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Results of persistent scatterer interferometry of the new planned Visaginas Nuclear Power Plant area, Lithuania

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Ground surface deformations can be related to tectonic motions, landsliding, flooding, erosion, groundwater pumping, karst processes, etc. Ground movement data can be obtained from stationary observations using standard geodetic methods, GPS as well as using geostationary satellites. The combination of the methods and additional geological information can improve the understanding of the processes and clarify the causes of the ground surface movements. In Lithuania, the ground surface deformations are usually related to landsliding, karst, suffusion, technogenic processes, which can trigger deformations of foundations, destruction of buildings, and other harmful accidents. Lithuania is planning to build a new Nuclear Power Plant (NPP), therefore the assessment of the stability of the ground (and structures upon it) across potential new NPP construction sites and their vicinity is a question of vital importance. IAEA SSG-9 safety guidelines recommend remote sensing imagery to be employed to better understand ongoing rates and the type of tectonic activity, therefore the rate of ground surface movements is the vital information for planning and designing a new NPP. The Persistent Scatterer Interferometry (PSI) data has been used to provide historical motion measurements across the new planned Visaginas NPP area. The aim of this paper is to present the PSI dataset interpretation results and clarify the causes of the ground surface vertical movements in the studied Visaginas area.

Key words: satellite remote sensing, synthetic aperture radar, interferometry, permanent scatterer, nuclear power plant, Lithuania

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INTRODUCTION

Space-borne Differential Synthetic Aperture Radar Interferometry (DInSAR) and a new advanced Permanent Scatterer Interferometry (PSInSAR or PSI, Ferretti et al., 2001) processing techniques offer a unique possibility for wide-area, regular monitoring of ground surface displacements. Furthermore, under suitable conditions it should be possible to detect precursory deformations associated with the initiation of ground instability, a key element for early warning and hazard mitigation (Colesanti, Wasowski, 2006; Ferretti et al., 2006). The satellite data can help to monitor the tectonic activity, prove or reject the rate of movements and clarify the causes of the movements. Satellite PSI data, however, have to be well ground truthed because they reflect performance of targets, whose actual or apparent displacements may arise from a variety of causes (e. g. slope movements, fill settlement, subsurface civil engineering, mining and fluid extraction, differential movements between cut and fill parts of a building site, structure deterioration, expansion / shrinkage of soils).

Indeed, the interpretation of millimetre-centimetre ground movements detected by the Persistent Scatterer Interferometry (PSI) is often difficult and some uncertainties can remain even after in situ controls (Čyžienė et al., 2010). This work illustrates considerable interpretative difficulties concerning the PSI dataset acquired over the Visaginas area (Lithuania) in the framework of the Terrafirma Project (www.terrafirma.eu.com). Modern satellite technology was used to determinate the ground surface movements in the Visaginas area. Radar interferometry (PSI and DifSAR techniques) has been applied in the Visaginas Municipality as well as in parts of the Zarasai and Ignalina districts municipalities (studied area covers 459.6 km^2).

GENERAL INFORMATION ON PS INTERFEROMETRY

Radar satellites, in orbit 800 km above the Earth, have been collecting data through the European Space Agency (ESA) since 1992, and have been providing information on ground movements at the centimetre scale. From 2001 a new technique (PSI – Persistent Scatterer Interferometry) developed by Tele-Rilevamento Europa (TRE) in Italy allowed a ten-fold improvement in capability so that movements of less than 1 millimetre per year can now be measured.

The interferometric synthetic aperture radar (InSAR) is a remote sensing and geodethic technique that can be used to accurately measure ground displacement. This geodetic method uses two or more synthetic aperture radar (SAR) images to generate maps of surface deformation or digital elevation, using differences in the phase of the waves returning to the satellite or aircraft. Radar sensors mounted on satellites transmit microwave signals toward a target area, some of which are reflected back to the satellite. These 'back scattered' signals are read and stored by the satellite sensor to form radar images of the target area. Sophisticated software then compares pairs of images of the same target to detect changes in the ground surface, such as displacement, that have occurred in the time span between the two acquisitions.

Satellite Differential Synthetic Aperture Radar Interferometry (DInSAR) is an attractive technique for detecting and monitoring ground surface deformations arising from regional scale processes, e. g. seismic, volcanic, or tectonic ones (Gabriel et al., 1989; Massonnet, Feigl, 1998). The technique, however, is not effective for site-specific evaluations because of coarse resolution, coherence loss (a typical problem for vegetated areas) and atmospheric artefacts limitations (e. g. Wasowski et al., 2002; Colesanti, Wasowski, 2006). Permanent Scatterers Interferometry (PSInSAR), developed at Politecnico di Milano (Ferretti et al., 2001; Colesanti et al., 2003), and similar innovative multi-temporal DInSAR techniques (e. g. Berardino et al., 2002; Werner et al., 2003; Bovenga et al., 2006) overcome in part the limitations of DInSAR and extend the applicability of radar interferometry to sub-regional and local-scale geological investigations of slope instability and soil settlement / ground subsidence. The PSI analysis allows the identification of numerous radar targets (the PS) where very precise displacement information can be obtained. Considering the regular re-visit time and wide area coverage of satellite radar sensors, and that PS usually corresponds to buildings and other man-made structures, this technique is particularly suitable for applications in urban / peri-urban environments, which often represent a harsh setting for GPS or conventional topographic surveying (Ferretti et al., 2006).

AVAILABLE GEOLOGICAL INFORMATION

Detailed geological investigations were performed during the period of 1988–1994 in the environs of the Ignalina Nuclear Power Plant (NPP), when a detailed integrated geological mapping at a scale of 1:50 000 for the Drūkšiai area was carried out. In a course of the geological mapping a wide complex of geological and geophysical investigations, such as seismic, gravimetric, aeromagnetic and radiometric studies, were fulfilled and a big number of wells were drilled in the area up till now: almost all of them reached the crystalline basement and / or Ordovician strata. 2D seismic survey covers approximately 1 000 km^2 around the Ignalina NPP. The survey comprises 321.6 km of seismic lines acquired in years 1988–1990. In the year 2009, these seismic data were reprocessed and interpreted in order to improve quality of seismic horizons at the Paleozoic levels and structural mapping for better understanding of the faulting pattern of the Ignalina and potential new Visaginas Nuclear Power

Plant region. In the year 2010, new 3D and 2D seismic data have been acquired and interpreted in the new Visaginas Nuclear Power Plant prospective sites' vicinity area in order to improve the understanding of the tectonic structure.

GEOLOGICAL SETTING

The geological section of the Visaginas area comprises rocks of the crystalline basement and the sedimentary cover. The crystalline basement is composed of the Palaeoproterozoic crystalline rocks, e. g. gneisses, crystalline schists. The sedimentary succession is represented by the Upper Proterozoic Vendian complex, overlain by sediments of the Paleozoic systems and Quaternary deposits.

The Vendian deposits are represented by a succession of gravelstone, feldspar-quartz sandstone of different grain size, siltstone and shale. The Palaeozoic section comprises the succession of the Lower and Middle Cambrian, the Ordovician, the Lower Silurian and the Middle and Upper Devonian sediments. The crystalline basement is covered by the rocks of the Vendian complex of Neoproterozoic age, while the dislocated and degraded surface of the Vendian layer is covered with terigenic rocks of the Lower Cambrian complex. The Vendian complex is stratified 732 to 596 m deep. It consists of quartz sandstone and siltstone. The argillite and sandstone layer with litified clay interlayers lying above the Vendian complex in the depth of 598 to 585 m is attributed to the Lower Cambrian complex. Fine-grained quartz sandstone is stratified at the depth from 585 to 570 m. This Middle Cambrian layer is in places covered by rocks of the Caledonian complex. The light-gray limestone and sandstone of the Lower Ordovician geological age are stratified above the Middle Cambrian rocks at the depth of 570–507.2 m, limestone and marl of the Middle Ordovician are stratified at the depth of 507.2–496.3 m, while light-gray limestone of the Upper Ordovician is stratified at the depth of 496.2 to 440.1 m. Rocks of the Ordovician system are in places covered with light-gray dolomitic marl of the Lower Silurian geological age, the layer of which lies at the depth of 440.1–354.0 m. Dolomite, limestone, and marl of the Upper Silurian lay at the depth of 354–220 m. On the degraded surface of the Silurian system rocks, the Hercynian complex rocks are stratified. These include light-gray siltstone, sandstone, and dolomite of the Middle Devonian. These rocks in the studied area are stratified very unevenly and it may only be predicted that the bore should reach this layer at the depth of 220–119.5 m. In some boreholes (Marcinkevičius et al., 1995) which were drilled in the area a bit southwest from Lake Drūkšiai, the sandstone and siltstone layers of the Devonian system reach up to 76–77 m, while in other places this layer is either completely degraded in palaeoincisions or remains thin. Rocks of the Narva Regional Stage of the Middle Devonian in the region comprise a regional aquiclude. At the places where degraded rocks of the Devonian system were eroded by palaeoincisions, the Narva aquicludal horizon is much thinner; in some places its thickness is barely 5 m. Middle–Upper Devonian Šventoji–Upninkai Formations sandstone layer is at places completely degraded in the area of the Visaginas NPP, while in other places only the lower part of the eroded layer remains. In the surveyed area, sandstone and siltstone of the Kukliai and Butkūnai Formations of the Upninkai series form erosion etched pre-Quaternary surface, which is covered by sediments formed during the Quaternary period. Total thickness of Devonian deposits is about 250 m (Marcinkevicius et al., 1995).

