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ASSESSING RESERVOIR DAM STABILITY USING C-BAND PERMANENT SCATTERERS INSAR

The purpose of this article is to analyze the results of processing time series of radar images using the Persistent Scatterer method to assess the stability of the vertical position of the reservoir dam. The object of this study is the dam of the cooling pond at the Khmelnytskyi Nuclear Power Plant. Due to production needs, the task arose to analyze the dam's stability in the vertical position using an independent method for the 2016-2022 period. Implementing such a task became possible only by utilizing a satellite radar image database for the specified area. The input data for the analysis consisted of 13 radar images of the specified area obtained from the Sentinel-1 satellite, covering the period from May 2016 to May 2022 with a six-month interval. Processing satellite radar data using the StaMPS algorithm allowed for creation of maps of average surface movement velocities. After applying spatial-correlated and tropospheric corrections, the vertical velocity range of the developed deformation maps for the investigated area was [-9.0; +8.3] mm/year. At the industrial site area, the average velocities of vertical displacements are close to zero, this indicates the stability of the specified area according to InSAR observations. Analyzing the plots of vertical movements of the dam it was observed that the displacements exhibit a cyclic pattern, which is associated with seasonal influences on the structure. The magnitude of maximum displacements during the investigated period ranged from [-10 mm; +10 mm]. The obtained data indicate the absence of hazardous deformation processes that could affect the operational reliability of the reservoir dam. A comparative analysis of the results with time series of vertical movements of reservoir dams in Poland (Niedzica Dam, Solina Dam, Włocławek Dam) was performed. The time series obtained from the European Ground Motion Service data confirm the presence of seasonal cyclic movements of the dams. The practical significance of the research results lies in confirming the effectiveness of using a time series of C-band radar images for geodetic monitoring of reservoir dam stability. Due to access to the existing database of radar images of the Sentinel-1 satellite, the task of assessing the stability of the vertical position of the dam of the cooling reservoir of the Khmelnytsky NPP for the period from 2016 to 2022 was solved.

Key words: geodetic monitoring, SAR images, Persistent Scatterer method, StaMPS, Sentinel-1, EGMS.

Introduction

Interferometric Synthetic Aperture Radar (InSAR) is an advanced technology utilized for processing radar images, serving as a crucial tool in discerning deformations across the Earth's surface, spanning vast regions. Initially conceived to generate digital elevation models and ascertain vertical shifts in terrain due to phenomena like volcanic eruptions, seismic activities, or human interventions such as mining, InSAR has evolved significantly. With advancements in radar image processing techniques, InSAR has transcended its original scope of monitoring expansive landscapes to enable precise measurements of localized engineering structures and facilities.

InSAR remote sensing technology provides users with systematically updated data, enabling the creation of time series of images and facilitating the analysis of spatio-temporal changes within them.

Many scientific publications confirm the widespread use and interest in using radar images to monitor the spatial position of various engineering objects: satellite radar interferometry data are used to monitor dams at large hydroelectric facilities [Cifres et al., 2018; Bayik et al., 2021], locks on navigable rivers [Kauther and Schulze, 2015], transport infrastructure [Dai et al., 2018; Macchiarulo et al., 2022], bridges [Selvakumaran, 2020; 2022], airports [Zhang, 2021], etc.

The short wavelength (≈5.6 cm) generated by the radar is highly sensitive to displacements of the Earth's surface in the direction of boresight. [Kelevitz, 2022]. This allows for capturing surface displacements between acquisitions with millimeter accuracy. Obviously, this fact requires additional verification of the obtained data. Therefore, satellite monitoring results are often compared with ground-based data. The combination of monitoring systems for railway bridges using InSAR and GNSS methods is described in the work [Qiang, 2020]. It has been established that both methods provide high accuracy in determining the position of bridge structures and are in agreement with each other. The article [Liu, 2011] presents the application of the Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) method for analyzing surface deformations in urban areas. The values of the obtained displacement are well aligned with the results of geometric leveling.

In addition to satellite interferometry, ground-based radar acquisition also warrants attention. Article [Qiu, 2020] focuses on monitoring surface deformations of a hydroelectric dam using ground-based radar. Data processing was performed using the Persistent Scatterer method, and the results clearly agreed with independently conducted deformation measurements. The accuracy of deformation results determined using InSAR technology, as declared in [Macchiarulo et al., 2022], at the level of traditional geodetic methods, leads us to compile a list of the main advantages of satellite radar monitoring method for assessing the structural condition of engineering objects:

1. Economic efficiency due to data accessibility.
2. High temporal resolution (the time interval between acquisitions for Sentinel-1 satellites is 6-12 days).
3. Access to satellite imagery databases allows not only the assessment of the current state of the structure but also the exploration of spatial position changes in the past.

