APPLICATION OF ASAR INTERFEROMETRY FOR MOTORWAY DEFORMATION MONITORING

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ABSTRACT

SAR Interferometry is a method that allows to measure land subsidence on radar coherent areas with high precision. This method can measure displacements of the terrain surface smaller than one centimeter. A very important feature of the method is that since the SAR data are acquired frequently it is possible to use archived data to measure deformations over the last fifteen years for almost any place on Earth.

The A4 motorway partly is located in the Upper Silesian, Poland. This area is characteristic because it is a region where underground black coal exploitation is conducted. For such types of mining, huge terrain surface deformations are very common [1]. The coal mining continued even during the construction of motorway. Before the start of the motorway construction, agreements were made between the coal mine and the motorway construction company, to define and regulate the rules of exploitation. Eight longwalls were exploited directly under the motorway. Seven of them do not induce any unexpected deformations of the road embankment, but one of them caused significant deformations such as cracks and step-faults on the surface of the road. Interferometry enables us to retrieve information about deformation mechanosms and helps us to explain the reason of the motorway damage.

1. EXPLOITATION UNDER MOTORWAY A4

Between 2001 and 2004, a 16 km long section of the A4 motorway in Southern Poland was constructed. This part of the motorway is crossing the province of Upper Silesia, where many areas of underground hard coal mining are located. For such types of mining, huge terrain surface deformations are very common, reaching several centimeters per month and affecting large areas above the mined coal fields. The mining exploitation continued during the motorway construction and special improved constructions for the road have been applied. In the central section of the motoway, some 10 km west from the city of Katowice, a high road embankment to link two local hills was constructed. To improve the resistance of the retaining embankment against in relation to potential mining deformation, it was necessary to apply special conditions for its construction. The coal mining continued even during the construction of the motorway. At that time 8 longwalls were exploited directly under embankment construction site. Seven of them do not give any unexpected deformations but in September 2004 on one part of newly constructed motorway some deformations were discovered. Their location was directly above longwall 4/c, which was mined at the depth of 588 m This longwall was exploited by the Kompania Weglowa S.A. “Polska -Wirek” Coalmine Division. That exploitation caused surprisingly significant deformations like cracks and step-faults on the road surface and within the road embankment.

Special agreements between the coal mine and the construction company regulate the rules of underground exploitation. According to these agreements, in combination with the design of the road construction, the reason of the infrastructural damage remains unclear. Due to lack of in-situ deformation measurements the question remained whether the road embankment construction was too weak or if the deformations caused by underground exploitation were significantly stronger than predicted. The answer to this liability question was evidently very important, to determine which party was responsible for the cost of repairing the infrastructure. To help to answer this question, satellite radar interferometry was applied.

2. ASAR DATA ANALYSIS

To obtain information about the extent and magnitude of the deformation caused by the exploitation of longwall 4c, the SAR interferometric method was chosen due to the lack of other measurements. Standard leveling was

Proc. ‘Envisat Symposium 2007’, Montreux, Switzerland 23–27 April 2007 (ESA SP-636, July 2007)

not available, as the construction works destroyed the benchmarks.

For the project purposes 10 Envisat ASAR images from two tracks (415 and 143) were selected. All images were acquired between 2004 and 2005. Due to the large temporal baselines and significant signal decorrelation only one out of the 11 processed interferograms appeared coherent enough to perform a quantitative interpretation of subsidence caused by coal exploitation from the longwall 4c.

All interferograms were generated with the public-domain Delft Object-Oriented Radar Interferometric Software (DORIS) [2]. On two other interferograms, deformation was detectable but the information about the rate of subsubsidence was not interpretable. One of the reasons for the difficulty in interpreting the interferograms was that the rate of subsidence was very high, up to 20 mm/day, leading to high fringe rates. To improve the interpretability of interferograms we oversampled the data in range direction instead of the typical multilooking in azimuth direction. The oversampling method was used only for the most coherent interferogram to avoid misinterpretation of phase noise. The resulting oversampled interferogram shows the detailed information about the rate of subsidence along azimuth. The high resolution interferogram is then geocoded and imported into the Mining Areas Information System for further interpretation (Fig. 1).

