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ANALYSIS OF VERTICAL MOVEMENTS DETECTED BY RADAR INTERFEROMETRY IN URBAN AREAS

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ABSTRACT
Persistent Scatterer Interferometry (PSI), a remote sensing technique, is used for detecting surface deformation in the cities of Prague and Ostrava. PSI is able to detect vertical movements with an accuracy of less than 1 mm for a long time series of the SAR data, but the maximum detectable rate of movement is only a few centimetres per year. This technique is quite suitable for detecting recent movements in most Prague localities. On the other hand, in Ostrava and its surroundings, affected by undermining, where subsidences (1992-2006) amount to decimetres per year, movements cannot be fully detected by the PSInSAR technique.
The paper presents results of analysing PSI data for two localities in Prague and one locality in the Ostrava areas. The localities are strictly situated in built-up areas with many suitable reflectors. Data from the ERS-1/2 and ENVISAT satellites covering a 13-year period for the Prague (1992-2005) and a 14-year period for the Ostrava (1992-2006) area were used. Annual movement velocities and time-series of reflectors were determined. At these three localities, where different types of movements were identified, the application and possible limitations of PSI in urban areas are shown.

KEYWORDS: InSAR, PSI, subsidence, undermining, Prague, Ostrava, Czech Republic

1. INTRODUCTION

The Institute of Rock Structure and Mechanics, v.v.i., belongs to thirty European countries which worked for six years on the ESA/GMES Terrafirma project "Pan-European Ground Movement Hazard Information Service in Support of Relevant Policies Aimed at Protecting the Citizen" (Terrafirma Atlas 2009). The project Terrafirma was based upon the application of InSAR technologies, mainly Persistent Scatterer Interferometry (PSI) to detect and monitor ground motions such as subsidence, uplift, landslides, etc. PSI has the ability to map millimetre ground motion phenomena over wide areas in urban and semi-urban environments from space. Terrafirma involved the integration of InSAR measurements with ground-based in situ measurements when data were combined and interpreted by geologists and geophysicists. Two test-sites were selected for the Czech Republic: the city of Prague and the Ostrava area (Schenk et al., 2007, 2008, 2009a, 2009b; Kadlečík et al., 2009).

The city of Prague is situated in the north-east of the synclinal closure of the Barrandien. The bedrock is characterized by Ordovician pelite-psammitic sediments which emerge as strips running WSW-ENE. There is a great petrographic variety of sediments, ranging from schist to quartzite, which have influenced the selective erosion, denudation and formation of the relief of the territory of Prague in the Quaternary. The whole area is crossed by several dislocations. Outstanding ridges, formed by the most resistive rocks, originated on the strikes of the layers. The intermediate depressions were partly filled by Quaternary colluvial deposits. Therefore, the foundation soils on the territory of Prague are formed by rocks of very different mechanical properties.

The Ostrava area belongs to the Upper Silesian Basin with black coal seams of the Carboniferous period. The Ostrava strata series was formed in a coastal environment and is characterized by high-quality coal in seams of small thickness. On the other hand, the younger Karviná strata series was formed after the ultimate recession of the sea. Ground motions are related both to coal mining and to geological structures including faults, folds and lithological boundaries. Mining has been carried out over the long term and has significantly influenced the landscape. In the 1990s the Czech government ordered the mining there to be gradually discontinued and mines in the built-up part of the city of Ostrava were gradually closed down. PSInSAR data show that subsidence trends continued for many years after the mines closed. Nevertheless, coal mining still continues in the region between the cities of Ostrava and Karviná. Undermining affects residential buildings located close to the mines. The PSInSAR data indicate that the subsidence trends carried on for at least five years after the mines were closed.

Table 1 Characteristics of areas processed by the IPTA.

	Prague	**Ostrava** (Czech part)
Satellites	ERS-1/2, ENVISAT	ERS-1/2, ENVISAT
Track	122, 2122	222, 2222
Period	1992-2005	1992-2006
Processed area	1100 km^2	417 km^2
Number of PS	~ 78 000	~ 36 000
PS density	71 PS/km^2	86 PS/km^2

2. RADAR INTERFEROMETRY

Radar interferometry (Interferometry SAR - InSAR) is the remote sensing technique exploiting SAR (Synthetic Aperture Radar) scenes acquired by satellites (e.g., ERS-1/2, ENVISAT, RADARSAT). Radar signals reflected from some SAR scenes are processed and terrain-motion can be detected with high accuracy (Ferretti et al., 2007). The resulting movement is measured in the 'line-of-sight' direction (direction satellite-Earth), containing its horizontal and vertical components. For SAR sensors with a small incidence angle (like ERS-1/2, ENVISAT) the resulting movement is mainly the vertical component. The acquired movement velocity is always related to a selected reference point in the processed area (Ferretti et al., 2007).

The Permanent Scatterer Interferometry (PSI) technique exploiting stable natural reflectors called permanent scatterers (PS) was used to detect ground motion in the Prague and Ostrava areas. The principle of this radar interferometry approach is that only these PS are used to detect the motion, where temporal and geometrical coherences on the SAR images remain high (Ferretti et al., 2000, 2001). PSI exploits a long time series of interferometric SAR data (typically at least 15-20 SAR images).