Several common methods are utilized to determine vertical deformations based on radar image data [Xu, 2022]: the differential interferograms method (DInSAR), as well as its derivatives - the Persistent Scatterer method (PSI) and the Small Baseline Subset method (SBAS). Each of these methods has its advantages for solving specific tasks. The method of differential interferograms is applied to individual pairs of images, yielding accurate results in determining vertical displacements of the terrain that occurred over a short period. Therefore, it is well-established for assessing geodynamic processes (Kopačková, 2019; Wempen, 2020; Tretyak, 2023) as well as determining vertical movements of engineering objects (Nesterenko, 2022). However, developing individual differential interferograms for processing large time series of radar images has several limitations (Parcharidis, 2009):

1. Low phase coherence on images due to long baseline;
2. Complete loss of coherence with increasing time intervals between acquisitions;
3. Challenges with interferogram unwrapping;
4. Increasing influence of atmospheric effects and lack of correction capabilities;
5. Inability to automate the data processing process.

Therefore, for processing large amounts of data during long-term monitoring, it is advisable to use the Persistent Scatterer method or Small Baseline Subset method [Yazici, 2020; Dorosh, 2021].

The object of this study is the dam of the cooling pond at the Khmelnytskyi Nuclear Power Plant. Due to production needs, the task arose to analyze the dam's stability in the vertical position using an independent method for the 2016-2022 period. Implementing such a task became possible only by utilizing a satellite radar image database for the specified area.

The purpose of this article is to analyze the results of processing time series of radar images using the Persistent Scatterer method to assess the stability of the vertical position of the reservoir dam.

Methods

To assess the stability of the vertical position of the reservoir dam, satellite radar imaging data and the Persistent Scatterer Interferometry (PSI) processing algorithm were employed. As mentioned earlier, PSI is a powerful tool for analyzing time series of radar images, particularly for monitoring vertical displacements of engineering structures.

The input data for the analysis consisted of 13 radar images of the specified area obtained from the Sentinel-1 satellite, covering the period from May 2016 to May 2022 with a six-month interval.

The Sentinel-1 satellites support several imaging modes, providing an intermediate level of radar image resolution. The radar images used for processing were acquired in IW (Interferometric Wide) mode with a spatial resolution of 5□20 meters per pixel.

The area of interest within one image is shown in Fig. 1.

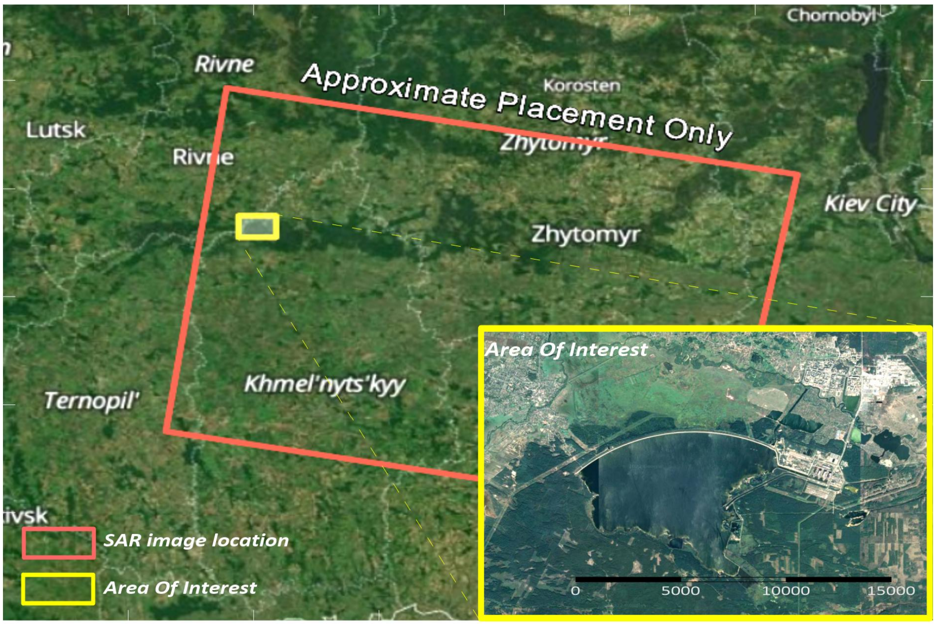

Fig. 1. Area of interest and footprint of the selected Sentinel-1 image

The processing of satellite radar imaging data using the Persistent Scatterer Interferometry (PSI) method was conducted in three stages using various software products:

1. Preliminary data preparation using the SNAP (Sentinel Application Platform) software.
2. Automated data preparation using the SNAP2StaMPS algorithm.
3. Implementation of the StaMPS (Stanford Method for Persistent Scatterers) method in the MatLab program.

