

POST MINING DEFORMATION MONITORING BASED ON SATELLITE RADAR INTERFEROMETRY (INSAR)

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Abstract: The development of remote sensing technologies allows larger and larger scale deformation monitoring of vast areas of Earth in a short time. The article presents the possibilities of using satellite radar scanning of the area by InSAR method, applied to determine the subsidence of the area, caused by underground mining exploitation. The results of the carried out so far studies show that, based on this technology, it is possible to determine temporary subsidence of the area, zones of present threat to constructions and also verification of the surface deformation forecasts. It was proved that the InSAR method allows the assessment of current threat to the mining area and objects by defining the areas of intensive subsidence as well as the estimation of maximal values of deformation indexes by current verification of the parameters in Knothe's theory, based on so-called elementary troughs. No necessity to establish a geodetic grid of points makes an advantage of this method.

1. INTRODUCTION

Underground mining exploitation of deposits causes negative effects on the surface of the area; seen as translocations and deformations. They cause unfavourable phenomena such as (among others) damage to construction and engineering objects and technical infrastructure. Because of the protection of objects and safety of people it is necessary to provide possibly on-line monitoring of the increase of surface changes and their impact on surface management. It is also crucial to make forecasts of any possible threats.

Satellite Radar Interferometry InSAR is a modern, constantly developing, remote sensing method, widely applied in many scientific disciplines and practical applications. In the protection of mining areas it can be used in the description and forecasting of the changes in the surface of the area, caused by the underground exploitation of deposits. By using radar repeatable scanning of large areas of the Earth - this method provides new quality of information, unavailable with other techniques used so far. This is the first special method of the measurement of deformation, where surface measurement, not point measurement is

applied. Providing data in a mass way; the method enables us to obtain a comprehensive picture of temporary area subsidence in a relatively short time.

In this paper the results of new studies (on the InSAR method) are presented. The studies were focussed on the detection and measurement of dynamic inclinations of temporary subsidence troughs, observed in the areas of copper ores deposits in Poland. These results confirm the reliability and usefulness of the InSAR method in the monitoring of the changes occurring in the areas of mining deformations.

2. CLASSICAL MONITORING OF A MINING AREA AND THE INSAR METHOD

Nowadays the information on the size of the deformation in the area surface and the state of the objects is mainly obtained with classical surveying methods. Stabilization of a huge number of measurement marks is required. The marks make vast observation networks, mainly consisting of observation lines or dispersed points. They, however, never cover the terrain completely. They merely allow point information. This is a serious disadvantage of surveying methods, because the area of deformation shows high variability in the whole mining region. The image of the surface changes in the area is - in this case - a matter of interpretation. Yet, it does not reflect the state of deformations at one defined time moment (the measurement usually takes several days or even weeks). Important drawbacks of surveying methods also include too small frequency of obtaining observations (e.g. the whole high-level LGOM network is measured only every second year).

Based on the observations of surveying lines, parameters of the theory of influences were determined. Based on them; deformation indexes were defined. In this case they can only be determined in the profiles of subsidence troughs, determined by the situation and the course of observation lines in the relation to exploitation fields. This makes a serious limitation in the definition of full and reliable distribution of parameter values in the whole mining area, influencing the reliability of the forecasts made for the deformation of the area.

Dynamic development of the techniques of remote sensing, referred to the information on the terrain, has lead to taking and implementing satellite imaging of the terrain and the use of radar signal. The first satellite with such equipment was ERS-1 sent to the orbit by the European Space Agency (ESA) in 1991. The success of the programme allowed - in 1995 – sending another satellite - ERS-2. The newest achievement of ESA in this area is sending in 2002 a modern satellite Envisat equipped with the instruments having improved parameters of radar imaging.

In the aspect of the monitoring of mining areas – basic advantages of radar interferometry are:

- the possibility of observing surface changes of the area without the necessity to establish expensive network of notch marks,
- frequent possibility of gaining information on vertical changes in the area,
- getting archive data on area subsidence, systematically collected since 1991.