PS are most frequent in urban areas, represented by buildings, parts of roads and other man-made objects. On the other hand, PS are sporadic in vegetated and mountain areas, where they are especially represented by rocky outcrops. Therefore, populated areas with a high density of man-made objects are very useful for PSI processing (e.g., Parcharidis et al., 2006; Stramondo et al., 2008; Zhao et al., 2009). The PSI was developed in Politecnico di Milano in the late 1990s – the PSInSAR^{TM} approach (Ferretti et al., 2000). Other PSI approaches also exist: CPT (Mora et al., 2003), IPTA (Werner et al., 2003), etc. The PSI technice takes conventiona l InSAR a step further by correcting for atmospheric, orbital and DEM errors to derive relatively-precise displacement and velocity measurements at specific points on the ground. Thus, the unique benefit of PSI is its ability to provide both annual motion rates and multi-year motion histories for individual scatterer points.

In our case the Interferometric Point Target Analysis (IPTA) was used. IPTA processing was carried out by the Swiss corporation GAMMA Remote Sensing Research and Consulting AG using ERS-1/2 and ENVISAT scenes. IPTA is a method to exploit the temporal and spatial characteristics of interferometric signatures collected from point targets to map surface deformation histories accurately. The most straightforward application is the monitoring of slow and temporally uniform deformations (Werner et al., 2003; Wegmüller et al., 2004).

3. PSI PROCESSING OF THE PRAGUE AND OSTRAVA AREAS

Details of the available radar scenes from which the Prague and Ostrava areas were processed by the IPTA approach are given in Table 1. Annual movement velocities (in the line-of-sight direction) for selected permanent scatterers were determined. Scenes from the period 1995-2000 formed the basis of the processing with time series for each permanent scatterer extracted. Uncertainties of annual movement velocities are less than 0.5 mm/yr.

The essential data processing for the Prague area was supplemented by PSI analyses for the periods 1992-1993 and 2001-2005, i.e. all scenes for the period 1992-2005 were analyzed together. Mining-induced subsidence in the Ostrava area required a much more detailed look at the annual movement velocities and their changes. Therefore, the processing was extended by short-term analyses of SAR scenes for several two-year periods (1992-1993, 1995-1996, etc.) and one four-year period (2003-2006). The short-term analyses allow higher annual movement velocities up to 40 mm/yr to be determined, while for long-term analysis (such as 1995-2000) annual movement velocities up to 16 mm/yr were detected (Table 2). However, the uncertainty in determining of these velocities is higher (up to 2 mm/yr). For undermined areas with subsidences up to decimetres per year such uncertainty is acceptable.

4. LOCALITIES STUDIED IN DETAIL

The annual motion velocities, detected for the PS reflectors in Prague and its vicinity, indicate that this is a stable region (93 % of the PS reflectors display

Table 2 Comparison of application of long-term and short-term PSI analyses for the Ostrava area.

	Annual movement velocities of the PS (mm/yr)		Uncertainty of annual movement velocities (mm/yr)
	max	min	
Long-term			
1995-2000 (ERS-1/2)	2.5	-16.1	0.1 - 0.4
Short-term			
1992-1993 (ERS-1)	9.0	-38.9	0.1 - 1.9
1995-1996 (ERS-1/2)	9.0	-32.1	0.1 - 1.7
1997-1998 (ERS-1/2)	7.6	-20.9	0.2 - 2.0
1999-2000 (ERS-1/2)	5.2	-19.5	0.2 - 1.6
2003-2006 (ENVISAT)	6.0	-38.8	0.0 - 2.0

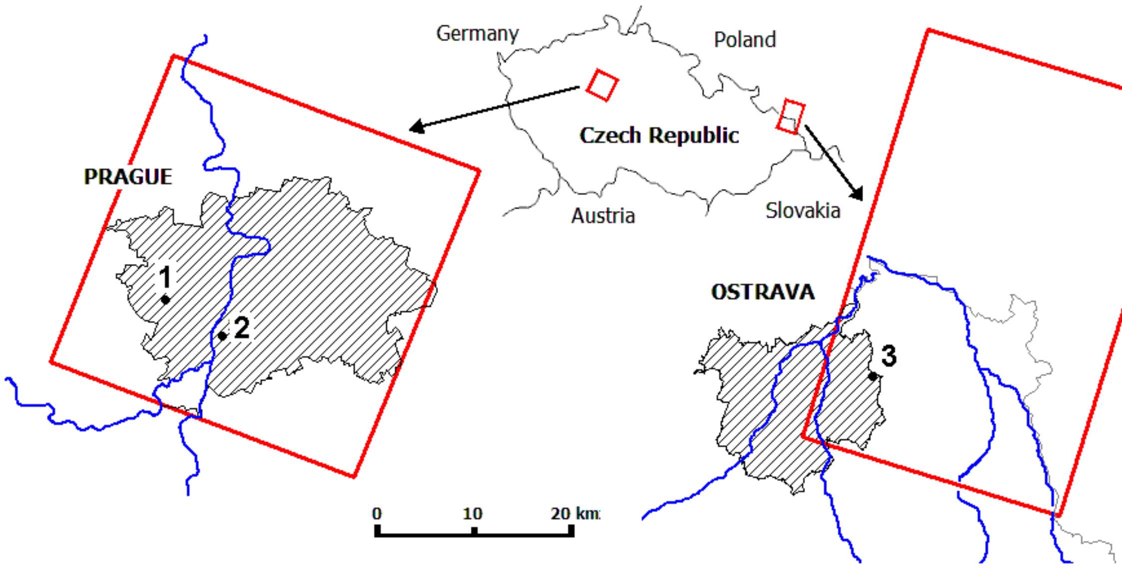

Fig. 1 Areas with localities studied in detail (1 – Stodůlky collection sewer, 2 – Braník-Modřany railway track, 3 – Michal mine). City borders of Prague and Ostrava are marked.

