-m mesh resolution, and 4.0-cm vertical error, which is much higher in accuracy than the existing topographic map and the standard specification for airborne laser scanning, i.e. 25 cm (Ministry of Land, Infrastructure, Transport and Tourism, 2008).

We estimated landform changes by integrating the present DEM-based topographic data and the existing levelling data. We used the “Precise levelling survey results in Chiba Prefecture” compiled by Chiba Prefectural Government (Environmental and Community Affairs Department, Chiba Prefecture, 1970–2007) to reconstruct the past ground level. The levelling survey has been carried out every year since 1969. The maximum value of accumulated subsidence was 100.7 cm in the northeastern part of the Mobara City and the minimum value was 39.2 cm in the southern part of Chosei Village during the period from 1969 to 2007. The landform changes were obtained by subtracting the ground-level changes from the present DEM in the study area.

Expansion of lowland
Figure 3(a) shows the expansion of lowland as a function of time. The area below 1 m was 2.4% of the whole study area in 1969, while it has expanded to 5.5% in 2009. Areas below 2 to 6 m have increased more rapidly. For example, the area below 6 m increased by 5.6% during the period 1969–2009. Lowland has expanded along the Nabaki River and partially in the swale behind the beach ridge along the shoreline (Fig. 3(b)). However, overall the spatial pattern of the geomorphological features such as beach ridges and backmarshes has been retained, i.e. regional difference of land subsidence has not caused significant change of the entire landforms during the last 40 years.
Fig. 2 One metre mesh digital elevation model obtained from the airborne laser scanning survey.

Fig. 3 Temporal change of landform in the past 40 years. (a) Altitude-area relations; and (b) an example of the landform change at the lower reach of the Nabaki River.
Shoreline change

The existing data related to shoreline change were summarized, and we compared the spatio-temporal changes of the shorelines with those of ground levels (Fig. 4). In Fig. 4(a), the sites and the timings of the installation of coastal architectures such as training dikes, jetties and breakwaters were also shown. The apparent and simple relationships between the shoreline retreat and the land subsidence (Fig. 4(b)) were not observed, i.e. the areas with a large amount of accumulated shoreline retreat do not correspond to those with a large amount of land subsidence. Spatio-temporal changes of the shoreline seem to be controlled more by artificial coastal structures. For example, the area of shoreline retreat has expanded after the completion of the construction of the breakwater in front of the sea cliff at Taito-misaki (see Fig. 1 for the location) at 1985, which is considered to be a major source of beach sand at the study area. In addition, the saw-like pattern of alternating high and low erosion areas are observed in between the Ichinomiya River and the Taito Fishing Port. These patterns are interpreted to be caused by the construction of headlands in the area.

Fig. 4 X-t diagrams showing spatio-temporal changes of shoreline and ground level. The vertical axis indicates time and the horizontal axis distance along the coast. The gradation from white to black indicates the amount of accumulated shoreline change in the upper figure (A) and ground level change in the lower figure (B). The year 1969 was chosen as a reference to construct the diagrams. Solid and dashed lines in the upper figure (A) show the coastal structures.

IMPROVEMENT OF INSAR TECHNIQUE TO MONITOR GROUND DISPLACEMENT

Interferometric Synthetic Aperture Radar (InSAR) is becoming established as a method for monitoring ground displacement that can observe subtle surface movement over a wide area at high resolution (e.g. Ferretti et al., 2001; Berardino et al., 2002). We recently developed a method to measure long-term deformation by combining InSAR and time series analysis, aiming at establishing the practical and flexible measurement technique (Deguchi et al., 2009). In our measuring method, the value of land deformation is set as an unknown parameter. Then, by applying a smoothness-constrained inversion algorithm, the optimal solution to the amount of land deformation was obtained. We applied our new method at the study area with ENVISAT/ASAR data, and verified its accuracy by comparing our results with levelling data (Fig. 5). It was shown that the local uplifts and subsidence detected by the proposed method were quite consistent with those obtained from levelling data both in spatial distribution and the amount of vertical movement.
FUTURE PERSPECTIVES

To evaluate and monitor the environmental impacts by subsurface resources abstraction, integration of the detailed analysis of surface topographic change with GIS platform and the detailed monitoring by InSAR technique is considered to be very effective. Combination of our approaches with numerical modelling of land subsidence by resources abstraction will provide us with reliable and scientifically sound recommendations for the sustainable production scheme, and it will help to build the possible consensus on the sustainable development (Fig. 6). The approach presented here is considered to be universal, and hence it will be used for the areas where similar subsurface development has been conducted and/or planned.

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**Fig. 5** Comparison among InSAR (left), levelling survey (centre), and the temporal changes of surface deformation obtained from our InSAR analysis (dots) and levelling survey results (triangles) (right).

**Fig. 6** Conceptual diagram showing the importance of integration of monitoring and modelling for sustainable development of subsurface resources.
Acknowledgements We would like to express our sincere gratitude to the Keiyo Natural Gas Association for supporting this study.

REFERENCES


