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Land subsidence evaluation for urban cities by time-series interferometric synthetic aperture radar analysis

Évaluation de l'affaissement des sols pour les villes urbaines par l'analyse des séries temporelles du radar à synthèse d'ouverture interférométrique

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ABSTRACT: Land subsidence in urban cities has been considered that the main factors are groundwater exploitation for industry, agriculture, snow melting, pumping of natural gas, and mines' excavation. Threatening people and urban infrastructures necessary for livelihoods, land subsidence have enormous potential for many hazards. Recent developments in remote sensing technology, including the Interferometric Synthetic Aperture Radar (InSAR), have been regarded as the most reliable surveying technique. This study shows recent land deformation using satellite data in Japan (Chiba and Niigata) and South Asia regions (Delhi and Bangkok) to verify the detection ability of the InSAR technique for land subsidence. The amount of land deformation by the time series analysis almost agreed with both range and volume of displacement, and this study identified the accuracy of time-series InSAR analysis. The results of the time series analysis were compared with those of the GPS survey, and it was shown that the maximum difference was sufficiently accurate to specify the land subsidence area of 1cm or more per year in any region and method. The coefficient of determination is 0.62 between GPS historical data and InSAR analysis results.

RÉSUMÉ : On considère que les principaux facteurs d'affaissement des sols dans les villes sont l'exploitation des eaux souterraines pour l'industrie, l'agriculture, la fonte des neiges, le pompage du gaz naturel et l'excavation des mines. Menaçant les personnes et les infrastructures urbaines nécessaires à la subsistance, les affaissements de terrain ont un potentiel énorme pour de nombreux risques. Les récents développements de la technologie de télédétection, notamment le radar interférométrique à synthèse d'ouverture (InSAR), ont été considérés comme la technique d'arpentage la plus fiable. Cette étude montre la déformation récente du sol en utilisant des données satellitaires au Japon (Chiba et Niigata) et dans les régions d'Asie du Sud (Delhi et Bangkok) pour vérifier la capacité de détection de la technique InSAR pour l'affaissement du sol. L'ampleur de la déformation des terres par l'analyse des séries chronologiques correspondait presque à la portée et au volume du déplacement, et cette étude a permis d'identifier la précision de l'analyse InSAR des séries chronologiques. Les résultats de l'analyse des séries temporelles ont été comparés à ceux de l'enquête GPS, et il a été démontré que la différence maximale était suffisamment précise pour spécifier la zone d'affaissement des terres de 2 cm ou plus par an dans n'importe quelle région et méthode. Le coefficient de détermination est de 0,62 entre les données historiques GPS et les résultats de l'analyse InSAR.

KEYWORDS: land subsidence, interferometric synthetic aperture radar, time-series analysis, disaster risk management

1 INTRODUCTION

In many countries, specifically economically growing cities, land subsidence occurs, such as Jakarta, Manila, Bangkok, and Shanghai. As a result, it suffers residents' lives and necessary infrastructures, including commercial and residential buildings, lifelines of underground gas pipes, and vulnerability to tsunami and storm surges. Researchers discuss the main factors of excessive disaster pumping groundwater for industries, agriculture, snow-melting, cooling, pumping of gas, and mines' excavation.

Chiba and Niigata prefectures in Japan have been in controversy of land subsidence disasters for a long time. The extraction of groundwater containing natural gas is considered the main factor of the land subsidence in Chiba, and in the five years (2014 to 2019), 3.3 square kilometers had subsidence of 10 centimeters or more. In the Katsunan and Chiba/Ichihara areas, where land subsidence was severe in the 1970s, groundwater extraction was significantly reduced due to regulations such as the Industrial Water Law and the Chiba Prefectural Ordinance for Environmental Conservation, and natural gas brine extraction was reduced due to the "Agreement on the Prevention of Land Sinking" and the purchase of natural gas mining areas. On the other hand, in the Hokuso region, there has been no significant change in the amount of groundwater extracted, and land subsidence continues. In the Kujukuri area, where natural gas extraction is conducted, efforts are being made to reduce the extraction of natural gas brine based on the "Detailed Agreement on Prevention of Ground Sinking," but land subsidence continues (Chiba Prefecture (a), 2021). The extraction of water-soluble natural gas mainly causes land subsidence in Niigata Plain. In the Niigata and Shibata areas, the maximum annual land subsidence reached 54 cm in the late 1950s, but the situation has generally subsided except in some areas since the late 1950s due to regulations on the extraction of water-soluble natural gas (Niigata Prefecture, 2021).