annual movement velocities of ±1.5 mm/yr). Nevertheless, in the densely built-up parts of Prague, one can observe local phenomena (in particular subsidence) associated with the construction of underground supply mains. In the locality of Stodůlky (Fig. 1) the PSI detected a collection sewer driven in the years 1997-2000. A large number of PS is also located along the railway track from Braník to Modřany (Fig. 1) where subsidence occurred during the whole period the locality was monitored.

In the Ostrava area, where the mining of black coal is still going on, PSI analysis could not be employed due to the rate of subsidence of the territory which amounted to tens of centimetres per year. However, in the built-up parts of Ostrava, where all the mines were closed down in the 1990's, gradual abatement of the subsidence can be observed. The subsidence before and after termination of mining is described on the example of the Michal Mine (Fig. 1).

The studied subsidence localities differ in the amoun t of suitable PS identified, in the duration of the subsidence and particularly in the cause and nature of the motion itself (Table 3).

4.1. LOCALITY STODŮLKY

Stodůlky is a district located in the south-western part of Prague, in the community of Řeporyje and the Stodůlky housing estate. Subsidence can be observed in some 50 PS of the total number of roughly 200 PS reflectors in this locality during the 1997-1999 period. The subsidence corresponds to the construction work carried out from July 1997 to January 1999 when the “P” – Chaby-Řeporyje-South Western City collection sewer, which became a part of the Prague collection sewer system, was being driven (Barták and Krátký, 1999).

The driven part of the collection sewer is 1730 m long and runs roughly from NNE to SSW. Its depth

Table 3 Characteristics of the studied localities.

Area *Locality*	Studied period	Number of PS	Source of movement	Character of movement
Prague		**~ 78 000**		
Stodůlky	1995-2000	~ 50	excavation of collection sewer	fast subsidence
Braník-Modřany	1992-2005	~ 200	compression of diversified railway embankment	slow subsidence
Ostrava		**~ 36 000**		
Michal mine	1992-2006	~ 1 000	undermining	fast and slow subsidence

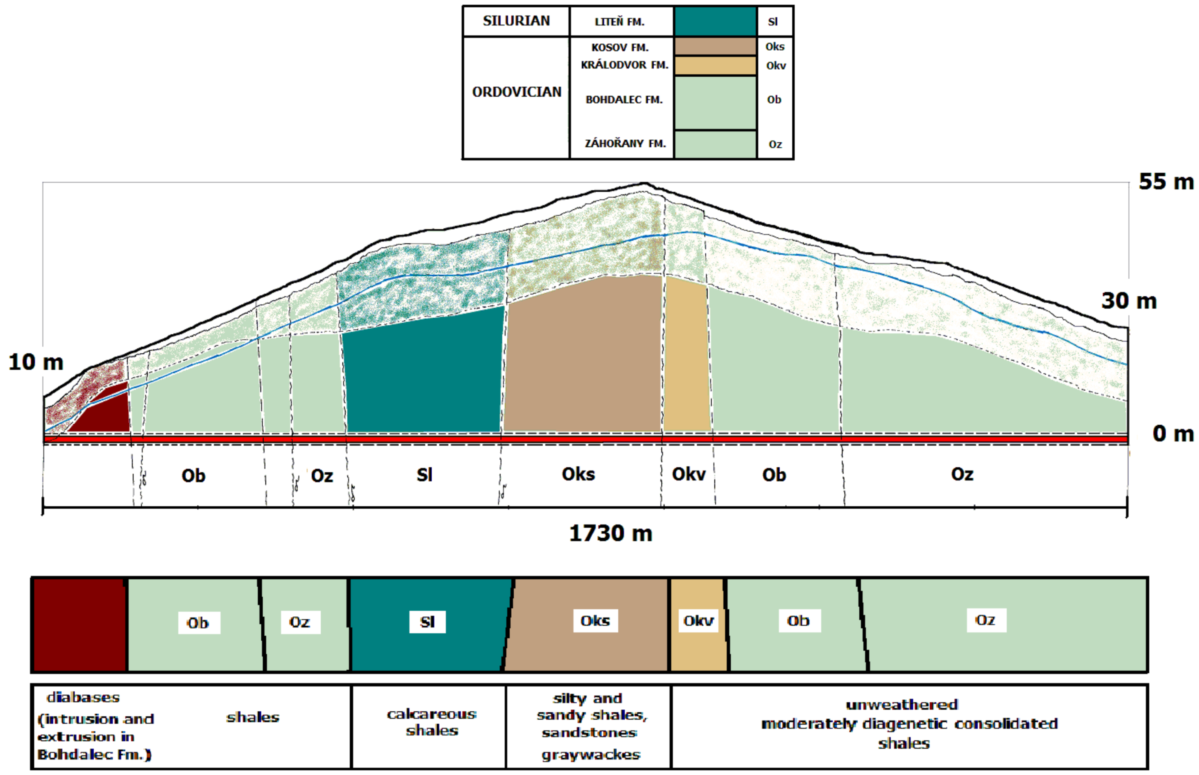

Fig. 2 Geological section of the studied part of the collection sewer in the Stodůlky locality (adapted from Brandejs et al., 1996).

