The use of the DInSAR method in the monitoring of road damage caused by mining activities

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Abstract. This paper reviews existing remote sensing methods of road damage detection and demonstrates the possibility of using DInSAR (Differential Interferometry SAR) method to identify endangered road sections. In this study two radar images collected by Sentinel-1 satellite have been used. Images were acquired with 24 days interval in 2015. The analysis allowed to estimate the scale of the post-mining deformation that occurred in Upper Silesia and to indicate areas where road infrastructure is particularly vulnerable to damage.

Keywords: DInSAR, road damage, Sentinel-1

1 Introduction

One of the biggest challenges in road infrastructure management is early detection of its damages and taking actions to reduce repairing costs. Many studies shows that early detection of damages increase the road quality life and reduce the total maintenance cost. Therefore, there is a need for road monitoring methods that facilitate the detection of the road damage.

   Roads and railways are very sensitive for ground deformation. In the paper [1] authors described destructive effects of subsidence in case of linear, large infrastructure objects (like railway and highway). Authors presented parameters responsible for horizontal deformation, inclination and curvature as a reason of problems with infrastructure and even its destruction. Among other threats, changing the slope of the terrain can lead to slide off slowly moving vehicles inside the curve or slide off outside the curve of the track when driving at the maximum speed for which the radius of movement was designed. Horizontal deformation of the ground surface may lead to loosening of the ground of embankment and lowering its bearing capacity and to cracks in the pavement structure. In the case of vertical displacements, there may also be changes in water relations within the road and its neighbourhood. It have to be note that some buildings are also part of the road infrastructure. Vertical dislocations may cause serious damage in the form of additional compression, tensile, torsional stress, etc. This can significantly limit or even prevent from use of communication routes subjected to such processes. Hence the monitoring of road

damage can be extremely important both in terms of safety and minimization of repair costs.

Many authors indicate the large potential for the use of satellite remote sensing in detecting road infrastructure damage. One of the remote sensing system is Synthetic Aperture Radar (SAR). SAR system is most often mounted on satellite platform. It emits microwaves towards Earth surface. Back-scattered rays are collected on SAR antenna. It gives information about signal strength and its phase for each resolution cell in SAR imagery [2]. The aim of this work is to review existing SAR methods of road damage detection as well as to demonstrate the possibility of using Differential Interferometry SAR (DInSAR) method.

2 Road damage detection using remote sensing data

Remote sensing methods can be used to detect road damage. The most commonly used sensors to accomplish that task are: multispectral camera, hyperspectral camera, Synthetic Aperture Radar (SAR), LIDAR and Terrestial Laser Scanning. Some methods work in a direct way, indicating places where the road surface is cracked while others indirectly - indicating potentially endangered areas (for example where the ground was unstable), which could lead to road damage. The detection methods presented here concerns paved roads built of such materials as asphalt or concrete cement.

2.1 Multispectral reflectance analysis

One of the most commonly used remote sensing methods of investigating road damage is spectral reflectance analysis. Paved road structural damages like cracking result in high reflectance detected by multispectral sensor. On the other side, undamaged, good quality paved road shows lower reflectance values.

Wei et al. in [3] analyze the spectral properties of asphalt in order to distinguish an old and deteriorated road from a new-built road. Authors conclude that the minimum reflectance for each type of road is near 350 nm wavelength and it rises with wavelength used in sensing system. The most noticeable differences of the observed reflectivity for the new and old roads are visible in the SWIR regions – 1750 nm wavelength. It is also worth to note, that different types of asphalt reflect radiation in various ways, so only roads of the same type of material can be compared.

In [4] authors use airborne MIVIS (Multispectral Infrared Visible Imaging Spectrometer) sensor data. The results of this study demonstrate the utility of airborne remote sensing for discriminating roads which requires a maintenance work. When the road paving asphalt is made of a mixture of limestone granules and bitumen, then surface defects are related to the decrease of the oily components of the bitumen. This causes percentage increase of limestone granules fraction in an asphalt. Such phenomenon enables to distinguish deteriorated surface from a good quality one by retrieving the emissivity spectral features of asphalt in 8-13μm TIR range.

Another work points out [5], that not only asphalt has higher reflectance values as it degrades, but also becomes less uniform in texture on multispectral images. The calculation of asphalt pavement statistics in the image indicated that road damages leads to broadening of the data range on image and variance and entropy increase.

2.2 SAR backscattering analysis

The usefulness of SAR data in the study of road quality has been confirmed by many authors. Especially the robust method is the backscatter signal analysis registered on an image as an amplitude.

Suanpaga and Yoshikazu [6] proposed an approach to determine the level of highway riding service using SAR data. The aim of this work was to investigate the influence of backscattering values of Phase Array SAR (PALSAR, L-band). Performed analysis showed that a poor condition of the road was manifested in the image by higher backscattering value for copolarization (HH or VV polarization). Authors concluded that the most robust variable for developing riding quality evaluation was the HH backscattering value. The accuracy of presented approach was 87.00%.