Besides, Bangkok and Delhi are also in controversy of historical land subsidence. The land subsidence in Bangkok started in 1907, and both public and private sectors had freely developed groundwater for several decades before the consequent effect was revealed. Due to the past uncontrolled over-pumping of groundwater, certain aquifers and overlying clay layers are under significant stress, leading to critical land deformation results, which at its most severe amounts to 10 cm/year in the later 1970s. It is required to consider mitigation laws and actions if they are to be reinstated and stabilized. The strict mitigations finally return a good result (Lorphensri et al., 2011). Delhi is also facing the looming groundwater crisis due to urbanization and illegal pumping and is considered a critical zone by the government of India. The groundwater use in India is considerably more than in the USA and China combined. Due to rapid urbanization and illegal extraction, India's National capital region (NCR) has severe groundwater depletion, and Delhi is declared the most significant land subsidence zone by the national government. The looming groundwater depletion crisis and supporting hydrogeology make this region prone to land deformation (Garg et al., 2020). The rapid extraction of groundwater and supporting physiography and hydrogeology of this region makes it prone to land subsidence.

Several geodetic methods such as total station, leveling instrument, electronic distance meter, and GNSS (Differential GPS) have investigated land subsidence in controversial cities concerning this type of land deformation disaster. However, these measurement techniques have shown only point-wise surveying data from observations. Therefore, it is challenging to understand subsidence details in the entire region with pixel-based monitoring. Recent developments in monitoring methods using Interferometric Synthetic Aperture Radar (InSAR) for land subsidence have contributed to the growth of satellite surveying regarding free-available SAR data and high-precision in orbital errors in satellites. SAR satellites measure the position in one wave cycle of a receiving signal. Therefore, multiple observations of the phase information are necessary to estimate how much the object has moved. This technique is called the InSAR technique. Internationally recognized, the InSAR technique to monitor land deformation for geohazard events and construction management is recommended. ISO 18674 -1: 2015 Geotechnical investigation and testing specify the necessity of using satellites as surveying.

Time-series InSAR analysis has been developed for higher precision techniques and uses multiple SAR images and statistical processing to estimate high precision land deformation. The Small Baseline Subset (SBAS) analysis method (Berardino et al., 2002) is one of the most robust time-series InSAR analysis methods in historical research developments. This study also uses time-series InSAR analysis to show the recent land subsidence trends in land subsidence issues and verify the accuracy of using the InSAR technique by comparing SBAS-InSAR analysis and GPS data results.

2 MATERIAL AND METHOD

2.1 *Concept of Small Baseline Subset method*

Many different time-series analyses based on the InSAR technique have been developed by researchers and evaluated for land subsidence analysis. In general, three factors limit the robustness of the InSAR analysis result: spatial decorrelation, temporal decorrelation, and the misinterpretation of topography and atmospheric delay. Nevertheless, recent time-series InSAR analysis methods, including permanent (persistent) scatterer (PS) (Ferretti, 2001) and SBAS-InSAR analysis, represent conventionally accepted time-series InSAR analysis techniques to research land subsidence over decades. Moreover, both methods have shown practical applications to different cases: landslides, ground deformation, and infrastructure evaluation.

SBAS technique creates more interferograms with small spatial and temporal baselines that were reliable coherent. This SBAS technique combines the multiple small baseline subsets by decomposition method (Shanker et al. 2011, Gonnuru & Kumar 2018). Multi-reference time-series interferometric stacking method reduces the effects of interferometric decorrelation and has the advantage of being able to achieve a planar evaluation and to correct topographic and atmospheric effects. This method uses multi-look images and formulates the relationship between the time and change of the interferogram results with good coherence (high reliability). The equations obtained for all interference results are solved as simultaneous equations.