below the surface varies within the range 10-55 m (Fig. 2) and its whole length runs through consolidated rocks (Brandejs et al., 1996). The rock bed, through which the sewer intersects, is formed by a folded complex of sedimentary rocks of the Middle and Upper Ordovician and Lower Silurian with manifestations of volcanism (penetrations of diabase bodies and veins). The area is located in the NW wing of the Prague synform, which is a part of the Barrandien; the layers dip to the SE and run parallel with the synform axis. The separate groups of beds consist mostly of clay and silty shales with the exception of the Kosovský group of beds (Oks, Fig. 2) which contain sandy shales to sandstones and partly graywackes. The locality displays considerable tectonic termination.

The driving of the collection sewer under complicated geological conditions was reflected in the subsidence of objects on the surface. The most PS, which reflect the movement, are located in the housing estate of Stodůlky, where there are panel buildings of up to 12 storeys dating back to

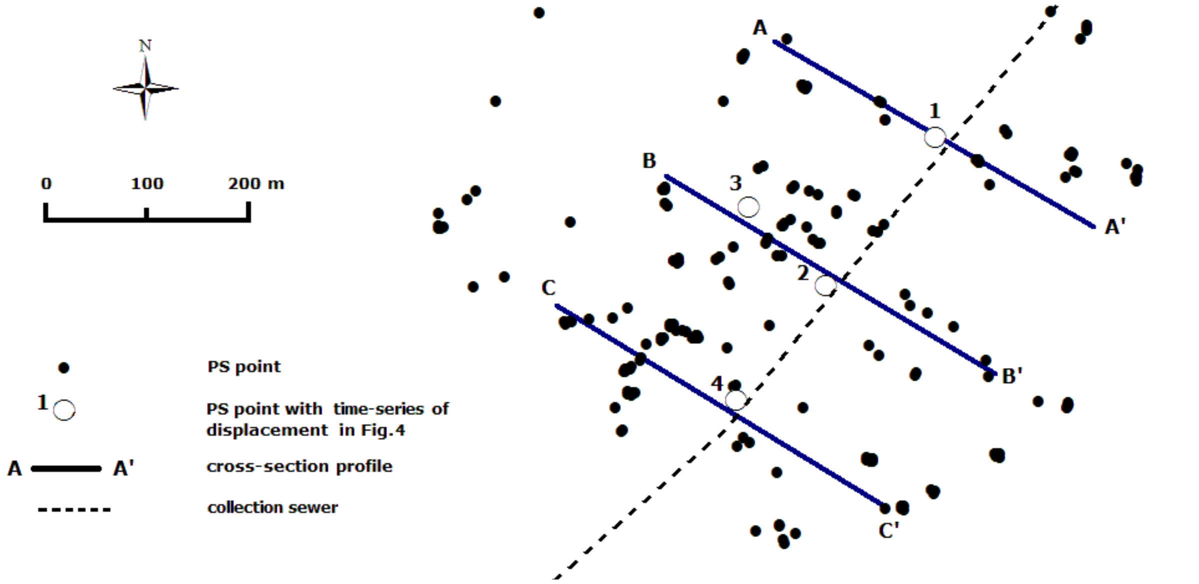

Fig. 3 Distribution of permanent scatterers (PS) along the collection sewer in the Stodůlky locality during the

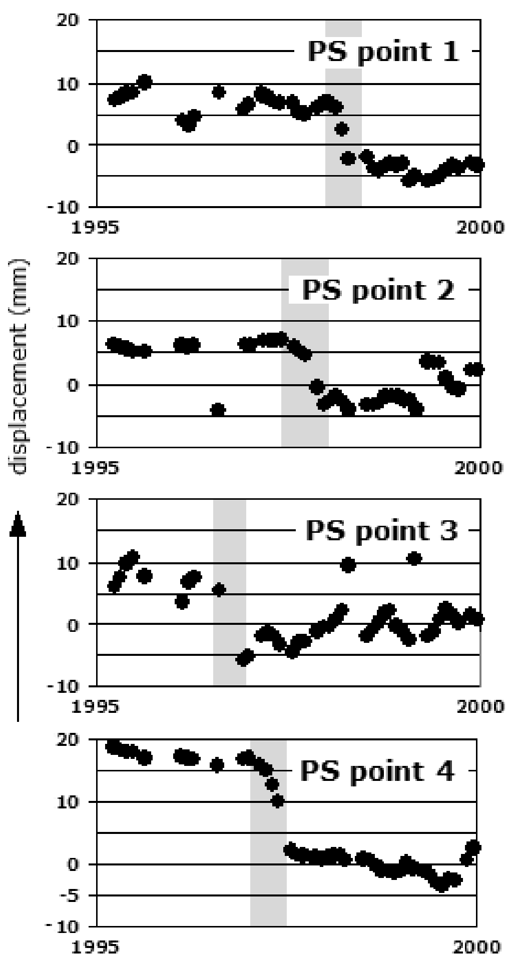

Fig. 4 Time series of displacements of selected PS (marked in Fig. 3) for the 1995-2000 period close to the collection sewer in the Stodůlky locality (the grey column indicates the time interval when the surface displacement for the given scatterer could be observed).