Moreover, the picture of surface changes of the area reflects their state in one established moment for the whole measurement area.

First in Poland studies of this type, confirming high reliability of the obtained interferometric data, were carried out in 1997, in the Upper Silesia Industrial Area [4]. The parameters that can be directly read from the distribution of interferometric striae include: momentary curve

and the gradient of the inclination of the subsidence trough, current range of the impact of mining exploitation and the width and shape of the inclination of the trough.

Recently the attempts to direct these studies into the problems of the forecasting of the surface deformation have been made. It was proved that, based on subsidence troughs, it is possible to verify (among others) the parameters of the theory of influences; which improves the accuracy of forecasting the deformations of the area surface [5].

3. COMPARISON OF THE INCREASES IN SUBSIDENCE MEASURED WITH SURVEYING AND THE INSAR METHOD

The reliability of the results obtained by InSAR method was checked by the comparative analysis, using the results of the processing of surveying measurements made on observation lines.

1.2. Selection of study areas

Because of the specifics of the analyses, the selection of study areas was determined by several factors. Preliminary selection started from the analysis of interferograms, defining the regions of exploitation where subsidence troughs were observed. In the next step the usefulness of a given region was determined by the course and situation of the observation line. At least a fragment of the line should be situated within the borders of the range of the area of subsidence registered by the InSAR method. The final criterion of selection was made of repeatable surveying measurements carried out on the observation line in the period, including the period of the generated interferogram.

Finally, comparative analyses were made, based on 25 observation lines situated in 16 exploitation regions located within the borders of LGOM.

1.3. Methods of estimation of the increases of area subsidence in the period between the satellite flights and the insar method

Increases in subsidence of the area in InSAR method are represented in the interferogram by the sequence of the examined striae. The accepted full sequence of colours, starting from red through blue and green represents the height difference by 3 cm.

The comparison of the increases in subsidence in the interferogram with the values obtained from surveying requires numerical processing of contour-line maps of these increases. It is necessary to digitalize the image of interferometric striae, carried out in Microstation environment. This includes giving to the borders of coloured areas an interpolated value of subsidence. The attributed value results from the number of coloured striae contained in one full sequence of colours (in this case 1 cm per colour). Results of digitalisation were processed in a computer program SURFER of GOLDEN SOFTWARE pack, obtaining a numeric image of subsidence isoclines in the period between satellite flights.

Surveying methods record subsidence and its temporary increases only in the notch marks of the observation lines. To compare two methods one should make longitudinal profiles of interferometric growths of subsidence, along these lines.

An important aspect is to make surveying cover possibly accurately the period included in interferogram. In case of the lack of required time correlation between the carried out surveying and processed interferogram, the quantitative comparison can turn out to be not very accurate. The cause of possible inaccuracies is the necessity of making linear interpolation (or extrapolation) of subsidence growths measured by surveying, which – in longer term – can generate considerable errors. This is because the subsidence of the points on the surface of the area, from the moment of their start to the moment of their stopping is not linear. Altogether, only the results obtained in the same place and in the same period of time allow full comparison of the mentioned above methods, both in qualitative and quantitative way.

1.4. Comparison of the results of the monitoring of subsidence growths

The comparison of the InSAR measurement method and surveying in the aspect of the determination of the growths of subsidence was presented for the exploitation region of the Mining Enterprise „Rudna”. In the study period of 1993-94 surveying was made on the observation lines running by distinct interferometric troughs (fig. 1). Exploitation in the presented region was carried out under the town of Polkowice, which also included the turn of 1993 and 1994. Because of the protection of buildings, workings were liquidated in a system of filling and it resulted in small increases of subsidence in time.