Geological and structural information for the deeper geological layers of the new selected Visaginas NPP sites is available from the new 2D/3D seismic surveying results and 2 new deep boreholes. The Middle Devonian Narva Regional Stage varies in thickness from 90 to 100 m, however, in the western part of the Western Site the deep palaeoincision intersects the Devonian rocks. The altitude of the surface of the Narva Regional Stage reaches up to –35–40 m. According to 3D seismic data results, the altitude of the surface of Silurian rocks varying from –135 to –155 m, the altitude of the surface of Ordovician rocks is from –180 m to –200 m. The surface of crystalline basement rocks has been determined at the altitude of depths varying in a range of –575 – –600 m and dissected by faults.

The Quaternary succession has a very complex composition and is very uneven. It consists of sediments and deposits formed during glacial periods. This layer includes Pleistocene and Holocene sediments (peat, sapropel, and peaty deposits). The area is made up of glacial deposits (till) of the Middle Pleistocene and of the Upper Pleistocene. The intertill glaciofluvial (sand, gravel, cobble, pebble) and glaciolacustrine (fine-grained sand, silt, clay) sediments are detected in the region. The thickness of the intertill deposits varies from 10–15 m up to 25–30 m. A layer of Quaternary sediments and deposits at the Visaginas area reaches up to 120 meters. Thickness of sediments depends on surface relief altitude and absolute heights of the pre-Quaternary surface.

Glacigenic formations resulting from several arrivals of glaciers may be identified in the complex cross-section of Quaternary system sediments. The layer of these sediments consists of scaly and monolithic layers and interbeds with prevailing tills and sandy loams. These layers are separated by layers and interbeds of glaciolacustrine and glaciofluvial sediments. The lower part of the Quaternary succession consists of the Dzūkija Formation. Glacigenic sediments of this formation (g II dz) lie directly on the eroded pre-Quaternary surface. Moraine of the Dzūkija Formation is massive, monolithic and with few interstices. It consists of till and sandy loam with gravel and pebble. Sediments of the Dzūkija Formation in some places are covered with intertill proglacial sediments – aquaglacial sand or gravel. Glacigenic formations of the Dainava Formation (g II dn) are distributed unevenly, locally. Glacigenic till formations of the Dainava Formation – massive till with gravel and pebble – form local interbeds and layers with thickness of up to 10 m (Marcinkevičius et al., 1995). The intertill formations of the Middle Pleistocene – aquaglacial sand and glaciolacustrine silt – are stratified at the lower part of the cross-section of the Quaternary geological system, under glacigenic sediments of the Žemaitija Formation. The till of the Žemaitija Formation (g II žm) has less pebble and gravel interbeds than the Dainava moraine (Marcinkevičius et al., 1995). Glacigenic formations of the Medininkai Formation (g II md) form a complex of glaciolacustrine, glaciofluvial, and glacial sediments. Till formations of Medininkai – sandy loam – are of characteristic brown and reddish brown color with pebble and cobble of sedimentary, igneous and metamorphic rocks. Glaciolacustrine clays of the Medininkai Formation (lg II md) are also present. A part of the cross-section of the Quaternary geological system consists of the Neo-Pleistocene Grūda moraine (g III gr). Grūda till has been found in geological cross-sections of the region. Grūda moraine sediments form entire layers, which are the basis of the main Baltic moraine and marginal moraine formations of the Baltic Sub-Formation. Sediments of the Baltic Sub-Formation have been formed by the Baltic glacier of the last glacial advance. The geological cross-section of the Quaternary system sediments is completed by Holocene sediments. These are lacustrine sediments formed in moraine troughs, bog peat, peaty grounds, and filler grounds of mounds (t IV).

RECENT TECTONIC ACTIVITY OF THE VISAGINAS AREA

The recent tectonic activity of the studied area has been previously investigated by geodetic measurements of the recent movements of the ground surface in the polygon established around Lake Drūkšiai (Zakarevičius, 1995). The geodynamic polygon was carried out in 1989. The precise geodetic levelling of the polygon was carried out in 1989, 1990, 1991, 1992, 1994, and 1998. The southern part of the polygon was levelled four times, the northern part was measured twice.

The first geodetic survey was performed in August and September 1989. Same benchmarks were re-levelled in June and August 1990. The whole Ignalina NPP polygon was measured in the third and fourth campaigns in June–October 1991 and July–August 1992. Only the northern part was measured during the fifth survey in September–November 1994. The Lithuanian part of the polygon was re-levelled in June 1998.

The data collected during different periods of the years from 1989 to 1998 indicated the vertical movements of the ground that, in the context of the existing understanding of the geological structure of the region, were interpreted as being related to the activity of the tectonic blocks bounded by the faults of the crystalline basement and sedimentary cover. The relative magnitude of the vertical movements was interpreted as reaching 2–6 mm per year (Zakarevičius, 1995; Zakarevičius et al., 2008). However, the influence and especially the magnitude of other processes, such as the effect of the glacial isostatic rebound of all the region, local effects of water extraction, ground water level fluctuations, soil compaction, etc., have not been considered in the interpretation of geodetic data.

PSI DATASET OF THE VISAGINAS AREA AND RESULTS OF ITS INTERPRETATION

The Persistent Scatterer Interferometry (PSInSAR) technology has been used to assess the general terrain-stability across the region. The PSInSAR data has been used to provide historical motion measurements across the Ignalina NPP infrastructure and new planned Visaginas NPP area.

The study is made according to the Service Level Agreement between Fugro NPA Ltd., Lithuanian Geological Survey, UAB Visagino Atominė Elektrinė, INGV and Altamira Information SL. The PSI dataset of the Visaginas area was acquired on the basis of the agreement between the Lithuanian Geological Survey and the TERRAFIRMA Consortium and was processed by Fugro NPA SAR Interfero metry (United Kingdom) using the GAMMA IPTA software. For PSI processing overall 38 ERS-1/2 scenes were used for analysis, covering the time period between 2 August 1992 and 13 September 2000. For DifSAR processing 9 and 12 descending Envisat scenes were used, covering the period between 15 July 2004 and 26 November 2009 and between 12 March 2003 and 3 June 2009, respectively. Totally, 1 456 ERS-1/2 PS were identified. The average PS density amounts to 4 PS/km^2. The following statistics of ground motion in five selected velocity classes is revealed in Table 1 (according to Fugro NPA). PSI detected in the Visaginas area are characterized by velocities mainly ranging between –1.5 to = 1.5 mm/year (87.4% of observed 1 456 points) during about 8-year period of observation. The average annual motion rate of the entire processed area is –0.3 and could be considered as generally stable.

The reference point is located at Lat: 6161520.3289 and Lon: 465000.5131 at UTM 35 projection and was selected with assumption that surroundings are rather stabile (Fig. 2). The Google Earth™ was used for the geo-referencing; the accuracy (X, Y) is ±10 m. For detail interpretation orthophoto images at a scale of 1:10 000 were used. The production dates of these images are 1997, 2005–2007 and 2010. Also the topographic geodatabase at a scale of 1:50 000 was used.