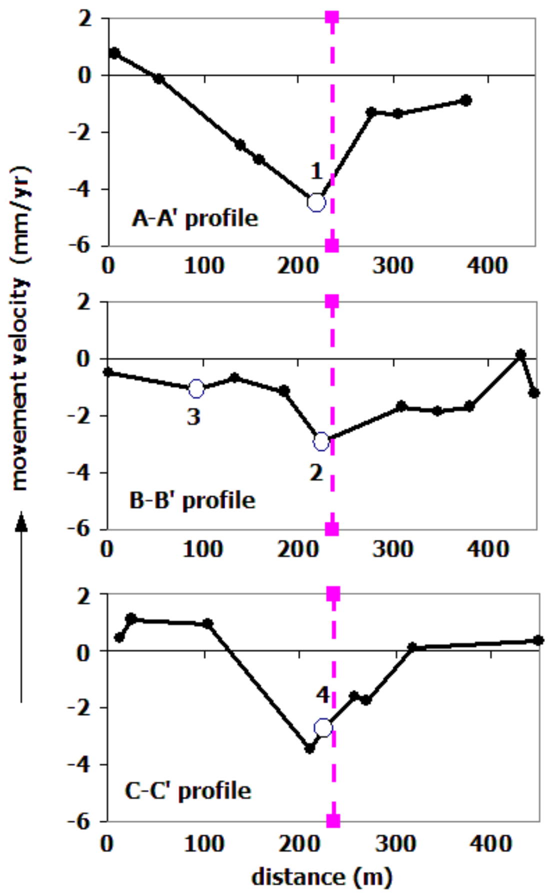

Fig. 5 Annual movement velocities for the nearest PS (marked in Fig. 3) along the cross-sections.

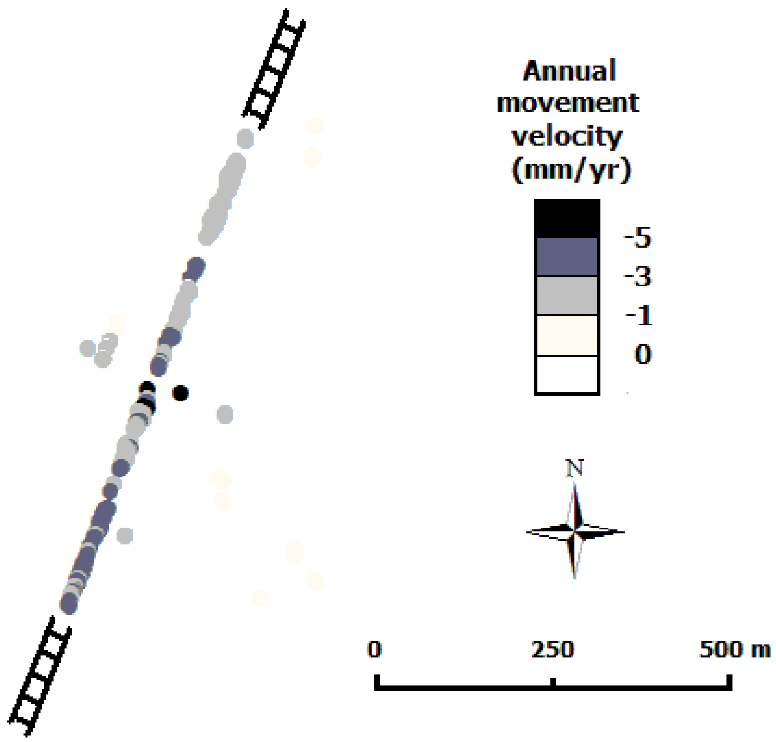

Fig. 6 Distribution of PS along the railway track in the locality Braník-Modřany and their annual movement velocities during the period 1995-2000 (direction of railway track is illustrated).

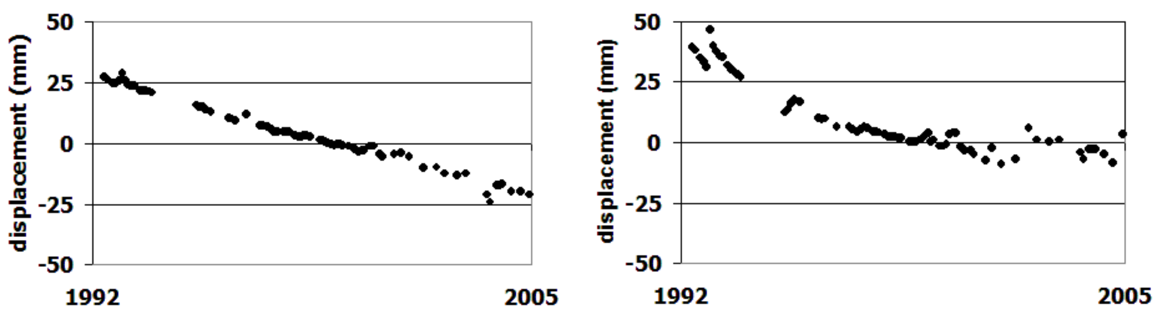

Fig. 7 Time series of displacements for two PS in the locality of Braník–Modřany for the period 1992-2005.