2.2 *Datasets Used*

Sentinel-1 (S1) satellites launched by European Space Agency (ESA) have the interferometric wide-swath (IWS) mode as the primary acquisition mode. Using the Terrain Observation with Progressive Scans in azimuth (TOPS) mode, the data with the IWS mode is acquired (de Zan & Monti Guarnieri, 2006). The IWS mode has the advantage of a broad swath width of about 250km. In combination with S1A and S1B, S1 satellites are in operation with a C-band sensor at an orbit repeat cycle of 6 days at the best. Both S1A and S1B IWS data are available as RAW, SLC (Single Look Complex), and GRD (Ground Range Dataset) products. The S1 IWS SLC product is a set of three burst SLC, and each one includes nine or ten bursts over one of the sub-swaths.

In this study, around 60 SAR images within 2019 to 2020 years for each target region from January 2019 to December 2020 obtained from S1A and S1B satellites were used to analyze its time-series land subsidence data in the direction of the satellite's line-of-site (LOS). The datasets used in this study are shown in Table 1. Unwrapped images contain orbit error and atmospheric delay error. Therefore, we corrected the orbit fringe, the landform fringe, and the atmospheric phase delay error before solving the time-series land subsidence data. For these errors, the modeled errors are estimated for the whole region where no fluctuation can be assumed, and the errors are corrected by subtracting them from the original interference images.

Table 1. Sentinel-1 satellite data specifications for time-series InSAR analysis at each target area: Chiba, Niigata, Bangkok, and Delhi (Asc: ascending and Des: descending bound orbits)

Area	*Chiba*	*Niigata*	*Bangkok*	*Delhi*
Num. of images	*61*	*61*	*58*	*61*
Orbit	*Asc*	*Des*	*Asc*	*Asc*
Ref. scene	*Jan. 3 2020*	*Jan. 11 2020*	*Jan. 7 2020*	*Jan. 9 2020*

We used MAGNET GPS Network (Nevada Geodetic Laboratory) to evaluate the accuracy of time-series InSAR analysis results, supported by the NSF and USGS NEHRP program (Blewitt et al., 2018). This GPS network holds 13,000 stations and hundreds of different network operators providing open data processed at Nevada Geodetic Laboratory. These daily data are updated since they have been ingested into their data analysis system. In this study, the number of GPS stations overlapped with SBAS-InSAR analysis pixel-wise results is 8 points. Therefore, we included all 8 points for comparison with satellite surveying results. These points are shown in Table 2.

Table 2. GPS datasets used in comparison with SBAS-InSAR results

Location	*GPS station*	*Latitude*	*Longitude.*
Chiba	I015	35.803	140.407
	I020	35.717	140.315
	I027	35.53	140.318
	I033	35.421	140.337
Niigata	J050	37.896	138.989
	J571	37.752	139.074
Bangkok	CUSV	13.736	100.534
Delhi	LIAA	28.637	77.172

2.3 *Framework and Procedure*

The processing in this study is various interferometric time-series analyses, including SBAS with multi-looked interferometric phase and multi-reference stacks to derive the deformation time series (Wegnüller et al., 2016). Due to the small stack and the unstable fluctuation of land surface motion in each region, we used multi-reference stacks for the SBAS processing. We downloaded SLC images from Open Access Hub at the first step, providing free available S1A and S1B products. The S1 IWS SLC product consists of three sub-swaths, and each includes nine to ten bursts. In the next step, we co-registered all the S1 IWS SLC to one selected reference data as shown in Table 2 and then deramped the co-registered SLC mosaics for the azimuth phase ramps. The SBAS procedure followed (Berardino et al., 2002) and multi-looked differential interferometric phases. All the baselines are below 150m. we considered the shorter time intervals to maximize the temporal coherence and facilitate the phase unwrapping, including all pairs between scenes up to 3 positions away from each other in the time series. We selected the differential interferogram for each pair using the SRTM elevation data as a topographic reference with a 30m resolution. To check the quality information, we used the standard deviation from the time series, and for areas where unwrapping errors and ambiguity errors occurred, phase standard deviation from the time series tends to be higher, and we excluded these areas from the solution.