The SNAP software was used to analyze a series of radar images and determine a perpendicular baseline (Table). Based on this analysis, the master image (date of acquisition: 2019/11/04) and secondary images were identified.

The SNAP2StaMPS algorithm consists of scripts written in Python, which are freely available. With their assistance, data preparation for processing was carried out, as well as the initial stages of generating interferograms between the master and secondary images. These processes include [Blasco et al., 2019]: subsetting the radar image to the boundaries of the study area; applying satellite orbit correction data; coregistration pairs of the master and secondary images, and interferogram formation. The results of this processing stage are presented in Fig. 2.

The implementation of the Stanford Method for Persistent Scatterers (StaMPS) is carried out in the MatLab program. Therefore, the final stage of the SNAP2StaMPS algorithm was preparing the data for export to the MatLab environment.

№	Acquisition date	Perpendicular baseline, m	Temporal baseline, days
1	20160511	-36.83	1272.00
2	20161107	10.17	1092.00
3	20170506	15.81	912.00
4	20171102	60.23	732.00
5	20180513	51.50	540.00
6	20181109	87.90	360.00
7	20190508	-29.27	180.00
8	20191104	0.00	0.00
9	20200502	-53.64	180.00
10	20201110	4.17	372.00
11	20210509	41.20	552.00
12	20211105	33.77	732.00
13	20220504	-144.16	912.00

The Persistent Scatterer method by StaMPS algorithm consists of eight steps [Serco, 2020], which enable fully automated processing (except for changes or adjustments to individual parameters), as well as introducing corrections for terrain, satellite orbit, and estimating the magnitude of tropospheric signal delay.

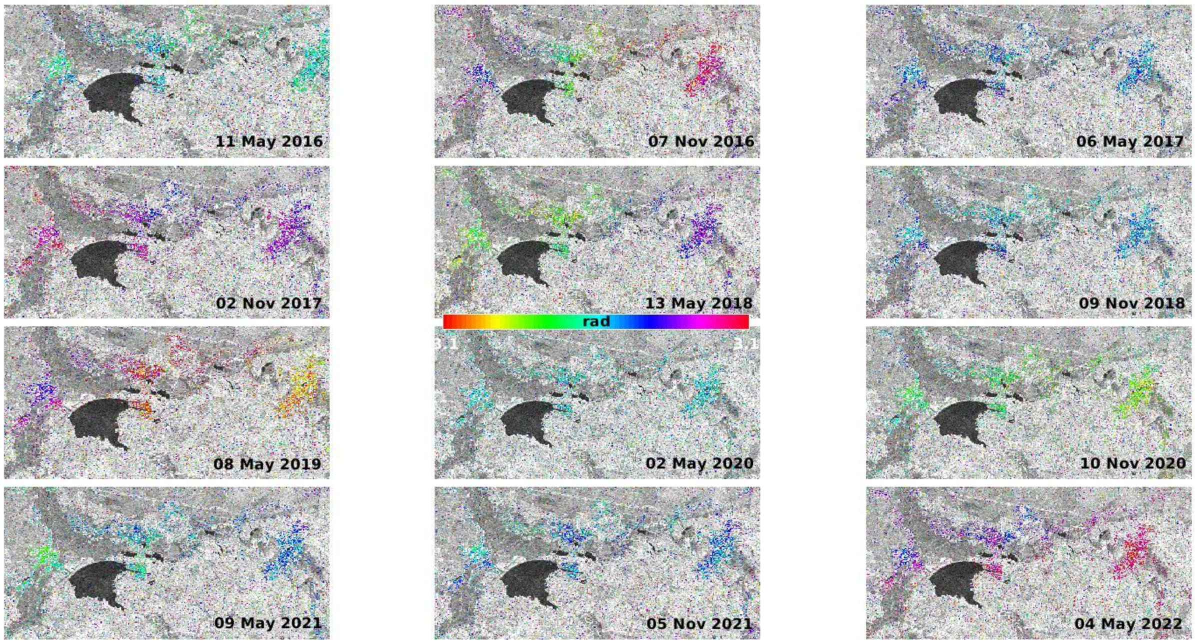

Fig. 2. Complex interferograms of each pair (master-secondary) of images. The date on the interferogram corresponds to the date of the secondary image. The phase range on the wrapped interferogram is [-3.14; +3.14]

Results

Processing satellite radar data using the StaMPS algorithm helped create maps of average vertical surface movement velocities. Since only radar images from a descending satellite orbit were used for processing, the results represent surface movements along the satellite line-of-sight. This is due to the inclination of the satellite radar during the imaging process. The actual values of vertical movements of the Earth's surface will not exceed the obtained values.