For motion interpretation purposes the PSI dataset was combined with a digital orthophoto based on aerial photos. This enables to locate precisely negative and positive velocity PS, respectively indicative of downward and upward displacements. The PSI dataset was divided in five categories: PS with velocities greater than +3.5 mm/year, PS between +3.5 mm/year and +1.5 mm/year, PS between +1.5 mm/year and –1.5 mm/year, PS between –1.5 mm/year and –3.5 mm/year, and PS with velocities lower than –3.5 mm/year (Fig. 1). These groups of the dataset are facilitated comparison and interpretation of PSI data with other cartographic material.

The Visaginas area PSI dataset has been analyzed with the aid of different geological data, among them: a Quaternary geological map of the Drūkšiai area at a scale of 1:50 000 (Marcinkevičius et al., 1995), a pre-Quaternary geological map of the Drūkšiai area at a scale of 1:50 000 (Marcinkevičius et al., 1995), a revised pre-Quaternary geological map of the Drūkšiai area at a scale of 1:50 000 (Šliaupa, 2005), a tectonic map of the Drūkšiai area at a scale of 1:50 000 (Marcinkevičius et al., 1995), structural maps of the top of the Ordovician based on 2D

Table 1. **Statistics of ground motion in five selected velocity classes according to Fugro NPA**

1 lentelė. **Žemės paviršiaus vertikalių svyruojamųjų judesių statistika pagal penkias atrinktas greičių kategorijas**

PSI points motion statistics (mm/year classes) Kiekvienos kategorijos vidutinių metinių pastovių atspindžio taškų (PSI) greičiai (mm/metus)	Points in each mm/year class Kiekvienos kategorijos pastovių atspindžio taškų (PSI) skaičius (mm/metus)	Percentage (%) of points in each mm/year class Kiekis %
max to –3.5	42	2.9
–3.5 to –1.5	119	8.2
–1.5 to +1.5	1 273	87.4
+1.5 to +3.5	15	1.1
+3.5 to +max	6	0.4

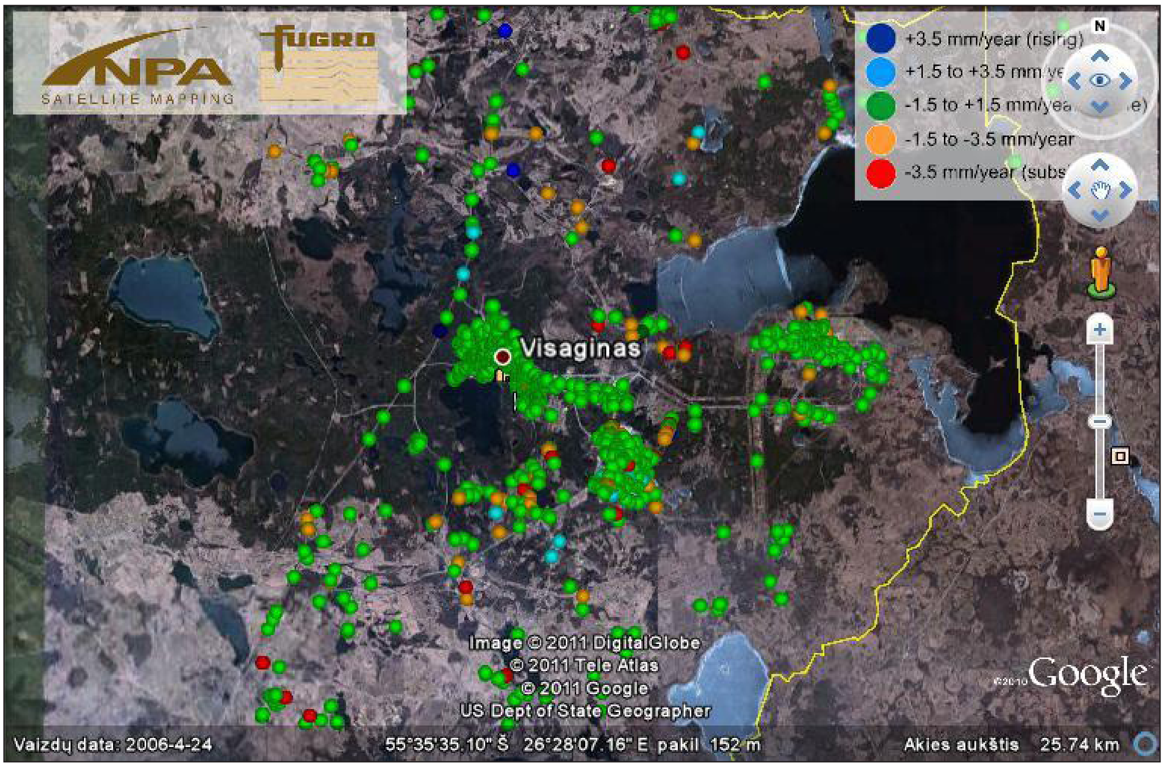

Fig. 1. Results of Persistent Scatterer Interferometry (PSI) for Visaginas area
1 pav. Visagino ploto satelitinės interferometrijos pastovių atspindžio taškų (PSI) žemėlapis

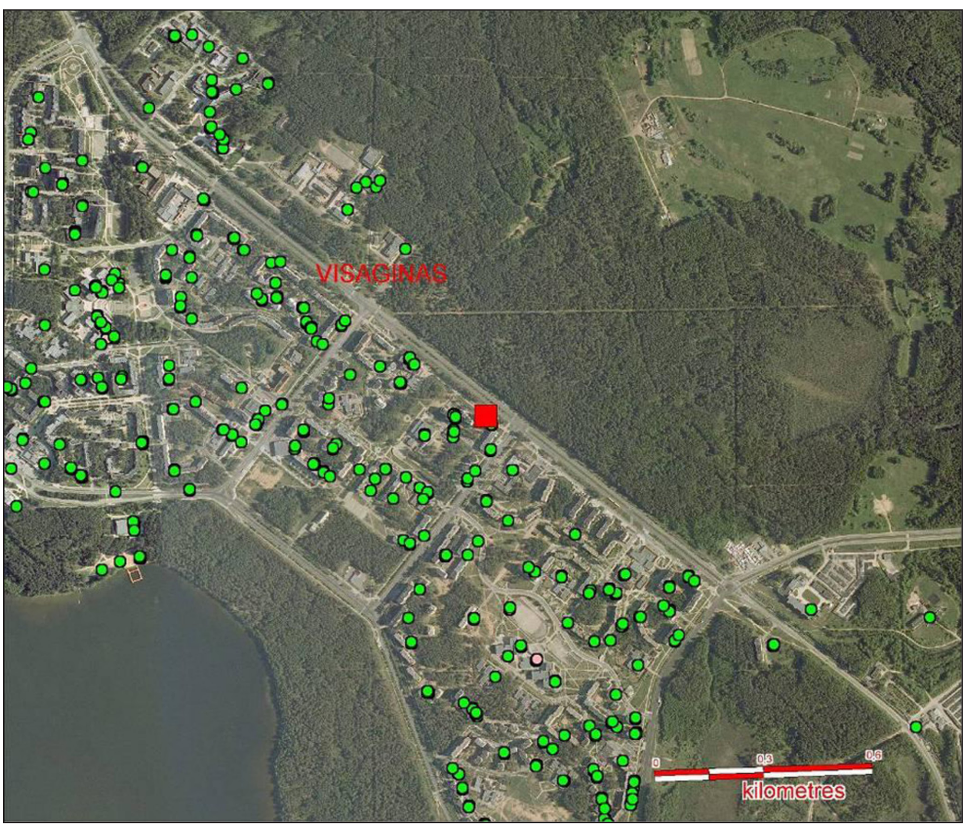

Fig. 2. Location of the reference point (red square)
2 pav. Atraminio taško vieta (raudonas kvadratas)

seismic data reinterpretation in 2009 (Potencialių Visagino AE..., 2009), structural maps of the top of the Crystalline basement, Ordovician and Silurian based on new 2D/3D seismic investigations data interpretation in 2010 (UAB Minijos nafta, 2010), an engineering geological map at a scale of 1:50 000 (Marcinkevičius et al., 1995), a Map of Sanitary Protection Zones, etc. The field reconnaissance in the selected parts of the studied area was also performed.