After the SBAS analysis and noise corrections, collecting GPS station archive datasets, and comparing them with the SBAS-InSAR results, the flow of work is shown in Figure 1.

3 RESULTS AND DISCUSSION

Figure 2 shows the displacement at the end of 2020 based on pixel values ranging from -0.20m to +0.20m in the direction of the satellite's LOS. Obtained deformation volumes are significant, and pixels coloring red indicated a significant subsidence area. As the deformation maps show, land displacements were successfully detected, and both ascending orbit results (Chiba, Bangkok, and Delhi) and descending orbit results (Niigata) show the applicability to detect land deformation in both orbits with time. The land subsidence in Chiba shows significant subsidence in most districts; land deformation in Niigata and Delhi shows the most uplifted areas in their regions. Land fluctuation in Bangkok did not show any deformation in this period, but few uplifted areas in the southern area have been shown. Comparing the results between ascending and descending orbits in each time-series analysis does not show any clear and specific difference in results and stability.

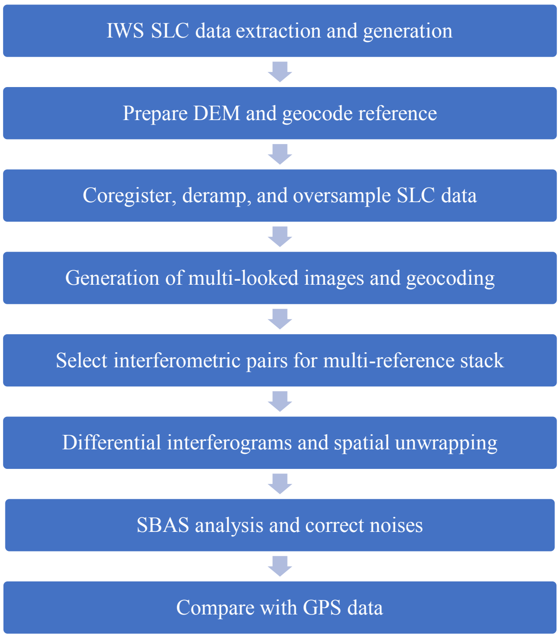


Figure 1. Workflow of the SBAS-InSAR analysis

Figure 2 also shows GPS station locations surveyed and conducted processing supported by the Nevada Geodetic Laboratory in the University of Nevada. These GPS stations were selected based on overlapping with the SBAS-InSAR analysis results. However, due to the statistical processing in the time-series analysis, overlapping pixels with each GPS station is relatively few. Finally, we chose four stations in Chiba, two stations in Niigata, and one in Bangkok and Delhi.

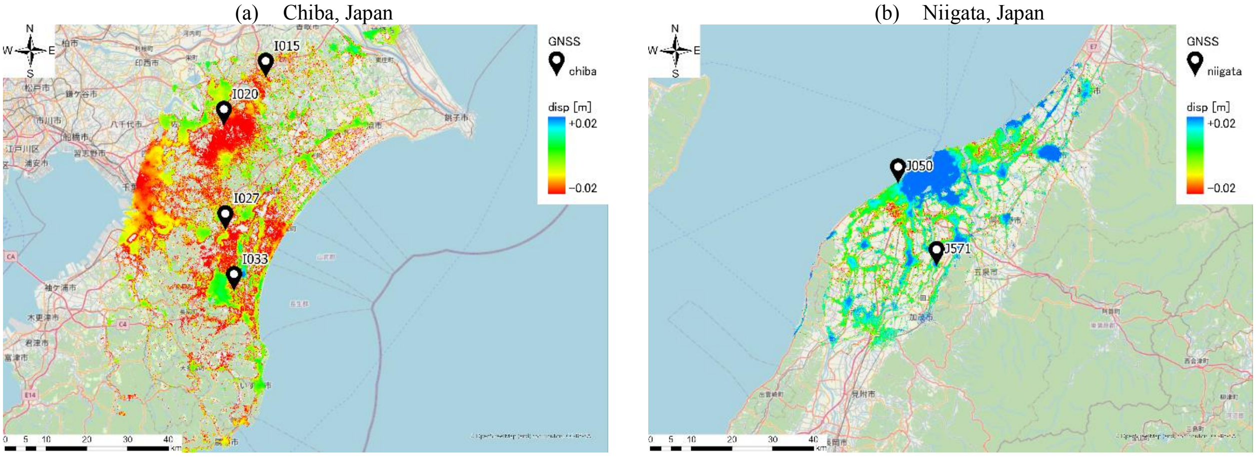
Table 3 shows the land displacement volume at the end of 2020, overlapping with GPS stations in Chiba, Niigata, Bangkok, and Delhi. As results show, each station shows a similar trend with SBAS-InSAR results except for Chiba. In Niigata, both J050 and J571 GPS stations show uplifted values, which is potentially due to seasonal changes, and there is no substantial deformation at the station of CUSV in Bangkok. The GPS station, LIAA, in Delhi shows uplifted values. Those SBAS-InSAR results matched with GPS station records within the error values ranging from 1.24 to 5.36mm. The difference of the cumulative deformation volume between GPS and SBAS-InSAR in the results of Chiba is thought to be the effect of atmospheric-related effects or other reasons.