Another study [7] exploits SAR data acquired at X-band frequencies. Authors compare high-resolution Cosmo-SkyMed data with road roughness data obtained with ground surveying methods. Research work shows significant correlation of SAR image radar cross section with pavement roughness. At X-band radar brightness generally increases when pavement roughness worsens. The overall accuracy obtained with this method was 92%.

2.3 Persistent Scatterer Interferometry

One of the satellite methods of road monitoring is Persistent Scatterer Interferometry (PSI). This method does not provide direct information on road surface damage. Its result is a vertical displacement map of persistent scatterers points. Such points may be buildings, rock outcrops or elements of road infrastructure. So this method enables to monitor the deformations of roads, their infrastructures and, surroundings. Its technical assumptions were described in [8].

An example of the use of the PSI method has been presented in [9]. The PSI analysis was performed using high-resolution TerraSAR-X data. Authors used 28 SAR images in order to derive vertical displacement map of pints in Barcelona metropolitan area. The analysis enabled to detect fragments of a new part of C-31 highway that is threatened with ground subsidence. Subsidence phenomenon is caused here by recent construction of this part of the highway, not by underground mining excavation.

Another example of the use of PSI technique is described in [10]. The purpose of this work was to detect active landslides in the Carpathian region based on ERS-1/2 satellite data obtained before the year 2000. Analysis revealed a linear deformation of the area along the Osielec-Jordanów road of 3.8 mm/year. In 2008, this road required renovation due to the damage caused by an active landslide. However authors indicates that analysis of landslide deformation using PSI in Carpathians is possible, but very difficult due to, among others, rough topography and dense vegetation cover.

3 Differential Interferometry SAR method

Another indirect method of detecting road damage as a result of mining activities is the detection of subsidence troughs that occurred under road infrastructure. To obtain vertical ground subsidence information SAR images can be processed with interferometric methods. One of them is Differential Interferometry SAR (DInSAR). To compute differential interferogram, at least two same-area SAR images are required. One of them is a reference image (master). Comparing master image with the second image (slave) it is possible to compute vertical ground deformations that occurred between time of slave and master images acquisition [11,12]. The inclusion of another SAR images into analysis enables to perform ground deformations analysis through time. DInSAR method accuracy

is about 1 cm in vertical direction. This method is particularly suitable to detect post-mining subsidence phenomenon. On differential interferogram ground deformations are represented as fringes of wrapped phase (values between -π and π). Then fringes can be converted into ground displacement values in the satellite Line of sight (LOS) direction. One interferometric fringe (in case of DInSAR analysis) is equal to the half of the SAR system wavelength.

Vertical displacements information can be used to identify sections of roads and railway tracks that have been (or may be) damaged due to mining activities. Single scene of radar imagery covers large area (even over 15000 km^2) which makes it possible to analyze all important roads in the city with a single analysis.

3.1 Exploited dataset

Ground subsidence can be caused by natural phenomena, but it can also be an effect of anthropological processes. Most common reason of subsidence caused by human activity is underground coal mining. In Poland the most intensive coal excavation activities are located in Upper Silesian Coal Basin (USCB). Even on areas where mining activity was stopped subsidence can occur [13].

DinSAR analysis was performed for Bytom city that is located within USCB. This city was selected for analysis due to the mining activity that has been conducted there for many years. Transport routes of regional significance run through Bytom. Many of them have been damaged as a result of underground mining excavation. Analysed city covers area of 69,5 km^2.

In this paper Sentinel-1A (5,5 cm wavelength) images acquired in 29.11.2015 and 23.12.2015 were used. 24 days time interval was chosen to achieve good coherence of radar images. High coherence made it possible to obtain results with a precision of up to 1 cm. Satellite data were processed in SNAP software provided by European Space Agency.

3.2 Results

First step of the analysis was to compute differential interferogram representing the surface deformations that occurred between 29.11.2015 and 23.12.2015. Quality of the interferogram can be measured with coherence values. Coherence is determined by the degree of compliance of the SAR signals phase – the higher the value, the more accurate the interpretation of the interferogram will be. Areas where coherence value is below 0.3 are not suitable for DinSAR analysis. The average coherence value of used images in Bytom city is 0.47.

Then interferogram was converted to ground subsidence map (fig.1). One subsidence trough in the central part of Bytom was detected. Depth of this trough was about 6 cm. The centre of detected trough is localized at 18°52'10"E, 50°21'24"N.