Fig. 3 shows maps of average deformation velocities for the investigated area: Fig. 3a – average velocities before applying spatially correlated (DEM) corrections; Fig. 3b - average velocities after applying corrections for digital elevation model, satellite orbit, and atmosphere delay. As a result of applying the above-mentioned corrections, the vertical velocity range decreased from [9.6; +9.3] mm/year to [-9.0; +8.3] mm/year.

Each point on the resulting map is identified as a persistent scatterer, which provides a stable and reliable signal during each acquisition. The preliminary assessment of the vertical velocity map indicates the overall stability of the investigated area - the average velocities are close to zero.

The map of standard deviations of mean surface movement velocities along the satellite line-of-sight is presented in Fig. 4. This value provides information about the variability or uncertainty associated with the calculated velocities of points identified as persistent scatterers across the studied area. A higher standard deviation indicates greater variability in the measured velocities, while a lower standard deviation suggests more consistent velocities among the persistent scatterers. The obtained values for the studied area do not exceed 1 mm/year, indicating the stability of the research area [Elias et al., 2009].

A map of velocities combined with an image of the average amplitude of the reflected radar signal presents better visualization of persistent scatterers in the study area, particularly on the reservoir dam (Fig. 5). On the area of the industrial site, the average velocities of vertical displacements are close to zero. This indicates the stability of the specified area according to InSAR observations.

Each point on the obtained deformation map (Fig. 5) contains information about the time series of height changes. Therefore, to solve the main task of assessing the stability of the height position of the reservoir dam, the results for all points on the dam surface were analyzed.

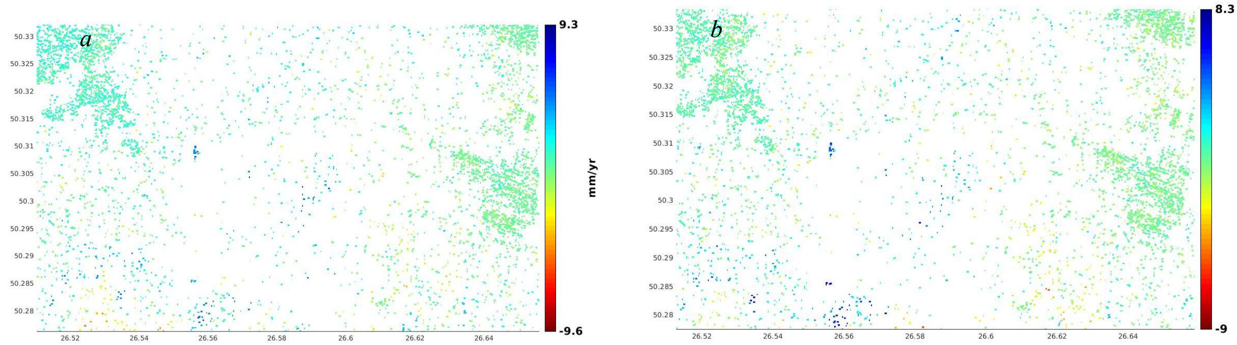

Fig. 3. Mean line-of-sight (LOS) velocity map: a) velocity range before corrections [9.6; +9.3] mm/year; b) velocity range after corrections for spatially correlated DEM error, orbital ramps, and atmosphere delay [-9.0; +8.3] mm/year

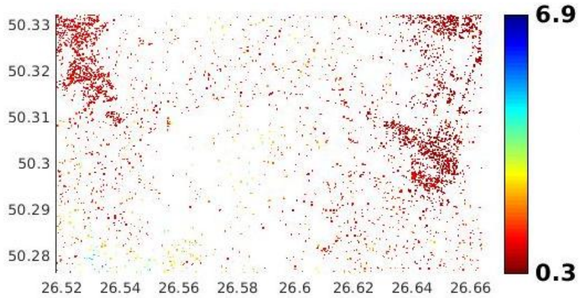

Fig. 4. Standard deviation of mean LOS velocity for the study area does not exceed 1 mm/year

To present the obtained results, three control points (CP1, CP2, CP3) were selected on the reservoir dam (Fig. 5). The Matlab program allows for developing displacement plots based on the data of persistent scatterers located in the vicinity of the specified (control) point within a defined radius. To obtain the history of vertical movements of persistent scatterers located exclusively on the dam, a radius of 10 meters was specified. Plots of vertical deformation for the three control points are presented in Fig. 6.