Table 3. Land subsidence results analyzed by SBAS-InSAR methods in each overlapping GPS station in 2 years.

Location	*GPS stations*	*GPS results (mm)*	*SBAS-InSAR results (mm)*
Chiba	I015	+21.22	-8.50
	I020	-1.66	-21.53
	I027	+9.45	-8.71
	I033	+10.25	-8.13
Niigata	J050	+12.81	+15.07
	J571	+22.07	+11.19
Bangkok	CUSV	-9.64	-1.90
Delhi	LIAA	+10.90	+7.99

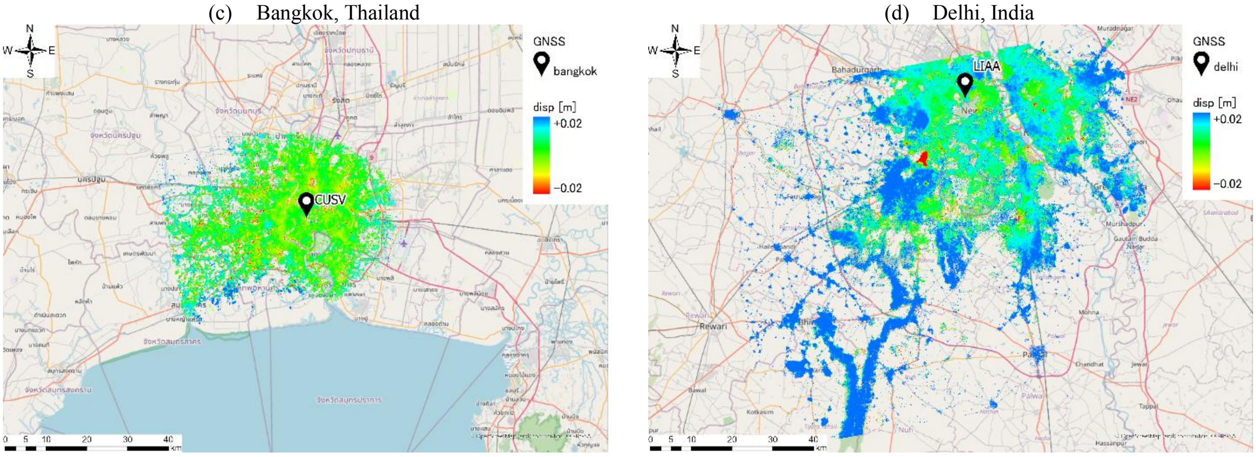
Figure 3 (a) compares GPS station results with SBAS-InSAR analysis results at Chiba's most subsided GPS station, I020. The SBAS-InSAR analysis is colored by orange, and GPS data shows in a blue line graph. Both results show a similar trend except for the last few months. The graph slightly shows the seasonal effects in 2 years, in which during the summer season there have been uplifted surface deformation in the time-series graph. Figure 3 (b) shows a correlation diagram by extracting error values at each time when both S1 satellites have been taken and the I020 GPS station recorded and matched. In the diagram, the coefficient of determination is 0.62, showing the good accuracy of SBAS-InSAR analysis results. Thus, there are no substantial differences between GPS stations' results and SBAS-InSAR analysis results at each time-series graph.