1978-1983. Cracks and fissures in the buildings and the disturbance of surrounding concrete surfaces above the sewer indicate terrain subsidence.

The highest annual rate of subsidence on the cross-sections, perpendicular to the collection sewer alignment (Fig. 3), can be observed in places through which the sewer runs (up to 5-6 mm/yr in the period 1995-2000, Fig. 5). The subsidence becomes smaller with distance from the sewer and 200 m away can no longer be observed. The total PS subsidence is as much as 20 mm, and has the nature of fast subsidence (Fig. 4). The subsidence of the separate PS differs in duration, from 2 to 8 months.

4.2. LOCALITY BRANÍK-MODŘANY

A large number of PS is situated in the locality of Braník–Modřany which is along the railway embankment between stations Praha–Braník and Praha–Modřany, 2-3 m high and which was completed in 1992. The embankment runs parallel to the River Vltava, nearly N to S, and 200 m from its bank. The PSI analysis for the period 1992-2005 indicates that subsidence occurred in the studied section, which was detected at roughly 200 PS (Fig. 6). The gradual subsidence amounted annually to values ranging from 1.5 to 6.5 mm/yr. An example of the time series of displacements for two PS is shown in Figure 7.

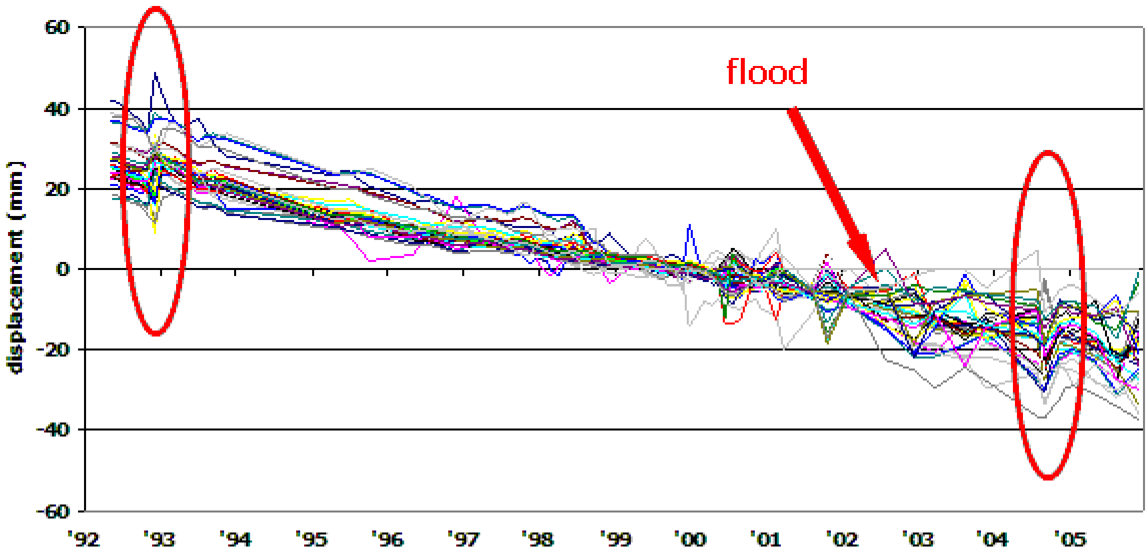

Fig. 8 Time series of displacements for all PS for a selected section of the railway embankment in the Braník–Modřany locality (red ellipses mark "up and down" displacements for two periods: November 1992 – January 1993 and August – November 2004).

Exploratory wells bored during the construction of the railway track indicated that the rock bed is located about 5 – 6 metres below the surface, and in some places even below 10 m. It consists of folded sediments of Ordovician and Silurian age, overlain by Pleistocene and Holocene fluvial sediments. The uppermost layer is formed by made-up ground of variable composition and thickness (2-5 m). The railway embankment was constructed on this made-up ground. The heterogeneous composition (construction waste, bulk rocks, etc.) and the large thickness of the made-up ground could be the cause of the settling of the surface objects, which is also the case elsewhere in Prague with objects built on anthropogenic sediments close to the River Vltava (Kovanda et al., 2001).

The subsidence of the separate PS along the whole section of the railway track in question is linear with small deviations (Fig. 8). More substantial changes occurred only within two periods: in November 1992 to January 1993 and in August to November 2004 (Fig. 8, red ellipses). The subsidence and subsequent rise in these two cases was more than 10 mm and was always concentrated at a particular place along the railway track. This is evidently caused by the heterogeneous composition of the material of the embankment, as well as its sedimentary underlying rock. The embankment is part of the anti-flood barrier along the River Vltava. During the catastrophic August 2002 flood, the water rose up to one metre below the top edge of the embankment. However, no more substantial changes were observed in the time series of the individual PS at that time (Fig. 8).