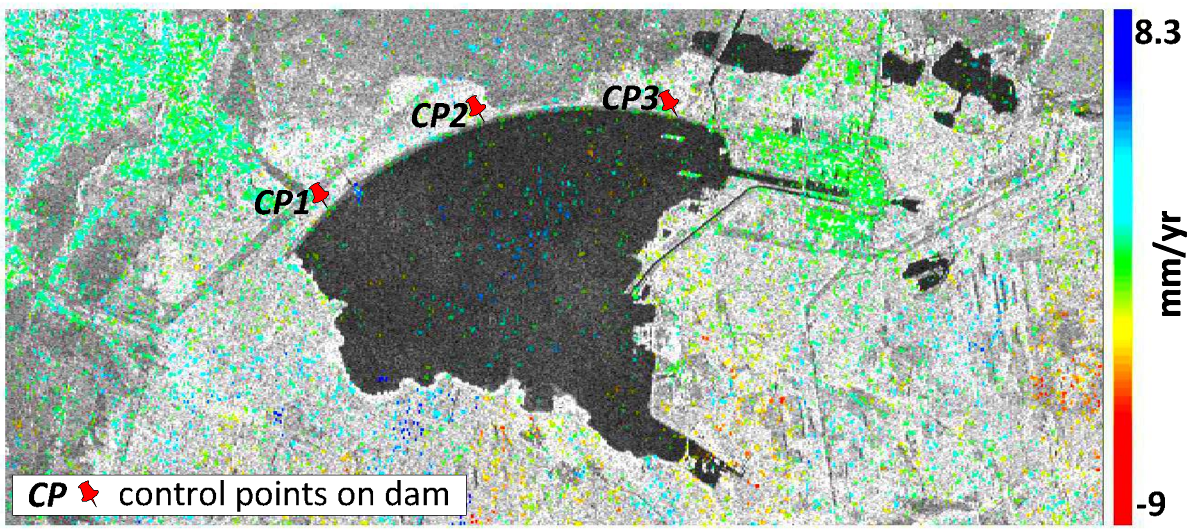

Fig. 5. Mean deformation velocity map considering spatially correlated corrections for the study area. The deformation history of the control points on the dam has been obtained from time-series analysis by the InSAR method.

Analyzing the plots of vertical movements of the dam, we observe that the displacements exhibit a cyclic pattern, which is associated with seasonal influences on the structure. The magnitude of maximum displacements during the investigated period ranged from [-8 mm; +5 mm] for control point CP1; [-10 mm; +10 mm] for control point CP2; and [-7 mm; +7 mm] for control point CP3. The obtained data indicate the absence of hazardous deformation processes that could affect the operational reliability of the reservoir dam.