Figure 4 (a) shows the distribution of land subsidence with cumulative subsidence over five years and (b) the distribution of land deformation with the groundwater dissolved natural gas grouped areas provided by Chiba Prefecture. The maximum subsided GPS station, I020, is located around the most significant subsided area. Other GPS stations, including I015, I027, and I033, are also in subsided areas. As this figure and SBAS-InSAR analysis result show, the leading cause of land subsidence in Chiba is the groundwater dissolved natural gas. Besides, this also indicates that using the InSAR analysis technique is crucial for monitoring a wide area.



(a) Chiba, Japan

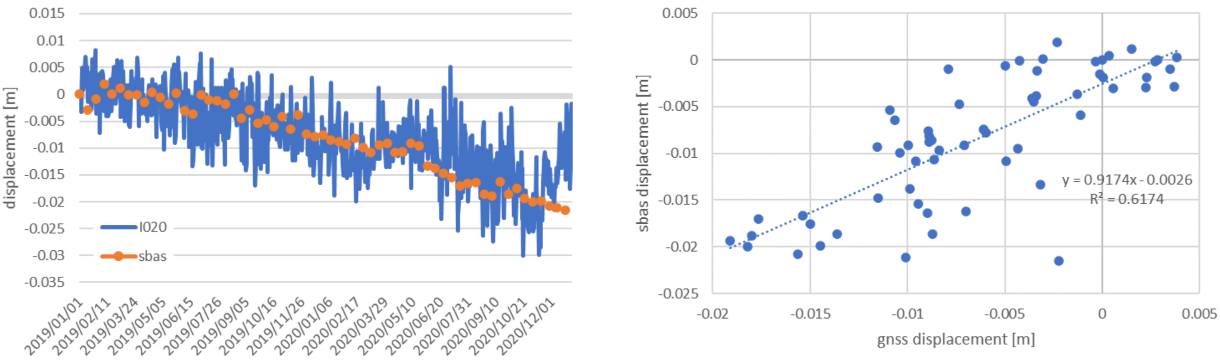
(b) Niigata, Japan



(c) Bangkok, Thailand

(d) Delhi, India

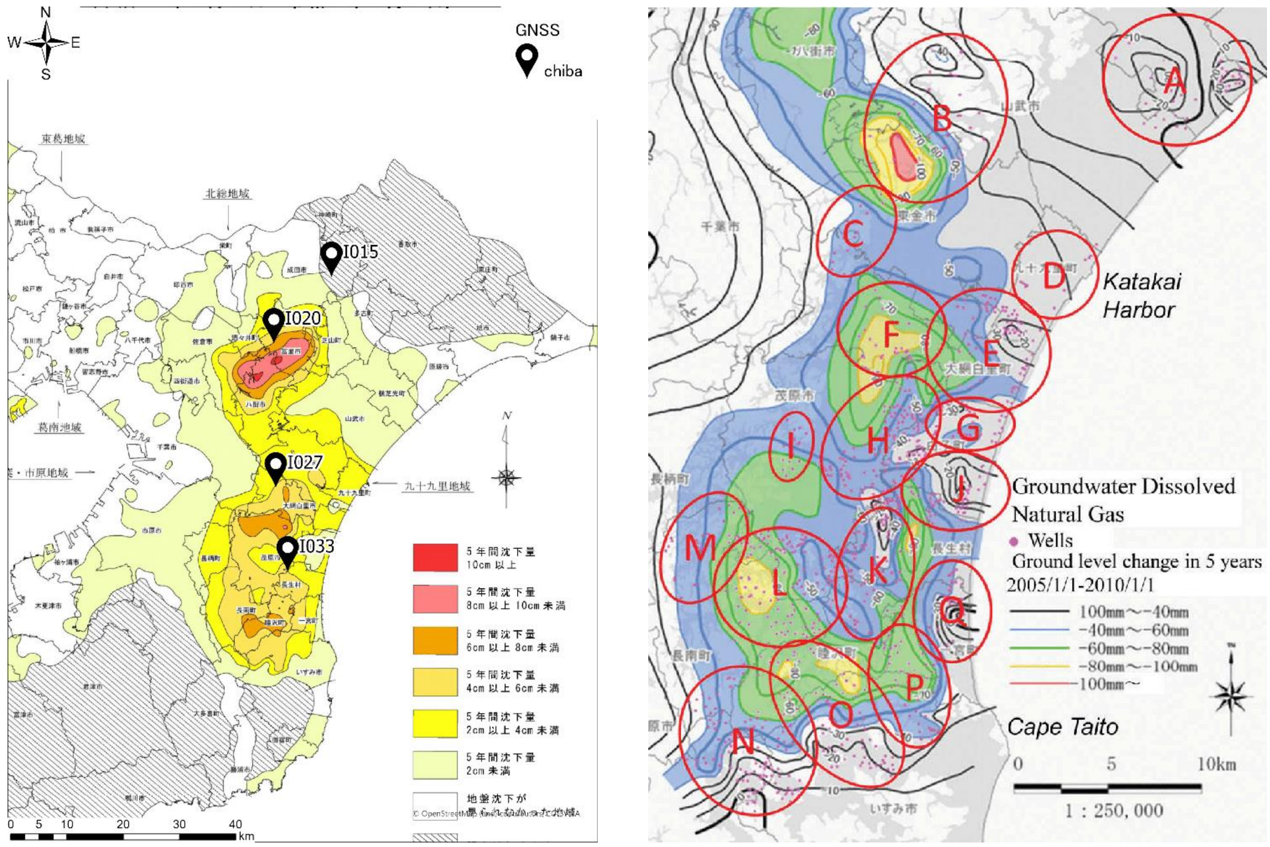
Figure 2. GPS stations: (a) Chiba, Japan, (b) Niigata, Japan, (c) Bangkok, Thailand, and (d) Delhi, India overlapping with SBAS-InSAR analysis results in four target regions at the end of December 2020



(a) Time-series graph of gnss and sbas results at I020

(b) Correlation between gnss and sbas at I020

Figure 3. The most subsided GPS station "I020" in Chiba overlapping with SBAS-InSAR analysis result (a) time-series graph and (b) correlation diagram at each time when Sentinel-1 satellites have taken in the series of January 2019 to December 2020.



(a) Land subsidence over last five years

(b) Groundwater Dissolved Natural Gas and Ground level change in five years

Figure 4. (a) Distribution of land subsidence with cumulative subsidence over five years (Chiba Prefecture (b), 2021) and (b) Distribution of land subsidence with wells grouped into A–N areas (Shibata et al., 2019)