The PSI dataset of the Visaginas area is characterized by the irregular distribution of moving and stable PS. The location of tectonic faults and PSI points shows that there is no evidence of active tectonic movements (Figs. 3–6). There are no visible general spatial or linear trends that could provide some evidence of a possible relation between ground motion and tectonic or neotectonic activity (Figs. 3–6).

Nevertheless, the interpretation of the PS dataset has enabled to identify several sites and local tendencies within the Visaginas area characterized by spatially consistent concentrations of the negative PS. The examples of movements detected by

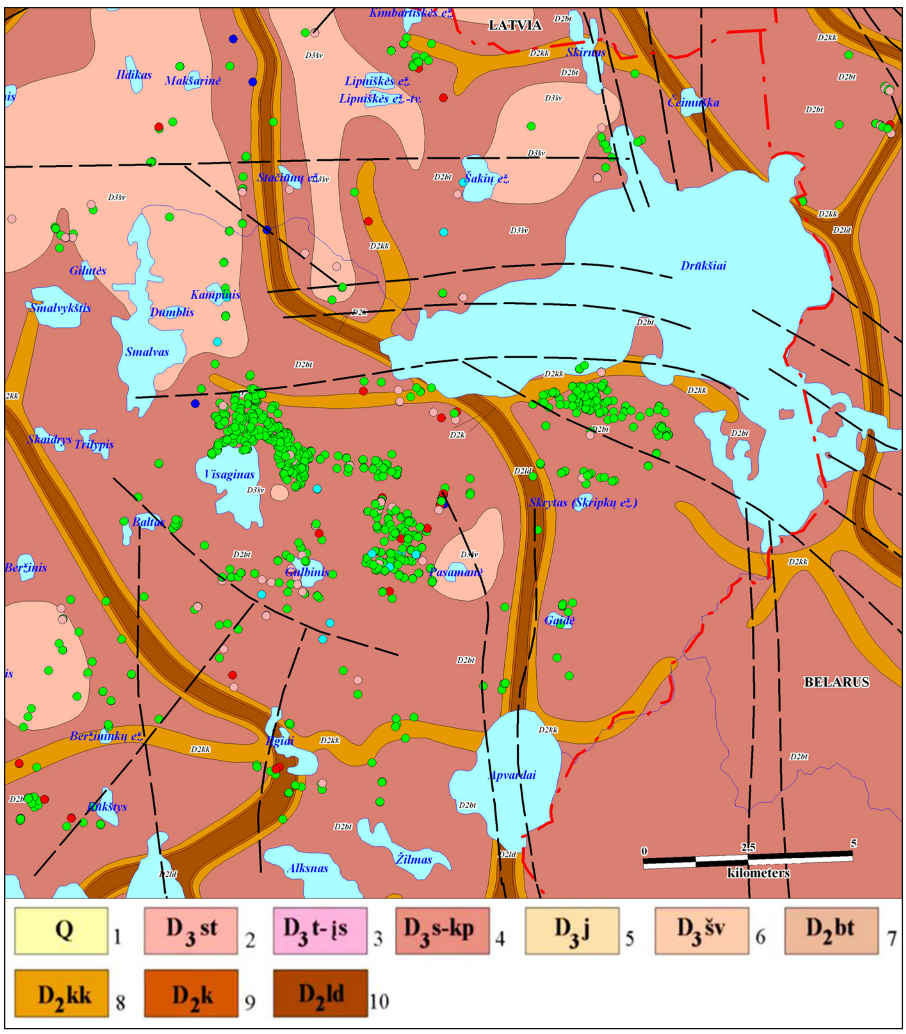

Fig. 3. Pre-Quaternary geological map and tectonic faults of Drūkšiai area (after Marcinkevičius et al., 1995; original scale 1:50 000) vs. PSI points. Legend: *1* – Quaternary deposits; Upper Devonian formations: *2* – Stipinai, *3* – Tatula-Įstras, *4* – Suosa-Kupiškis, *5* – Jara, *6* – Šventoji; Middle Devonian formations: *7* – Butkūnai, *8* – Kukliai, *9* – Kernavė, *10* – Ledai

3 pav. Drūkšių ploto prekvartero geologinio žemėlapio ir tektoninių lūžių (Marcinkevičius ir kt., 1995) palyginimas su PSI taškais. Legenda: *1* – kvartero dariniai (pjūvyje); viršutinio devono svitos: *2* – Stipinai, *3* – Tatula-Įstras, *4* – Suosa-Kupiškis; *5* – Jara, *6* – Šventoji; vidurinio devono svitos: *7* – Butkūnai, *8* – Kukliai, *9* – Kernavė, *10* – Ledai

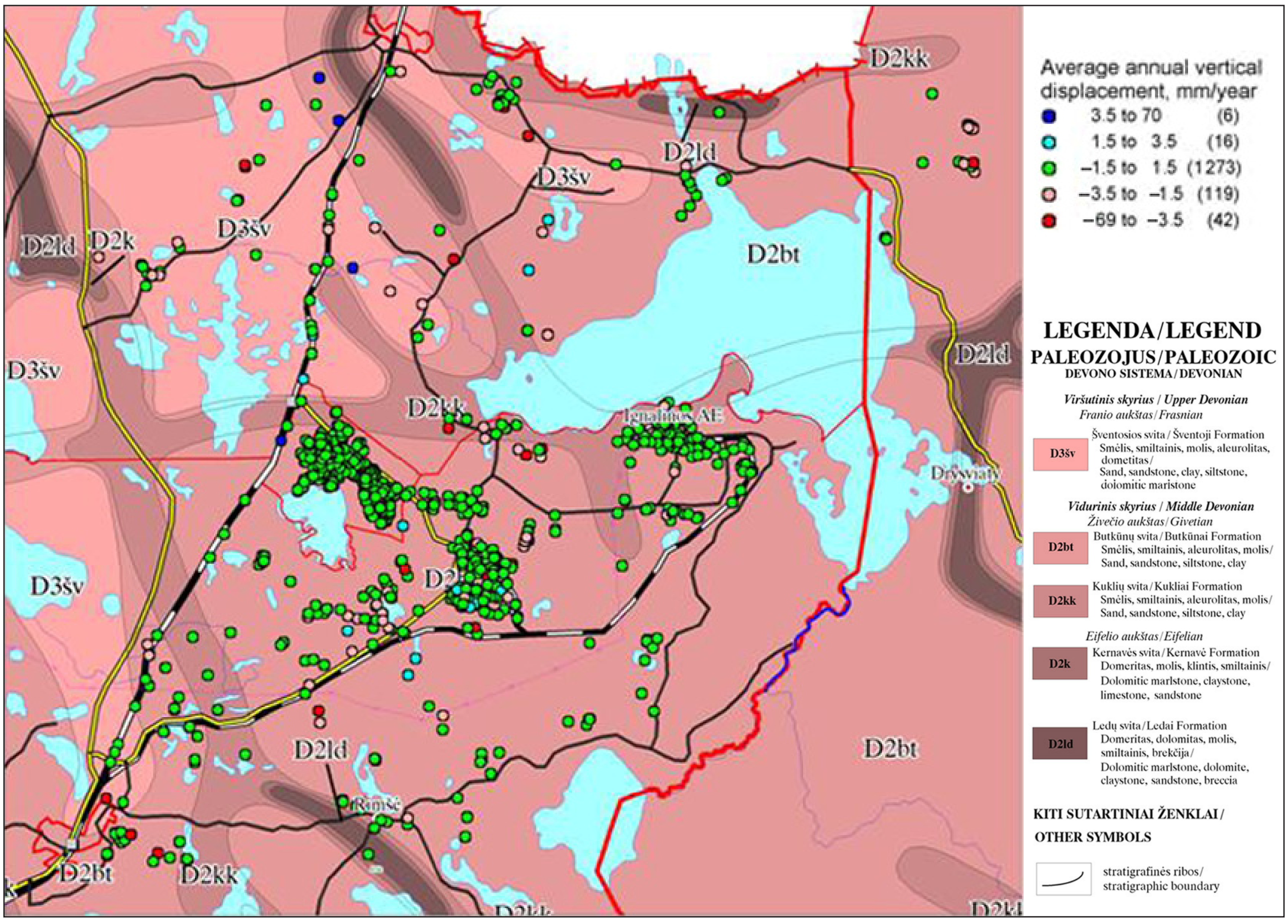

Fig. 4. Revised pre-Quaternary geological map of Drūkšiai area (after Šliaupa S., 2005) vs. PSI results
4 pav. Drūkšių ploto revizuoto prekvartero geologinio žemėlapio (Šliaupa, 2005) palyginimas su PSI taškais

PSI examined on site included subsidences linked to the presence of compressible deposits (organic, lacustrine) mass movements, location of engineering constructions and probably changes of groundwater level. These localities were checked during the field reconnaissance and some of them are discussed below.