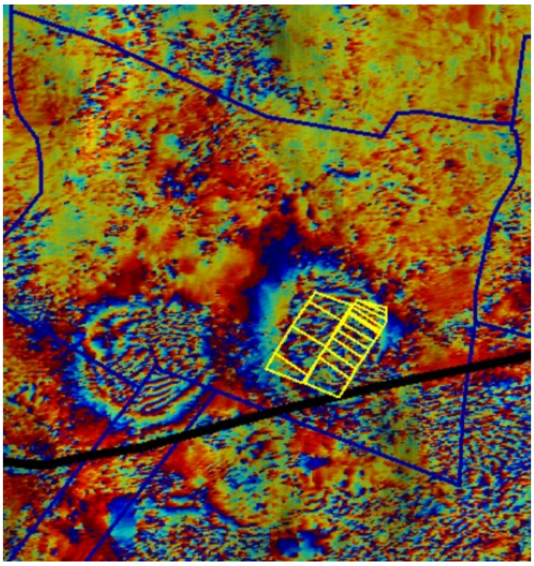

Figure 1. Interferogram over 4c longwall

Finally 3 subsidence bowls (subsidence trough) were analyzed for further interpretation. Two of them have 35 days time periods and a third has 140 time period.

3. ANGLE OF DRAW EVALUATION

The resulting information about the spatial and temporal extent of the subsidence enables us to adjust the calculated land deformation model and the interferometrically derived subsidence bowl was used to determine the parameters for the Knothe model, that describes the influences of underground exploitation [3].

The main parameters necessary for the calculations are the range of influence, *r*, and angle of draw, γ. Both of them are presented in Figure 2.

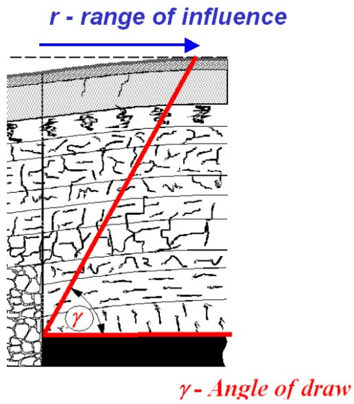

Figure 2. Meaning of range and angle of draw

To determine the parameters of this model, the assumption is made that the subsidence bowl is rotational symmetric [4] in its vertical section. For using this method some requirements of the subsidence bowl need to be verified. First, the interferometrically derived bowl must be close to theoretical elementary subsidence bowl. Elementary subsidence is generated by elementary numbers of exploited deposits. In nature such elementary subsidence bowls do not exist but some cases can be treated as sub-elementary subsidence bowls.

The first detected subsidence bowl was taken after 22 days of exploitation only. This subsidence bowl was in an initial, irregular form and it cannot be treated as a sub-elementary subsidence bowl which fits to a Gaussian's curve. The third bowl (140 days time period) loses coherence at its centre, making it difficult to determine the maximum subsidence (variable w_1), which is very important for deformation evaluating. Only the second subsidence bowl appeared to be of sufficient quality for further anlysis.

Finally we selected a sub-elementary subsidence bowl taken between 05 August 2004 and 09 September 2004 for the detail studies. The interferometric signal was still too noisy to use one of the automatic phase unwrapping algoritms and a manual unwrapping method was applied. The shape of the subsidence was digized based of manual interpretation and the subsidence values were calculated based on the wrapped phase. After interpolation of iso-phase contours the cross sections were generatrd in required directions (Fig. 3).