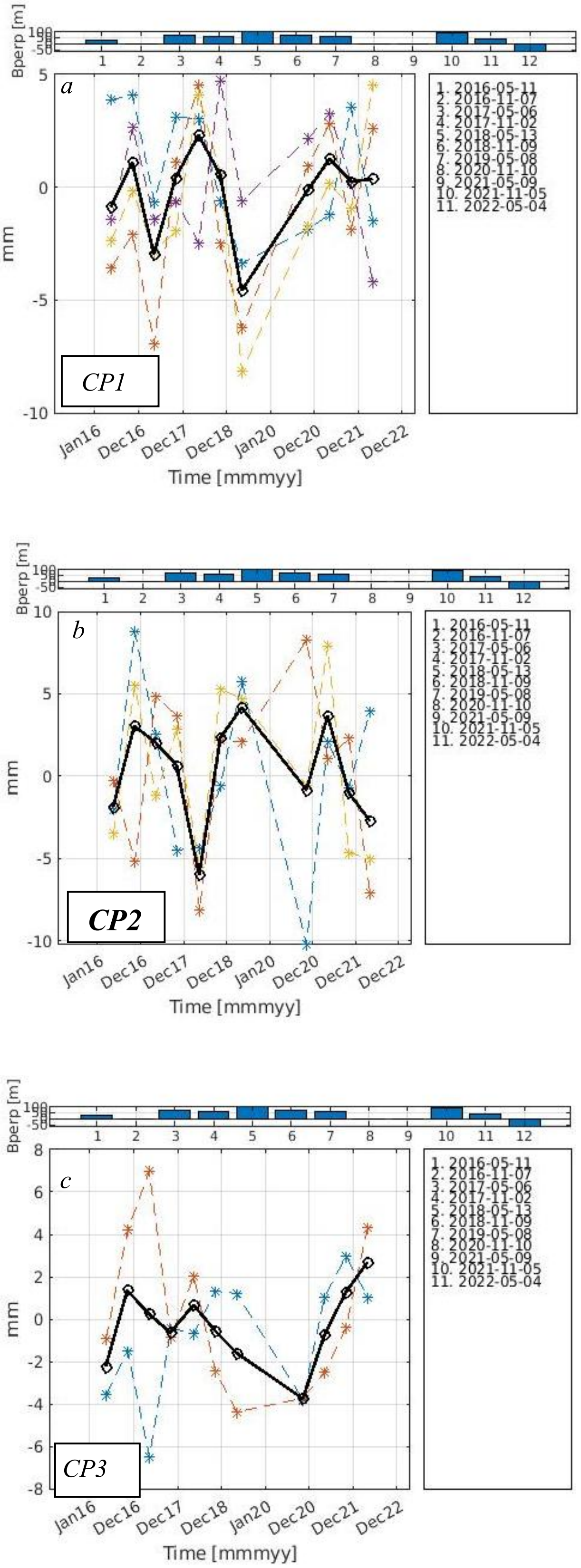

Fig. 6. Plots of average vertical displacements: a) control point CP1; b) control point CP2; c) control point CP3

Comparison of results

The monitoring results of several dams located in Poland were considered to confirm the nature of cyclic vertical movements of dams over a prolonged observation period. For this purpose, we utilized data from the EGMS - European Ground Motion Service (https://egms.land.copernicus.eu), managed by the Copernicus program.

EGMS is an online resource that utilizes data from radar satellite imaging by Sentinel-1 to detect and measure surface movements with millimeter precision for the territory of European Union countries. The processing of the presented results is carried out using the Persistent Scatterer Interferometry (PSInSAR) method. Therefore, users of the service are able to display a time series of vertical movements of a dense network of points covering the Earth's surface, engineering, and infrastructure objects.

Fig. 7 shows the locations of three hydropower complexes, including reservoir dams, in Poland: Niedzica Dam, Solina Dam, and Włocławek Dam.

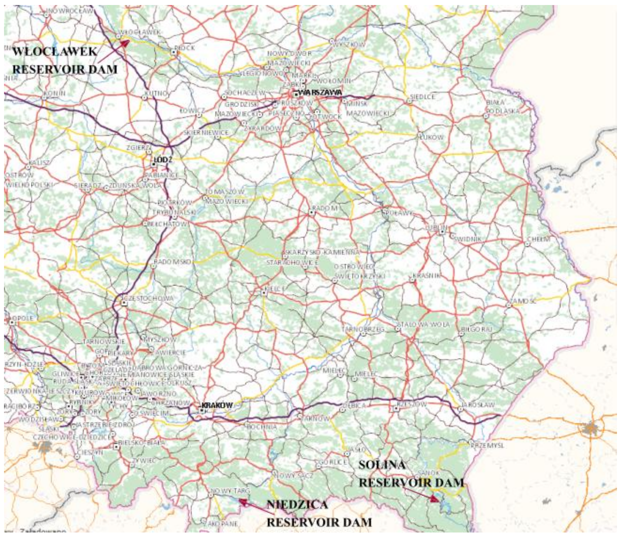

Fig. 7 Location of the three largest hydropower complexes on the territory of Poland

Time series of vertical movements of points located on the concrete dams of these hydropower facilities have been obtained according to EGMS data (see Fig. 8).

Fig. 8 presents data processed for the period from 2018 to 2023. The five-year study allowed for tracking the seasonal cyclic movements of the dams at all three facilities. A common characteristic of the presented trends is the attainment of maximum vertical position from June to August, while the minimum vertical position is observed from December to February.