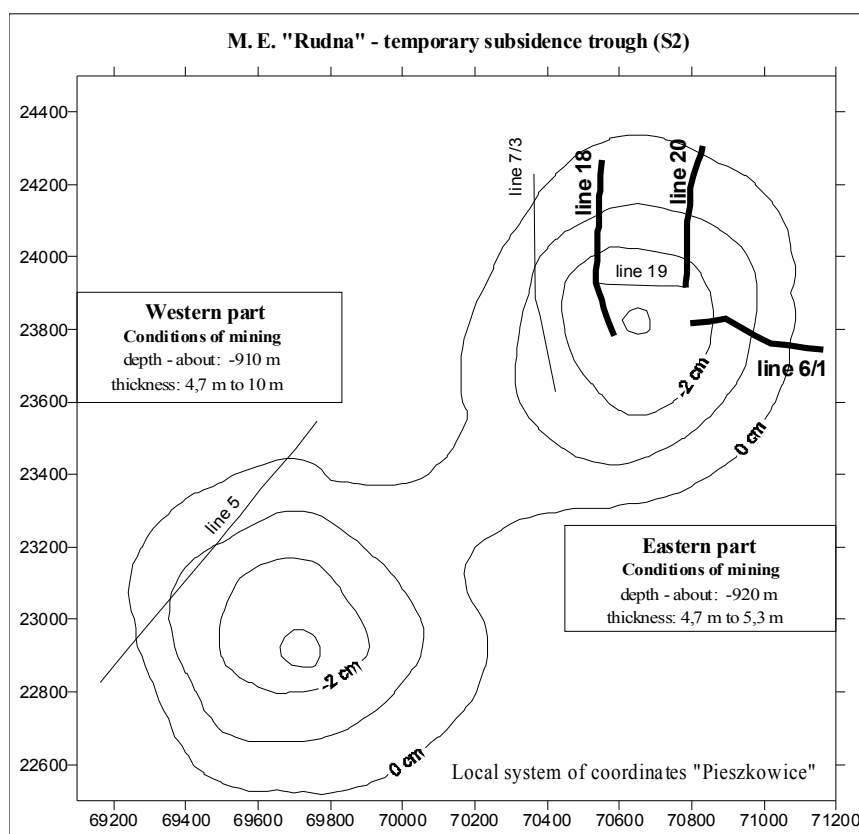


Figure1. Situation of observation lines in the relation to temporary subsidence troughs determined by InSAR method

Isoline numerical map of subsidence growths is presented in fig. 1. It was generated based on an interferogram covering the period of 2 months (10th January –11th March 1994). Data

available from surveying allowed comparative analysis only for the eastern part of this local trough. Surveying made within the 6-months time interval (October 1993 – March 1994) was carried out (among others) on lines no. 6/1, 7/3 18, 19 and 20. This period fully covers the time of making interferogram, however it is three times longer than that.

The results of comparing two methods of measurement were presented in a graphical form – as the charts of the growths in the area subsidence – recorded based on the interferogram and by surveying (fig. 2÷4). In this paper the results from observation lines, including a dynamic slope of the trough, are presented. From the comparison of the growths in the area subsidence - recorded by the InSAR method in 2 months period and surveying methods in the period of 6 months - one can state a qualitative compliance of the obtained results. This compliance refers both to the shape of the respective courses as well as the values. For it is logical to assume that within a longer period of time the growth of subsidence was bigger. To compare the methods in quantitative aspect, linear interpolation of 6 months' growths of subsidence of the notch marks in the observation lines into a 2 months' period covered by interferogram was made, applying the relation:

$$\frac{W_{6month}}{3} = W_{2month} \quad (1)$$

where: W_{6month} – growth of area subsidence within 6 months;
 W_{2month} – growth of area subsidence within 2 months.

After making the presented above calculations a very good compatibility of results was obtained, which is presented in graphs – fig. 2÷4. This was possible due to relatively weak dynamics of the movements of notch marks within the time covered by the surveying. The differences in the values of subsidence growths in the period of 2 months (the InSAR method and the interpolation of surveying) along the presented four examined observation lines is about 1 cm, which is probably caused by the inadequacy of linear interpolation. An example of such changes can be the convergence of the graphs of line no. 20 (fig. 4), obtained after introducing into defined interpolated values of subsidence growth a constant correction equal 1 cm. The correction was determined on the border of the range of exploitation impact (within the period of 2 months), drawing the value of subsidence growth (interpolation of surveying measurement) of point 1939 to zero. This was considered for 6 points lying over the body of the deposit (outside the exploitation field).