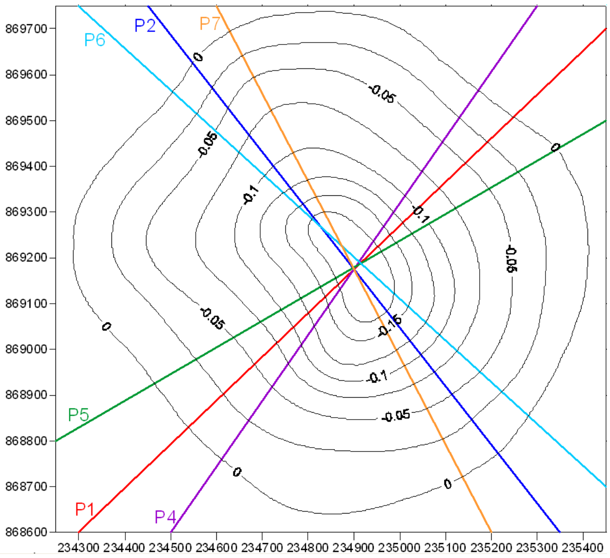

Figure 3. Cross sections for profiles [5]

Finally, each profile of the subsidence bowl, which is very similar to a Gaussian curve, was used as input for the angle of draw estimation (Fig. 4).

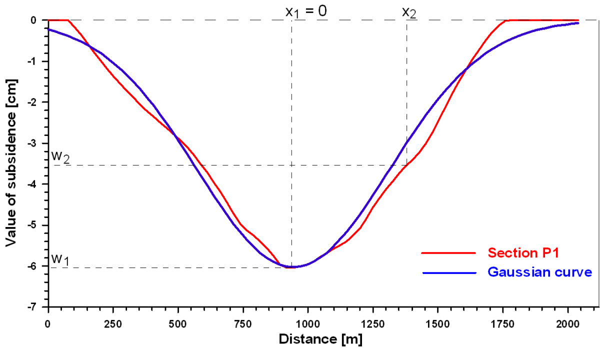

Figure 4. Profile of subsidence with Gaussian Curve [5]

The applied estimation technique [4] allows for the estimation of the range of influence *r*, For the calculations the following formula was used:

$$r = \frac{1{,}17 x_2}{\sqrt{\lg(w_1 : w_2)}} \tag{1}$$

where:

- w_1, maximum value of subsidence in a cross-section of the subsidence bowl (location $x_1 = 0$);
- w_2, value of subsidence on the slope of the subsidence bowl (location x_2, distance from x_1);

Parameter x_2 and respective subsidence w_2 (relation 2 – Fig. 3), were estimated directly from the selected cross sections. Based on the estimated *r*, and known depth *H* of the mined coal seam, the value of tanβ can be calculated from the linear function

$$r = \frac{1}{\tan\beta} H \Leftrightarrow \tan\beta = \frac{H}{r} \tag{2}$$

The ratio tanβ can be assumed as the parameter characterizing specific local rock-mass properties. The calculated parameter tanβ strictly differs from that which has been used for the deformation predictions at the stage of road embankment design. The difference between those values of tanβ was significant: original value was tanβ=2 whereas the value derived from interferometry is tanβ=3. In our opinion it shows the changeability parameters of the rock mass in the area of Silesia Coal Region related to multi seam, multi-year coal exploitation within the same area.

4. DEFORMATION EVALUATION

Those parameters were then used for subsidence modeling which allows to recalculate land deformation with a higher precision level. For calculations the MODEZ software has been used [6]. MODEZ includes algorithms for calculating horizontal deformation, subsidence, inclinations and other factors of ground changes caused underground exploitation.

In our case the calculation of deformation was performed based on evaluated value of tanβ. Within the motorway area the horizontal deformations reached maximal value of ε_{max}=3.3 mm/m. It means that they exceed the marginal value of predicted deformation of about 0.3 mm/m. For the method used in this research the evaluated accuracy was estimated to be $\sigma_\varepsilon = \pm$ 0.4 mm/m of ε_{max}. It means that deformations reached maximal permissible values, as mentioned in the agreement between the Coal Mine company and the Construction company. Finally the Mine Company paid only small amount of the costs of the motorway embankment repair.

5. CONCLUSIONS

In the presented case, differential satellite radar interferometry shows its high potential to perform effective monitoring of the deformation process by the determination of its maximal indexes. The result depended heavily on the temporal availability of ASAR acquisitions and the successful generation of coherent interferograms.

6. ACKNOWLEDGEMENT

This publication is financed by KBN, project: 4T12E 00126. ASAR SLCI data used in this work are the courtesy of ESA/EURIMAGE

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