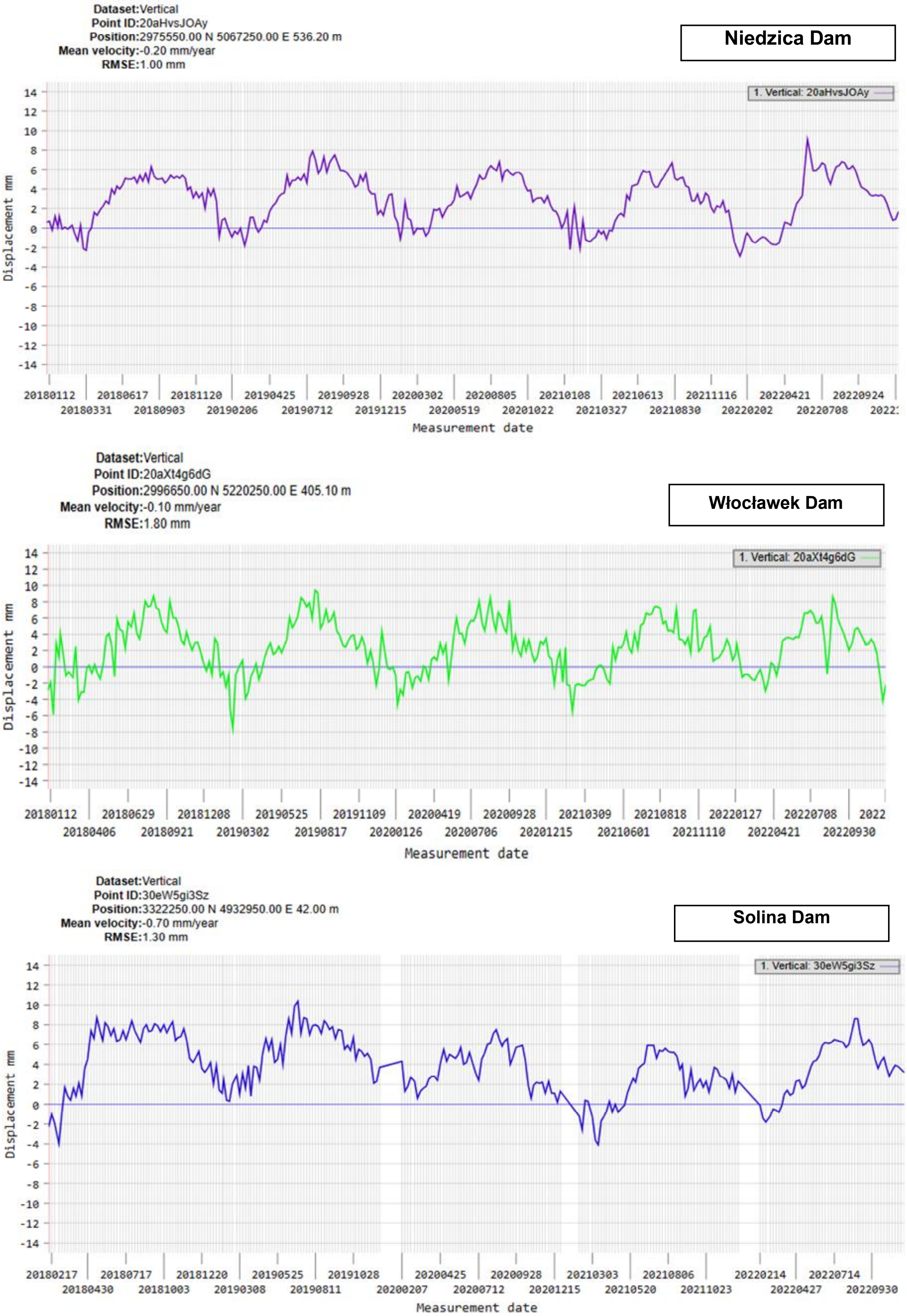

Fig. 8. Time series of vertical movements of dams: Niedzica Dam, Solina Dam, Włocławek Dam (according to EGMS)

The nature and range of vertical movements are more individualized and are determined by the structural peculiarities of the dam (including its dimensions), the location of the persistent scatterer point, and a combination of meteorological parameters. Throughout the study period, the magnitude of maximum vertical displacements on the Niedzica Dam ranged from [-3 mm; +9 mm]; on the Solina Dam from [-4 mm; +10 mm]; and the Włocławek Dam from [-8 mm; +9 mm].

Seasonal changes associated with variations in the vertical position of reservoir dams within the range of ±10 mm are observed on all investigated objects. The data from the EGMS service correlate with the results of processing radar images from the Sentinel-1 satellite for the cooling pond dam of the Khmelnytskyi Nuclear Power Plant.