<u>Site No. 1:</u> The analyses of the PS spatial distribution within the context of the lithologic boundaries of the Visaginas area Quaternary geological map are indicated by some interesting interrelations – the displacements related to compressible organic and other weak soil have been identified. Some examples come from the areas, where the coincidence between the lacustrine deposits and negative velocity PS is observed, the other example is the coincidence between the peat deposits and negative velocity PS (Fig. 7).

<u>Site No. 2:</u> The possible reason of PSI subsidence or uprising in some areas could be related also to exploitation of groundwater. There are

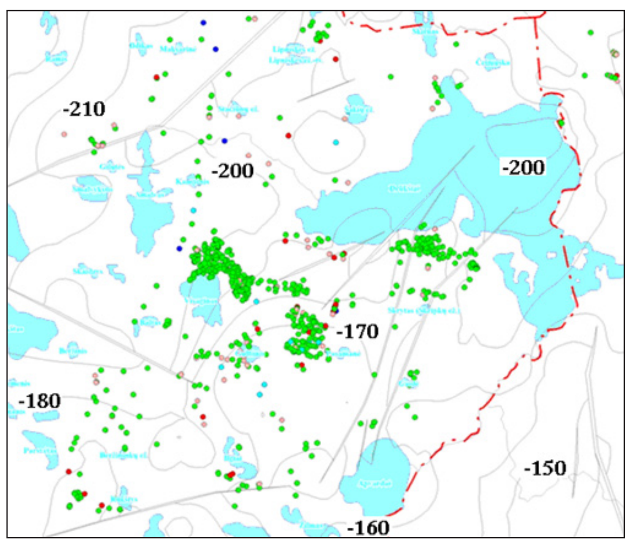

Fig. 5. Structural map of the top Ordovician based on 2D seismic data reinterpretation in 2009 (Potencialių Visagino AE..., 2009) vs. PSI results
5 pav. Ordoviko kraigo struktūrinio žemėlapio, sudaryto perinterpretavus 2D seisminius duomenis (Potencialių Visagino AE..., 2009), palyginimas su PSI rezultatais

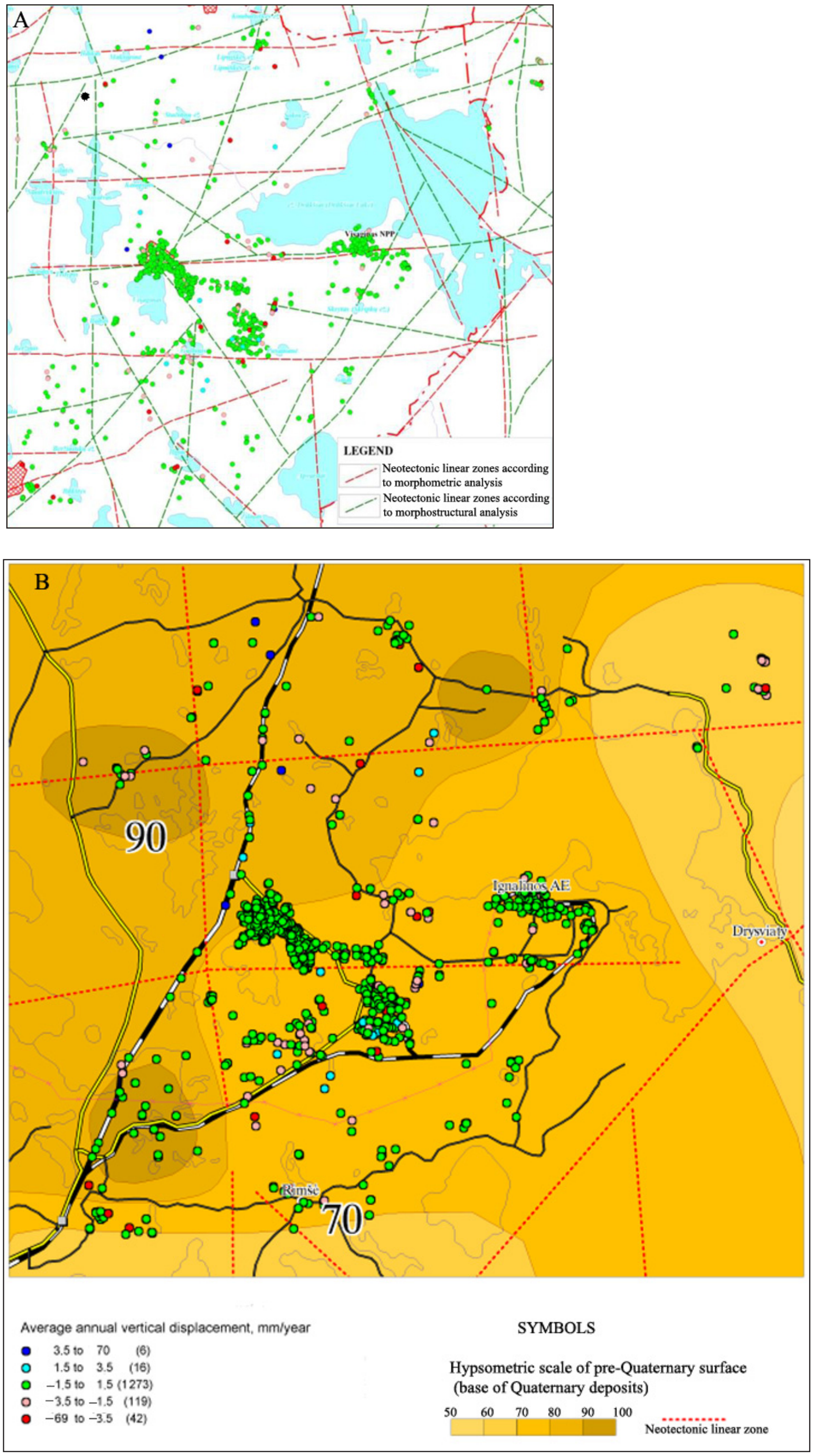

Fig. 6. Comparison of Neotectonic linear zones of Drūkšiai area (A)(after Marcinkevičius et al., 1995) and Neotectonic map (B) (after Šliaupa A., 2003) vs. PSI results

6 pav. Drūkšių ploto neotektoninių linijinių zonų (A) (Marcinkevičius et al., 1995) ir neotektoninio žemėlapio (B) (Šliaupa, 2003) palyginimas su PSI rezultatais

5 wellfields in the studied area and the most important is the water supply of the Visaginas town (Table 2). The groundwater extraction rate from 34 operational wells of the Visaginas wellfield is approximately 8,000–9,000 m^3/d at present. The wellfield was established in 1978 and the maximal pumping rate was in the period of 1986–1989 (Fig. 8).