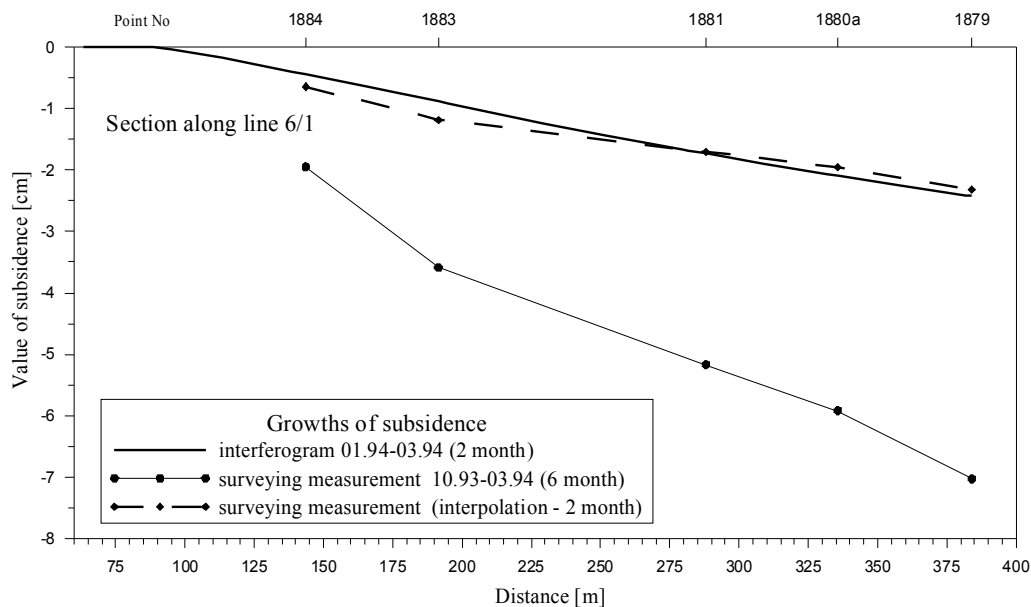


Figure.2: Comparison of the growths of area subsidence defined by surveying and the InSAR method for line no. 6/1, M.E. "Rudna"