4 CONCLUSIONS

Spatio-temporal details of land subsidence were investigated using the InSAR time series analysis using Sentinel-1A/1B SLC images from January 2019 to December 2020. The evident difference between GPS and SBAS-InSAR analysis results was not confirmed in the period, and it became clear that the subsidence progressed at an almost constant speed. This study shows that the deformation volume and uplifted/subsided land deformation trends are matched with GPS results. This fact indicates the usefulness of InSAR, especially for land subsidence monitoring using free-available satellite data.

This study carried out SBAS-InSAR analysis over two years from 2019 to 2020 in Chiba, Niigata, Bangkok, and Delhi, where land subsidence has been reported steadily and concerned for damaging assets, including residents' lives. In these land subsidence areas, the SAR satellite images' results almost agreed in both range and magnitude of fluctuation. To verify the accuracy of the SBAS-InSAR results, we compared the results with GPS measurements. As a result, it was confirmed that sufficient accuracy was obtained to specify the land subsidence area over 1cm/year. Thus, this study confirmed that the analysis using many satellite images was adequate for monitoring minute fluctuations that continued over a long period. In addition, when administrative organizations deal with infrastructure plan leveling of land subsidence investigation, it is expected that the leveling can be carried out after the subsidence range is grasped in the plane by utilizing the result of InSAR analysis and the efficient land subsidence investigation can be carried out.

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