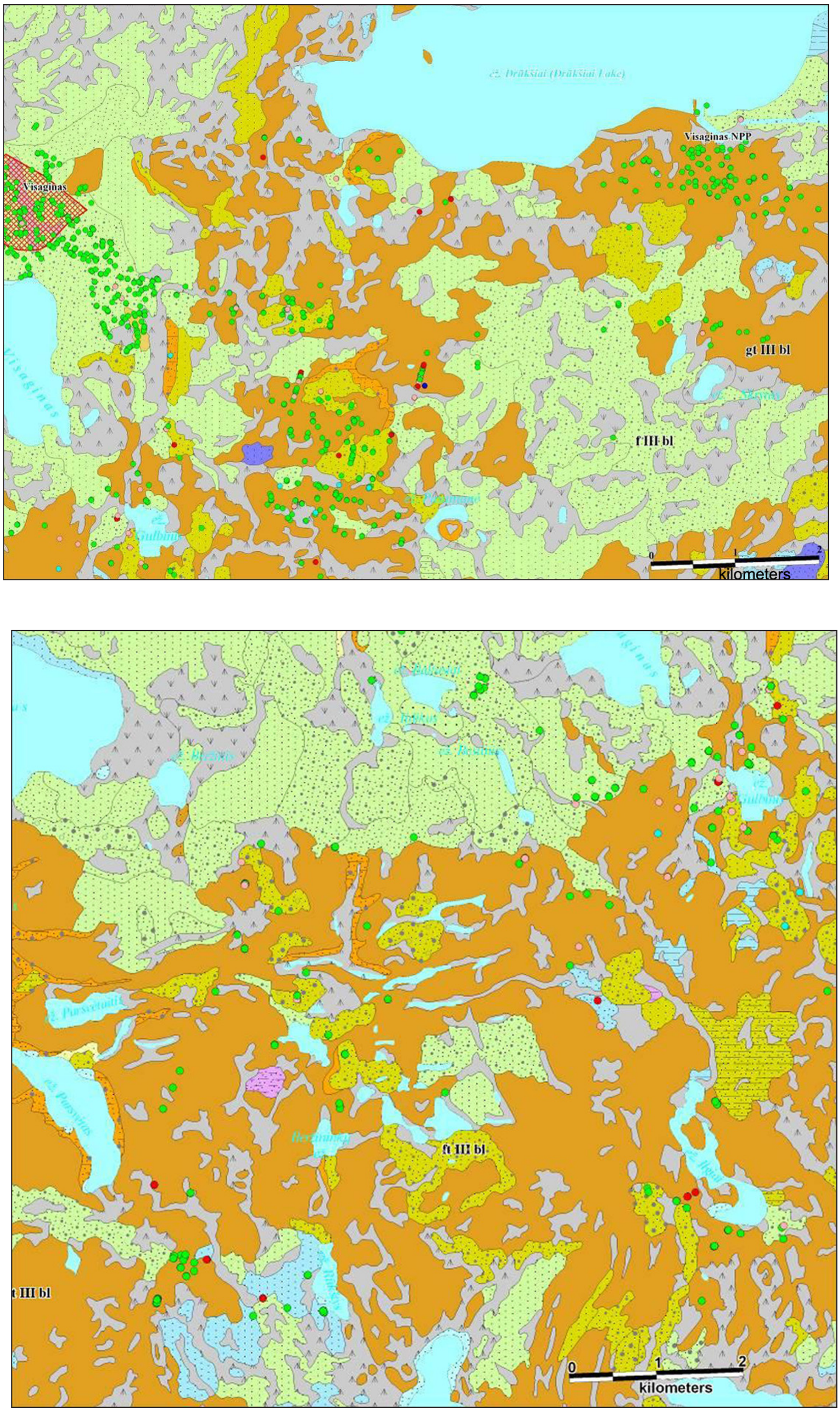

Fig. 7. Quaternary geological maps (after Guobytė, 1998; original scale 1:50 000) versus PSI results: displacements related to compressible organic and other weak soil

7 pav. Kvartero geologinis žemėlapis (Guobytė, 1998; originalus mastelis 1:50 000) ir PSI rezultatai: poslinkiai yra susiję su organiniais gruntais, pasižyminčiais dideliu susislėgimu, ir kitais silpnais gruntais

Table 2. **Information on groundwater wellfields in the studied area**
2 lentelė. **Informacija apie veikiančias vandenvietes tirtoje teritorijoje**

Address	Productive aquifer	Mean pumping rate in 2002–2009, m³/d
Visaginas Municipality, Visaginas	Upper–Middle Devonian	9.213
Zarasai District Municipality, Kimbartiškė Village	Quaternary	11
Zarasai District Municipality, Bartkiškė I Village	Quaternary	15
Zarasai District Municipality, Turmantas Railway Station	Upper–Middle Devonian	1
Ignalina District Municipality, Rimšė Village	Quaternary	9

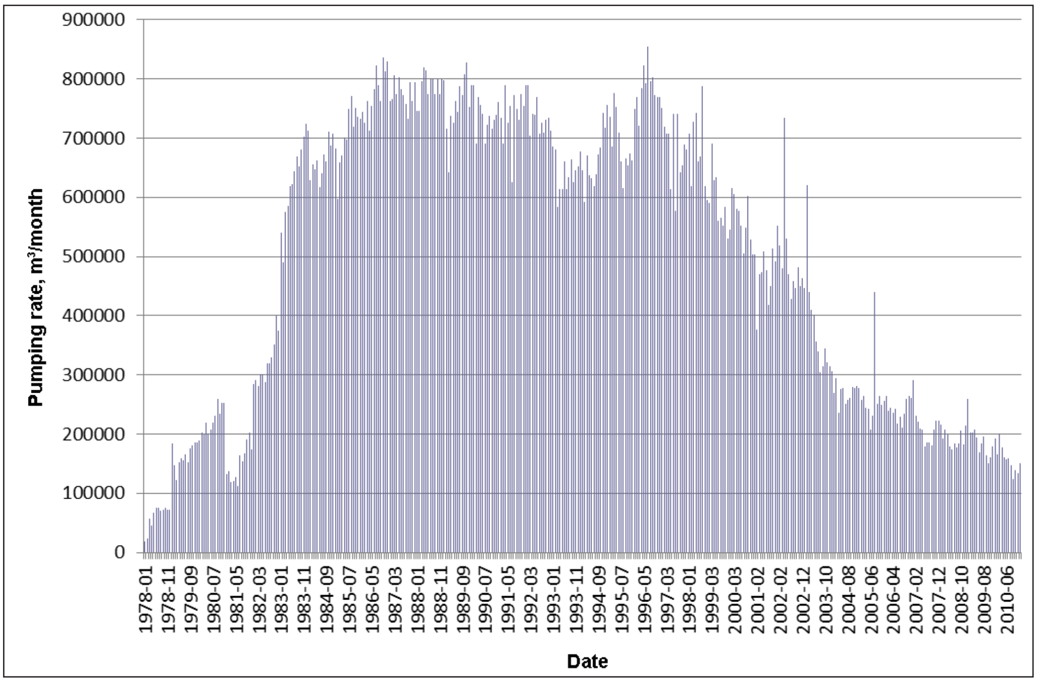

Fig. 8. Pumping rates in the Visaginas wellfield for the period from 1978 to 2010
8 pav. Išgaunamo vandens kiekis Visagino vandenvietėje (1978–2010)

It can be assumed there is no evidence that exploitation of the Visaginas wellfield causes subsidence or uprising of the earth surface (Fig. 9). Also the groundwater levels do not correlate with PSI observed subsidence (uprising) (Figs. 10–11). However, the general tendency of head rises and PSI point positive motion rate could be defined. Positive velocities could also be related with other processes. The high pumping rate between 1984 and 2000 caused lowering of groundwater heads in the exploitation aquifer. But the trends of PSI observation do not show any decrease in that period. Only the rise in values is observed. This proves that the exploitation of the Visaginas wellfield does not influence the vertical movements of ground surface.

Site No. 4: The negative velocity PS is also located near the Visaginas town. The radar signal is coming from the steel coated heating pipes which connect the Ignalina NPP, Visaginas town and other Ignalina objects (Fig. 12). The explanation for occurrence of the negative PS and detected subsidences can be related with organic soil compaction or with weak soils in the area.

Site No. 5: Some PS displacements have been detected in the railway system (Fig. 13). There are two main railroads in the area – one connects Vilnius and Daugavpils, the other leads to the Ignalina NPP. The earth surface deformations (vertical movements) on railroads could perhaps be related to deformation of rails and deformations of foundations of railway.