The PSI analysis clearly indicates that the whole studied section of the railway track in the Braník–Modřany locality, 750 m in length, is subsiding and probably continuing to do so up to the present. The linear subsidence corresponds to the regular daily load of railway traffic. With a view to the unsuitable engineering geological conditions, no larger number of PS reflectors, which would enable a more detailed analysis of the embankment's neighbourhood, is located in the vicinity of the railway track.

4.3. LOCALITY MICHAL MINE

The Michal Mine, also called Petr Cinger, is situated in the western part of Ostrava (working field Michálkovice). Black coal has been mined here until 1994; in subsequent years the working pits were filled in, and to-day the whole area of the mine has become a national memorial. The primary cause of the subsidence here and in the whole city of Ostrava is undermining. The PSI data cover the period 1992-2006, i.e. the time before as well as after mining in the Michal Mine was terminated.

According to the PSI results, the largest subsidence was recorded in the years 1992-1993, the annual subsidence in the middle of the subsidence depression (depression caused by anthropogenic activity) amounted to over 30 mm/yr (Table 4). The magnitude of the movement of some of the objects with reflectors in the middle of the subsidence depression was not recorded due to an even larger subsidence (beyond the range that PSI can follow).

The gradual abatement of the mining effects during the whole studied period can be seen clearly after mining was terminated (i.e. since 1995, Table 4). The rate of subsidence did not even amount to 10 mm/yr, and gradually decreased to 4 mm/yr in 1999-2000. Even in 2003-2006 it is still possible to

Table 4 Maximum annual movement velocity of PS in the Michal Mine area for different short intervals in the 1992-2006 period.

Period	1992-1993	1995-1996	1997-1998	1999-2000	2003-2006
Maximum annual movement velocity (mm/yr)	-32.6	-7.5	-7.5	-4.0	-3.4

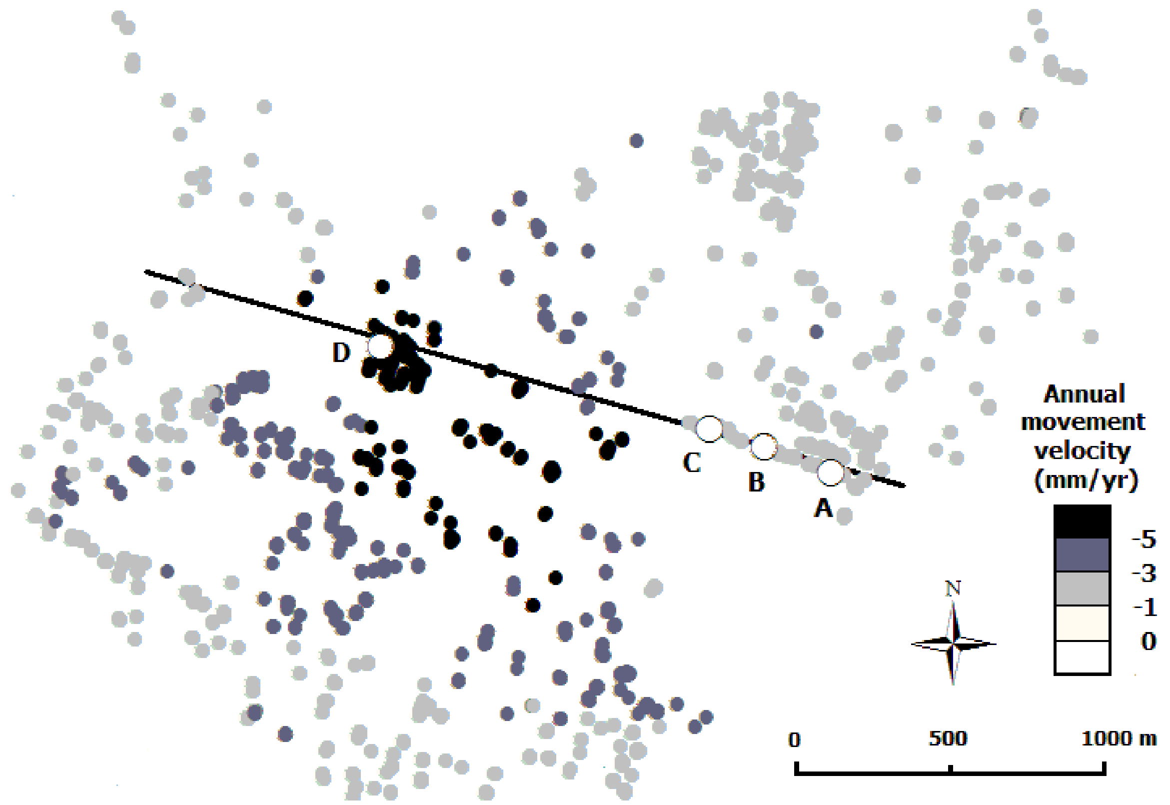

Fig. 9 Distribution of PS in the Michal Mine area and their annual movement velocities during the 1995-2000 period (the cross-section is marked by a black line).