Scientific novelty and practical significance

The practical significance of the research results lies in confirming the effectiveness of using a time series of C-band radar images for geodetic monitoring of reservoir dam stability. Due to access to the existing database of radar images of the Sentinel-1 satellite, the task of assessing the stability of the vertical position of the dam of the cooling reservoir of the Khmelnytsky NPP for the period from 2016 to 2022 was solved.

Conclusions

Access to databases of satellite radar images is a valuable tool that enables the analysis of spatiotemporal changes in images accumulated over the entire operational period of a satellite mission. Thus, it is possible not only to assess current spatial movements of the Earth's surface but also to analyze changes that occurred in the past.

Improved methods of radar interferometry, including Persistent Scatterer Interferometry (PSI), enable the determination of ground surface displacements with millimeter-level accuracy through the processing of large time series of radar images. This is particularly relevant and increasingly widespread for monitoring the spatial position of engineering objects and structures.

The application of the Persistent Scatterer method in processing satellite radar images for the territory of the Khmelnytskyi Nuclear Power Plant allows us to make conclusions about the stability of the object's territory in the vertical position. According to the created map of average vertical deformation velocities of the Earth's surface from 2016 to 2022, the average velocities within the industrial site of the station are close to zero. During the analysis of the persistent scatterer data located on the reservoir dam, it was found that the magnitude of the maximum vertical displacements during the study period did not exceed ±10 mm. The small amplitude of displacement values and their cyclic nature indicate a seasonal pattern in the displacement results. The obtained values of the standard deviations of the mean vertical deformation velocities of the investigated territory do not exceed 1 mm/year, further indicating the stability of the area of interest.

The results of radar monitoring of the reservoir dam of the Khmelnytskyi Nuclear Power Plant closely correlate with the time series of vertical movements of three dams in Poland, obtained from the European Ground Motion Service based on the PSInSAR method.

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ОЦІНКА СТАБІЛЬНОСТІ ДАМБИ ВОДОСХОВИЩА ЗА ДОПОМОГОЮ МЕТОДУ ПОСТІЙНИХ РОЗСІЮВАЧІВ INSAR C-ДІАПАЗОНУ

Метою даної статті є аналіз результатів обробки часових рядів радіолокаційних знімків методом постійних розсіювачів для оцінки стабільності вертикального положення дамби водосховища. Об'єктом дослідження є дамба ставка-охолоджувача Хмельницької атомної електростанції. У зв'язку з виробничою необхідністю постало завдання провести аналіз стійкості дамби у вертикальному положенні незалежним методом за період 2016-2022 рр. Реалізація такого завдання стала можливою лише за рахунок використання бази даних супутникових радіолокаційних знімків зазначеної території. Вхідними даними для аналізу стали 13 радіолокаційних зображень зазначеної місцевості, отриманих із супутника Sentinel-1, що охоплюють період з травня 2016 року по травень 2022 року з інтервалом у шість місяців. Обробка супутникових радіолокаційних даних за алгоритмом StaMPS забезпечила створення карт середніх швидкостей руху поверхні. Після застосування просторово-корельованих і тропосферних поправок діапазон швидкостей розробленої карти деформацій, для досліджуваної території, становив [-9,0; +8,3] мм/рік. В районі проммайданчика середні швидкості вертикальних переміщень близькі до нуля, що свідчить про стабільність зазначеного району за даними спостережень InSAR. Аналізуючи графіки вертикальних переміщень дамби, встановлено, що переміщення мають циклічний характер, який, очевидно, пов'язаний із сезонними впливами на конструкцію. Величина максимальних переміщень за досліджуваний період становила [-10 мм; +10 мм]. Отримані дані свідчать про відсутність небезпечних деформаційних процесів, які могли б вплинути на експлуатаційну надійність дамби водосховища. Виконано порівняльний аналіз результатів з часовими серіями вертикальних рухів дамб водосховищ на території Польщі (Niedzica Dam, Solina Dam, Włocławek Dam). Отримані за даними сервісу European Ground Monitoring Service часові серії підтверджують наявність сезонних циклічних рухів дамб. Практичне значення результатів дослідження полягає в підтвердженні ефективності використання часових рядів радіолокаційних зображень C-діапазону для геодезичного моніторингу стійкості греблі водосховища. Завдяки доступу до існуючої бази даних радіолокаційних знімків супутника Sentinel-1 вирішено завдання оцінки стійкості вертикального положення дамби водойми-охолоджувача Хмельницької АЕС за період з 2016 по 2022 роки.

Ключові слова: геодезичний моніторинг, радіолокаційні знімки, метод постійних розсіювачів, StaMPS, Sentinel-1, EGMS.

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