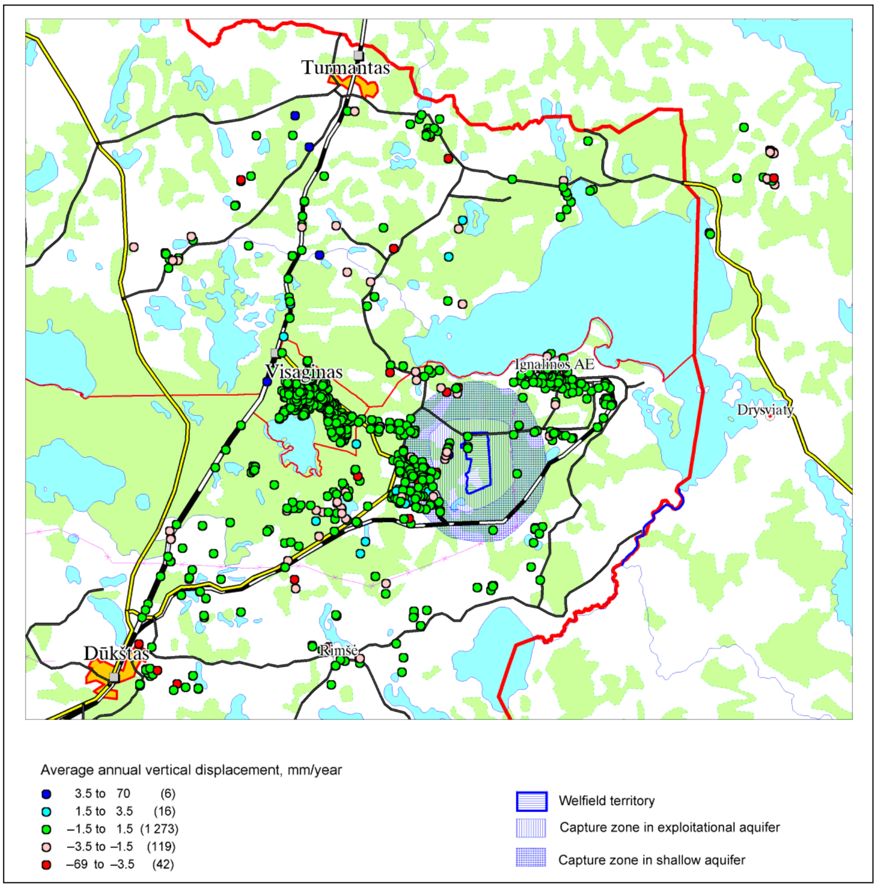

Fig. 9. Location of Visaginas wellfield, capture zones and PSI points
9 pav. Visagino ploto gręžiniai

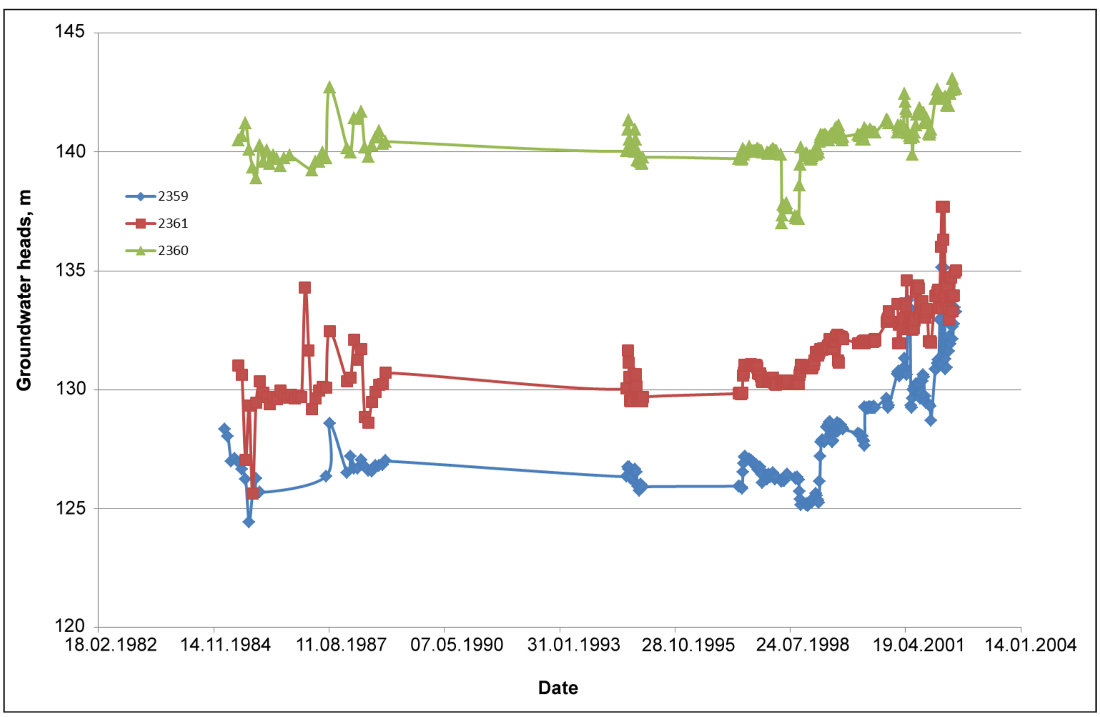

Fig. 10. Groundwater heads in observation wells No. 2359, 2361, 2360
10 pav. Požeminio vandens lygiai stebimuose gręžiniuose Nr. 2359, 2361, 2360

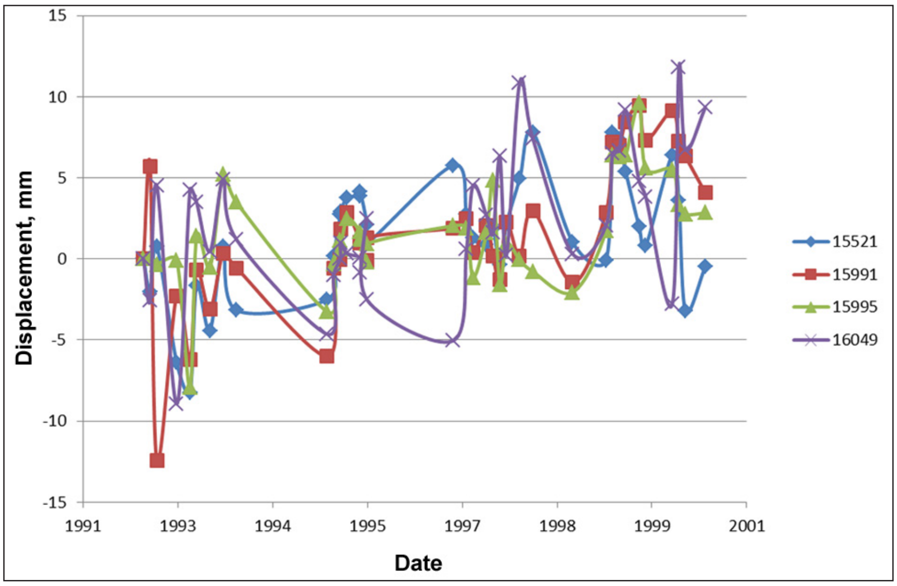

Fig. 11. PSI points (No. 15521, 15991, 15995, 16049) show observations of vertical displacements (mm) in Visaginas wellfield
11 pav. PSI taškai (Nr. 15521, 15991, 15995, 16049) žymi stebimus vertikalius judesius (mm) Visagino vandenvietėje