4 Discussion

The urban area where the greatest threat related to land displacement was detected is the central part of the city of Bytom (Karb district). It can be noticed that a significant part of the subsidence trough is located under the motorway interchange. This creates a risk of damaging the road infrastructure. This trough reaches 6 cm depth and covers the part of DK94 and DK88 roads, as well as the Family Garden Parks "Rekreacja", residential buildings between "Warszawska" street and "Celna" streets. The area of the trough is 0.95 km^2.
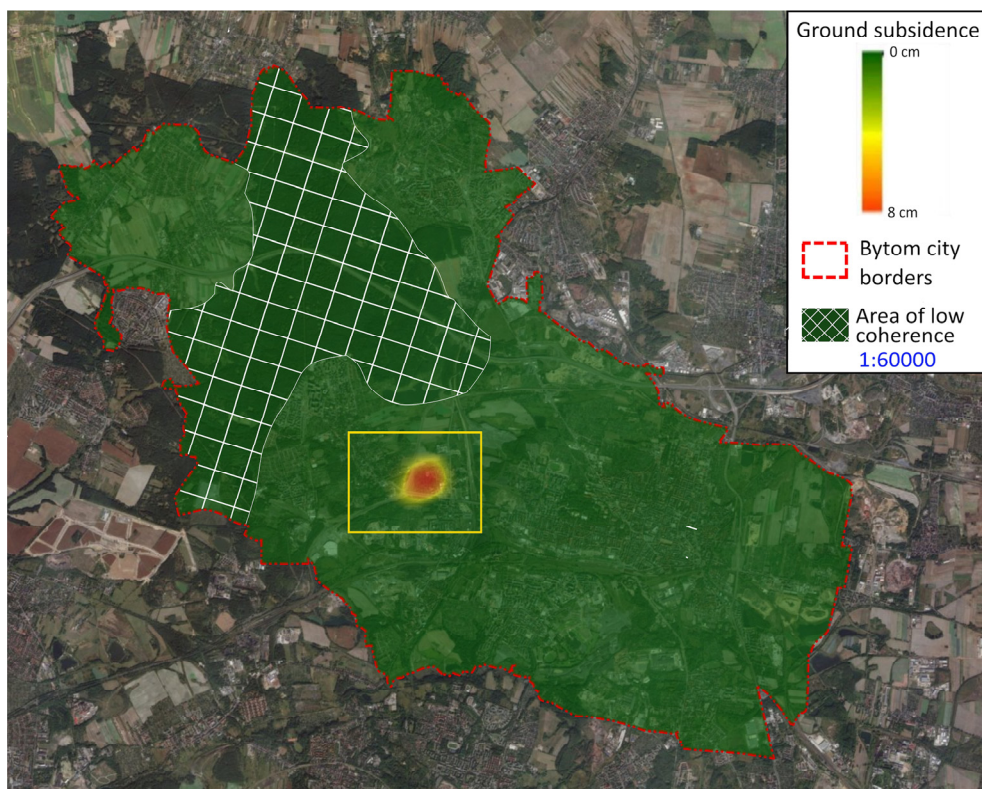
Fig.1. Map of ground subsidence that occurred between 29.11.2015 – 23.12.2015. One subsidence trough was detected in the central part of Bytom city. Area marked in white is the area of low coherence and was not included in analysis.

Area under DK94 route has collapsed on the section of about 1200 m, while under DK88 route on the section of about 1000 m. In both cases, the maximum subsidence exceeded 5 cm. It should be emphasized, that the detected terrain deformations occurred within only 24 days (between November 29, 2015 and December 23, 2015). Mining damage caused by mining operations conducted under the Karb district in Bytom has been registered for many years. Negative effects of coal mining have damaged, among others, water supply systems in the district, viaduct on Wrocławska street, or a nearby gas station [14]. In addition, in June 2016, the restaurant "McDonald's" located at Konstytucji street was closed. The reason for the decision was the poor technical condition of the building and high maintenance costs related to the growing costs of removing mining damage. Perhaps if the monitoring of the stability of this area was carried out earlier, the decision to build a restaurant in this place would not have been made and the DK88 and DK94 routes would be planned in a different way to avoid its destruction.

5 Conclusions

The results presented above confirm the usefulness of DInSAR method in detecting sections of roads threatened by damage associated with underground mining activities. This method does not show road surface damage but indicates the road sections where these damage occurred or may occur in the future. Such approach allows to identify the

endangered sections of not only large road sections , but also the smaller ones due to the indication of the whole area where ground subsidence was detected.

The differential radar interferometry method is well suited for monitoring of road damage caused by mining activities because of:

- single radar scene covers large area, which enables effective monitoring of the entire road network,
- results obtained for the entire area, not only in individual measurement points (contrary to PSI method),
- measurement accuracy of 1 cm vertically (for coherent areas),
- no need to conduct field tests,
- the type of asphalt covering the road does not limit the applicability of the method,
- prior knowledge about reflectance curve of undamaged road is not necessary (contrary to multispectral reflectance analysis method),

Despite many advantages, there are also some limitations of DInSAR method. First of all measurements are possible only for coherent areas. Moreover DInSAR does not allow the detection of horizontal displacements or discontinuous deformations. Nevertheless, the DInSAR method used together with other remote sensing methods can be a very powerful tool for detecting road damage.

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