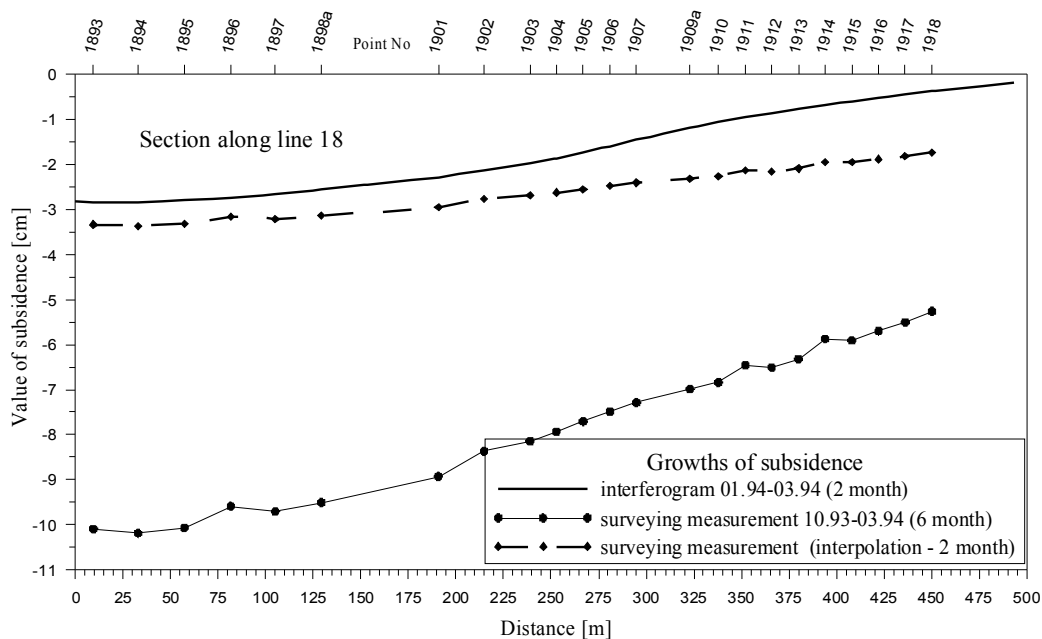


Figure 3. Comparison of the growths of area subsidence defined by surveying and InSAR method for line no. 18, M.A. "Rudna"

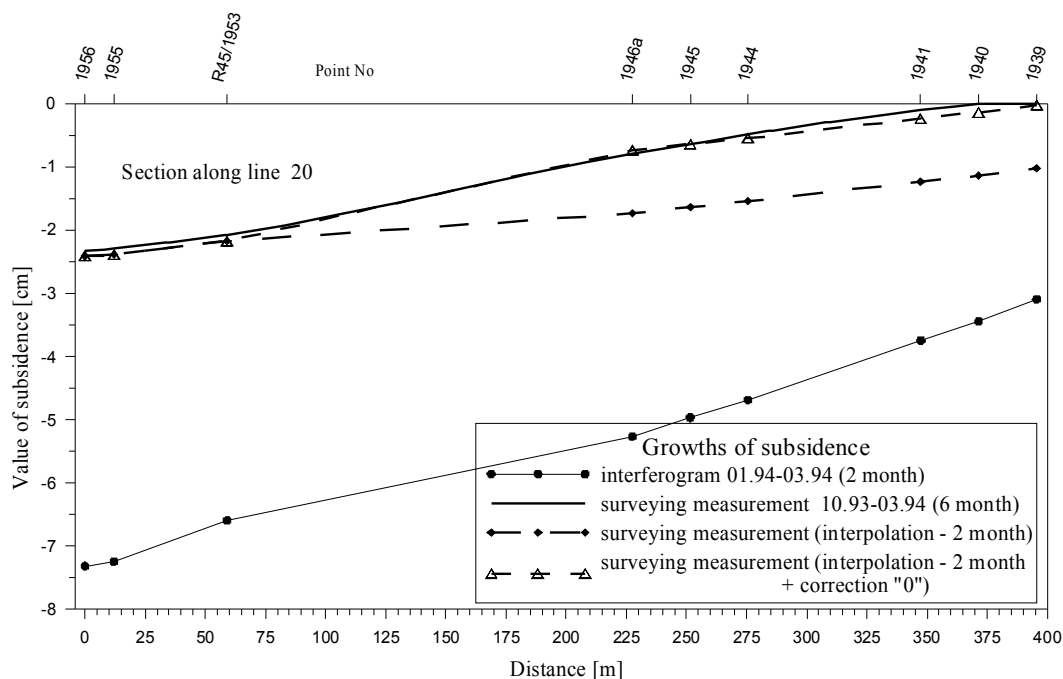


Figure 4. Comparison of the growths of area subsidence defined by surveying and InSAR method for line no. 20, M.E. "Rudna"

1. DETERMINATION OF PARAMETERS IN KNOTHE'S THEORY BASED ON THE OBSERVATION OF SUBSIDENCE IN THE INSAR METHOD

Studies of dynamic inclination of temporary interferometric subsidence trough, in the aspect of the measurement of subsidence were used to determine parameters of Knothe's theory of influences. Their on-line verification, with the development of mining exploitation, allows effective monitoring of the deformation process by the determination of its maximal indexes.

To determine the parameters of this theory, the calculation method was based on the assumption that subsidence trough is elementary [1] in its longitudinal vertical section.