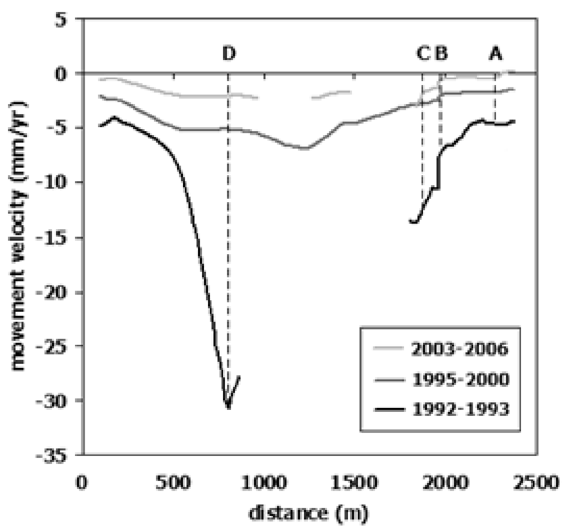

Fig. 10 Subsidence rates of PS along the cross-section in the Michal Mine area for three periods.

delineate clearly the region affected by undermining. The PS located along the cross-section running through the subsidence depression display a gradual decrease of the subsidence with time (Fig. 9). The subsidence curves for selected PS are illustrated in Figures 10 and 11, although data are unavailable for some interval in 1994-1995 and 2000-2003.

5. CONCLUSION

The PSI analysis enables the manifestations of changes of the Earth's surface to be monitored in urban areas as well as their retro-evaluation (since 1992). The results of processing using the PSI technique do not provide a complete picture of these changes in a particular area, but the amount of data and their accuracy provide a suitable complement of existing methods of GPS measurements and levelling (e.g., Doležalová et al., 2009, 2010).

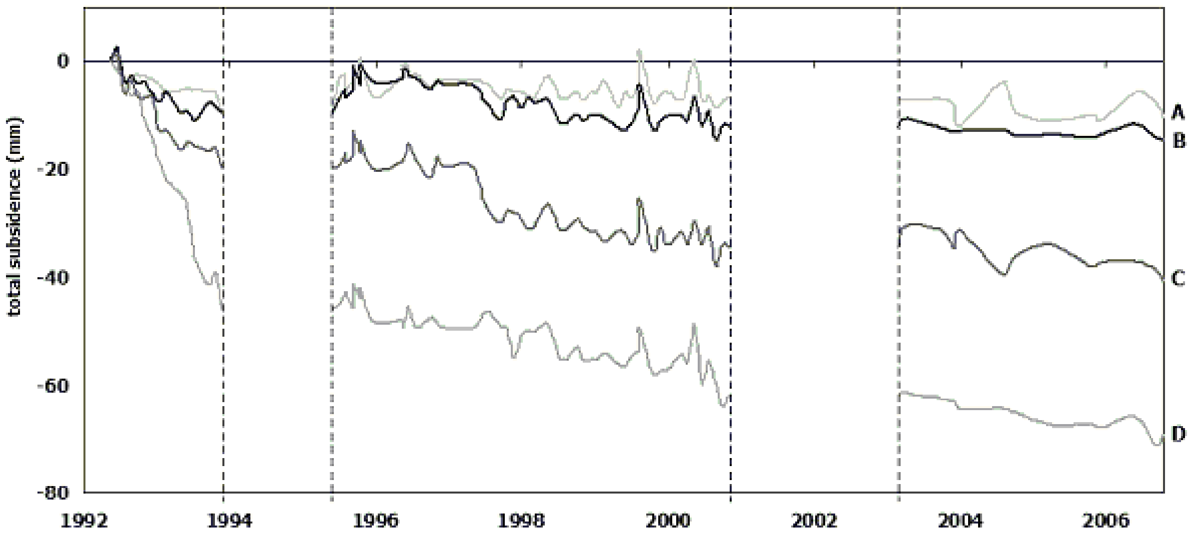

Fig. 11 Cumulative subsidence at four selected points A – D in the Michal Mine area during the period 1992-2006.

The large density of PS reflectors in Prague enables local ground motions to be monitored. Driving a collection sewer, running through tectonically disturbed layers of sediments of Ordovician and Silurian age, under the housing estate of Stodůlky in the south-western part of Prague, caused subsidence of as much as 20 mm in the period of 1997-1998. The time series of displacements for the separate PS indicate the motion was of a fast subsidence nature, i.e. the subsidence occurred in the course of 2 to 8 months as a response to driving the collection sewer.

A part of the railway track between the stations of Praha–Braník and Praha–Modřany, running along a railway embankment 2-3 m high, was monitored close to the River Vltava bank. The large thickness and heterogeneous composition of the anthropogenic sediments in the bedrock caused the subsidence during the whole studied period of 1992-2005. The subsidence is of a continual nature, ranging from 1.5 to 6 m/yr, along the monitored 750 m section of the railway track.

In the Ostrava area, areas of subsidence can be detected in the locations of the individual mines, as well as their subsidence evolution in the period 1992-2006. During the period of mining, the subsidence in the Ostrava area amounted to more than the 40 mm per year, i.e. more than maximum value measurable using the PSI technique. After the mines in the area of the city of Ostrava were closed down gradual abatement of the effects of mining can be observed, but the undermined localities can still be recognized even after 10 years. An example is the Michal Mine, where mining was terminated in 1993 or 1994; nevertheless, the average subsidence in the interval 2003-2006 was still more than 3 mm/yr.

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