Selected for the studies sub-elementary subsidence troughs, in selected sections (where cross-dimension of the exploitation field is significantly smaller than the depth of the deposit) approximate Gaussian curve quite well (Fig. 5a,b); fulfilling the established assumption. The accepted calculation technique allows the determination of the value of the parameter of influence dispersion „r”, defined in the mentioned theory of influences. Making calculations the following formula was used [1]:

$$r = \frac{1,17x_2}{\sqrt{\lg(w_1 : w_2)}} \quad (2)$$

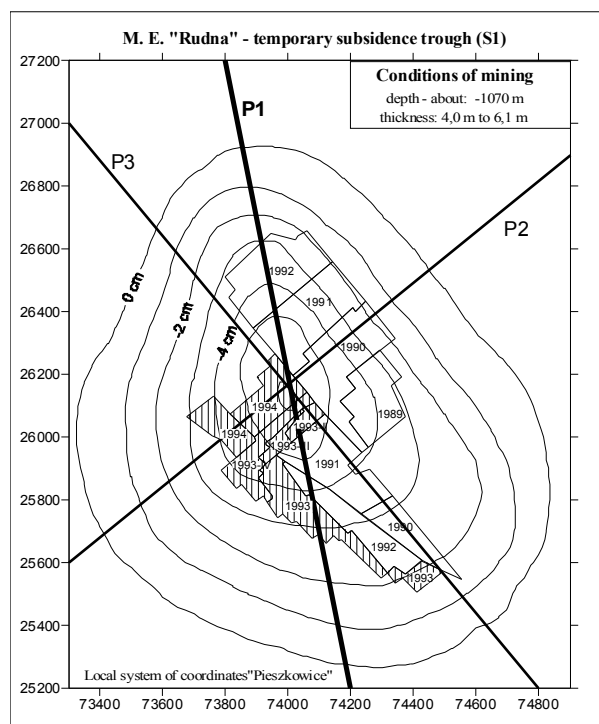
where: w_1 – maximal value of subsidence in a cross-section of the subsidence trough (in place $x_1 = 0$);
 w_2 – value of subsidence in the wing of the subsidence trough (in place x_2 – distance from x_1);

Value „ x_2 ” and respective subsidence „ w_2 ” (relation 2 – fig. 5b), were obtained from the spatial picture of the subsidence trough from selected cross sections. Based in calculated „ r ”, knowing depth „ H ” of the deposit, the value of the parameter of rock mass $\text{tg}\beta$ can be calculated from the linear function:

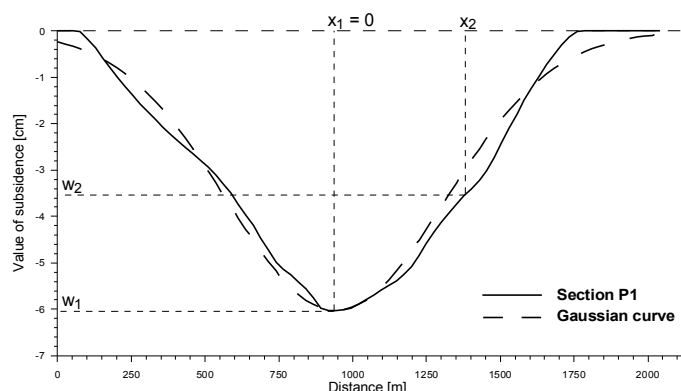
$$r = \frac{1}{\text{tg}\beta} H \Leftrightarrow \text{tg}\beta = \frac{H}{r} \quad (3)$$

To define parameter $\text{tg}\beta$, for underground exploitation of copper ore in the LGOM, six subsidence troughs, generated by InSAR technology were selected. The distribution of these troughs, numbered subsequently from S1 to S6 with the determined values of the parameter is presented in figure 6.

Values of calculated parameters $\text{tg}\beta$ do not differ from the accepted so far values in the influence forecasts. The differentiation of ultimate values $\text{tg}\beta$ within the range 1.26 – 1.69, in our opinion, shows the changeability of the rock mass in the area of LGOM. To characterize the rock mass in LGOM in a very general way, one can calculate the mean value for the area of LGOM with selected for the analysis elementary subsidence troughs (fig. 6). This value is $\text{tg}\beta_{sr} \approx 1.51$. This is close to the values obtained in direct surveying observations ($\text{tg}\beta$ between 1.4 and 1.7)



a)



b)

Figure 5. a) courses of interferometric sections of a sub-elementary subsidence trough
b) vertical profile of area subsidence along section P1

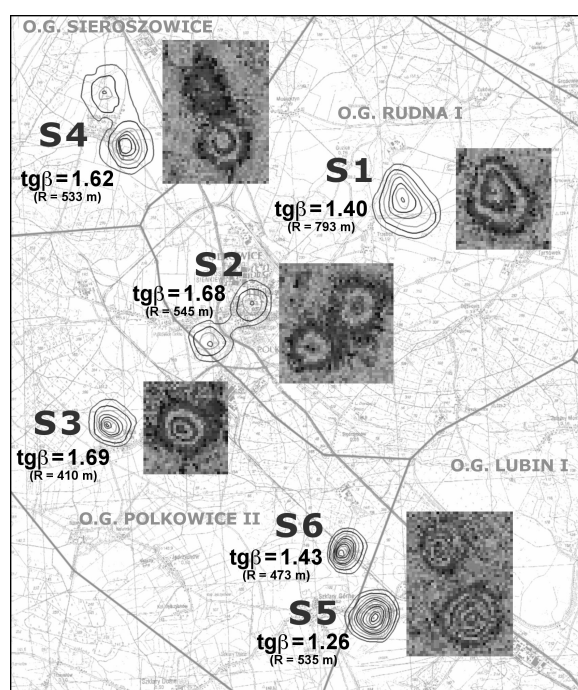


Figure 6. Distribution of subsidence troughs

1. FINAL REMARKS AND CONCLUSIONS

The carried out studies once more confirmed the usefulness of the InSAR method in the monitoring of mining areas. We presented the possibilities of supplementing current analyses of area subsidence with the analysis of the growths of area inclinations connected with the movements of exploitation fronts and the possibilities to determine parameters of the theory of forecasting from the dynamic front of exploitation.

The analysis of several observed subsidence troughs defining the growth of area subsidence in the period between radar images showed that they are clearly visible in the form of centric striae, being isoclines of temporary subsidence and their situation is compatible to the fields of the exploited deposit.

Comparison of the profiles of interferometric troughs and troughs based on surveying observations show good compliance both in qualitative and quantitative terms. This indicates the possibilities of the monitoring of vertical deformations of the area of LGOM without the need of establishing the network of notch marks and using expensive surveying measurements.

Determined based on sub-elementary interferometric troughs, parameters of Knothe's theory of influences enable on-line verification of the forecasts of surface deformations. Their values do not significantly differ from the values determined in a classical way in LGOM, from asymptotic states of subsidence troughs over large exploitation fields. They are correlated with the results of the analyses of the growths in the inclination of the area, showing milder inclinations of subsidence troughs outwards the exploited part of the deposit.

The analyses of the growths in the inclination, apart from a simple assessment of the inclination values, in terms of the danger to the surface of the area, can find other applications. One can consider the use of the InSAR method in the assessment of the changes of inclination in the built-up areas, where the analysis of subsidence growths and inclinations could be associated with the dates of the reports on damage to construction objects.

Carried out analyses and speculations, the results of which are presented in this article, indicate great opportunities of satellite methods of radar interferometry InSAR in solving the problems in the monitoring of the dynamics of negative influence of underground mining exploitation of deposits on the surface of the area and objects on the surface. This modern method of satellite remote sensing extends the possibilities of the monitoring of the influence of mining exploitation in the whole mining area. Its application has also important economical aspects, for it allows obtaining valuable spatial information on current mining influence, with a smaller cost.

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