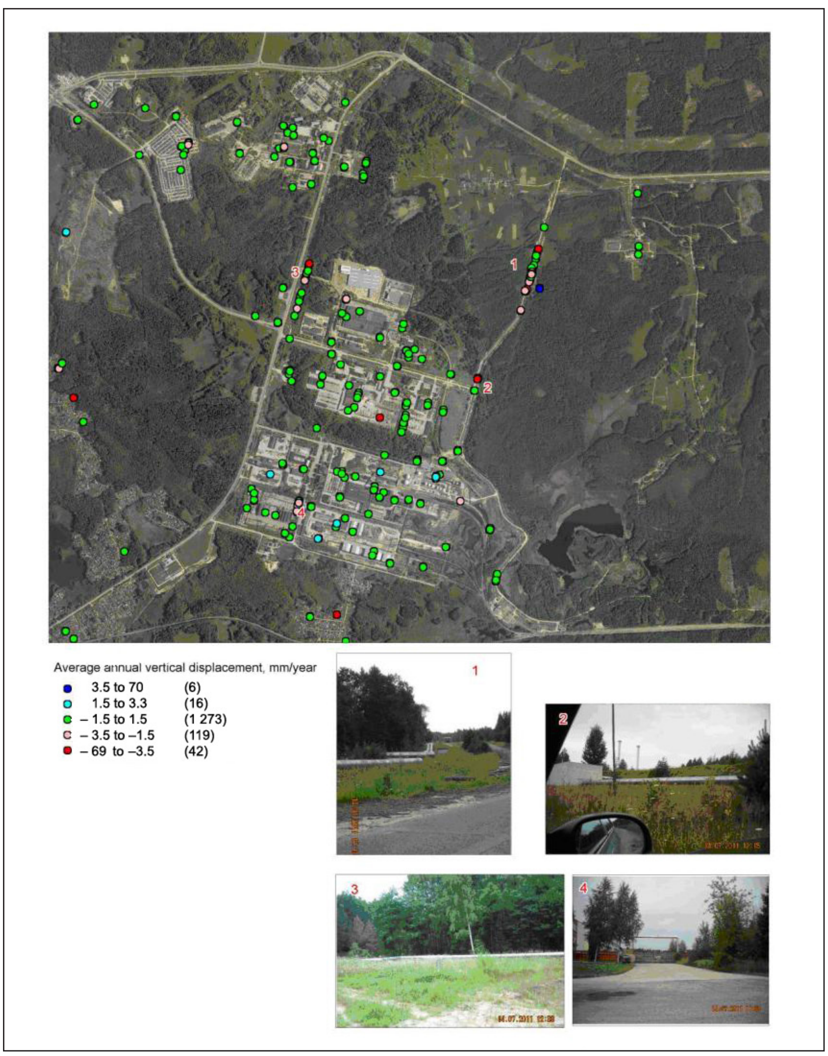

Fig. 12. Heating pipe systems and PSI points. Subsidences related to the organic soil compaction or weak soil in the area
12 pav. Poslinkiai yra susiję su organiniais gruntais, pasižyminčiais dideliu susislėgimu, ir kitais silpnais gruntais

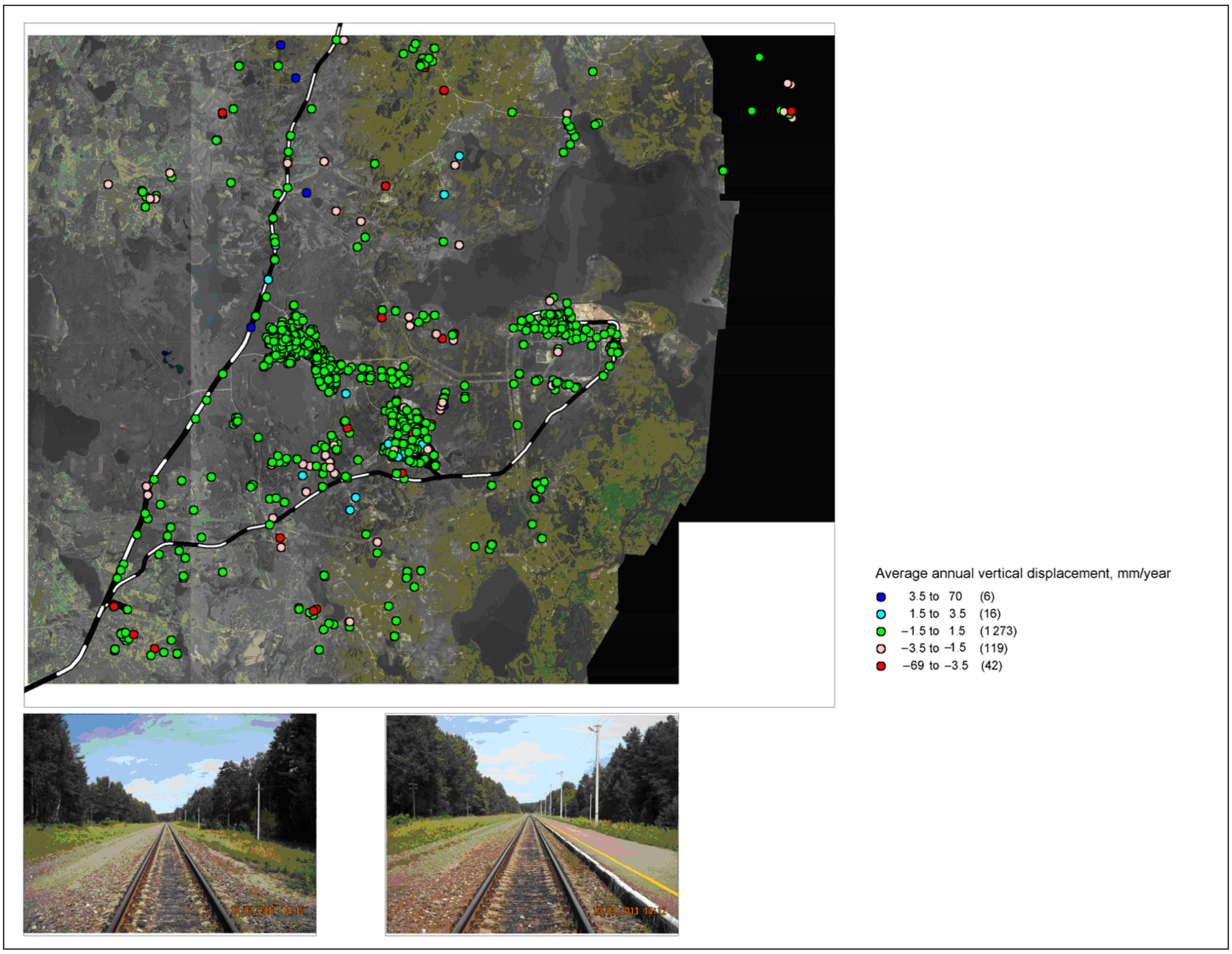

Fig. 13. Railroads vs PSI dataset
13 pav. PSI taškų išsidėstymas šalia geležinkelio

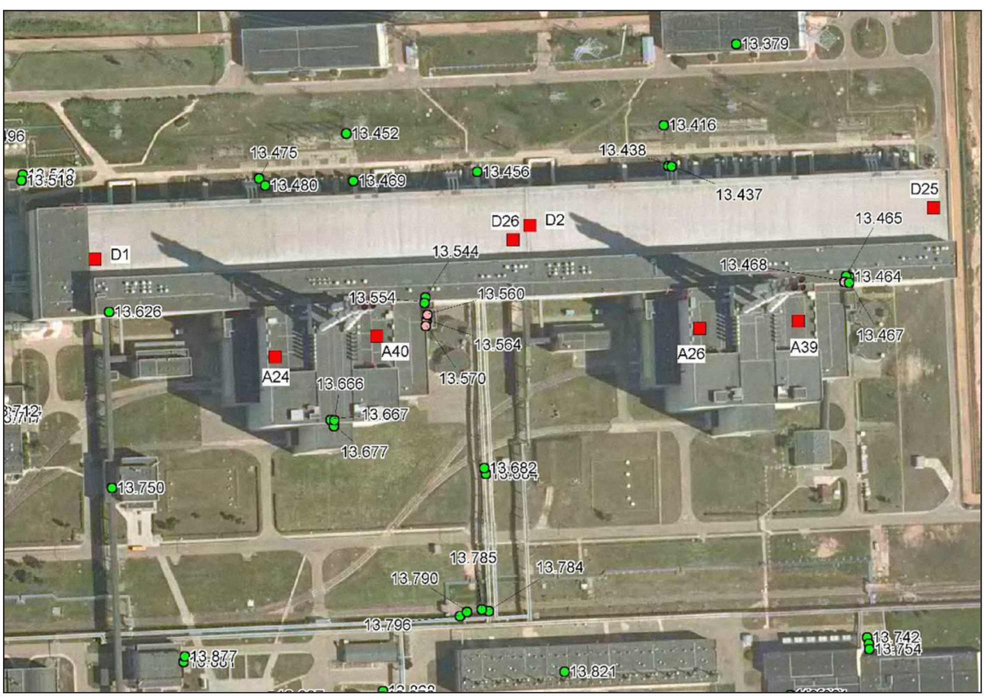

Fig. 14. PSI points (circular) and displacement observation points (square) in Ignalina NPP
14 pav. PSI taškai (apskritimai) ir poslinkių stebėjimo taškai (kvadratai) Ignalinos AE teritorijoje

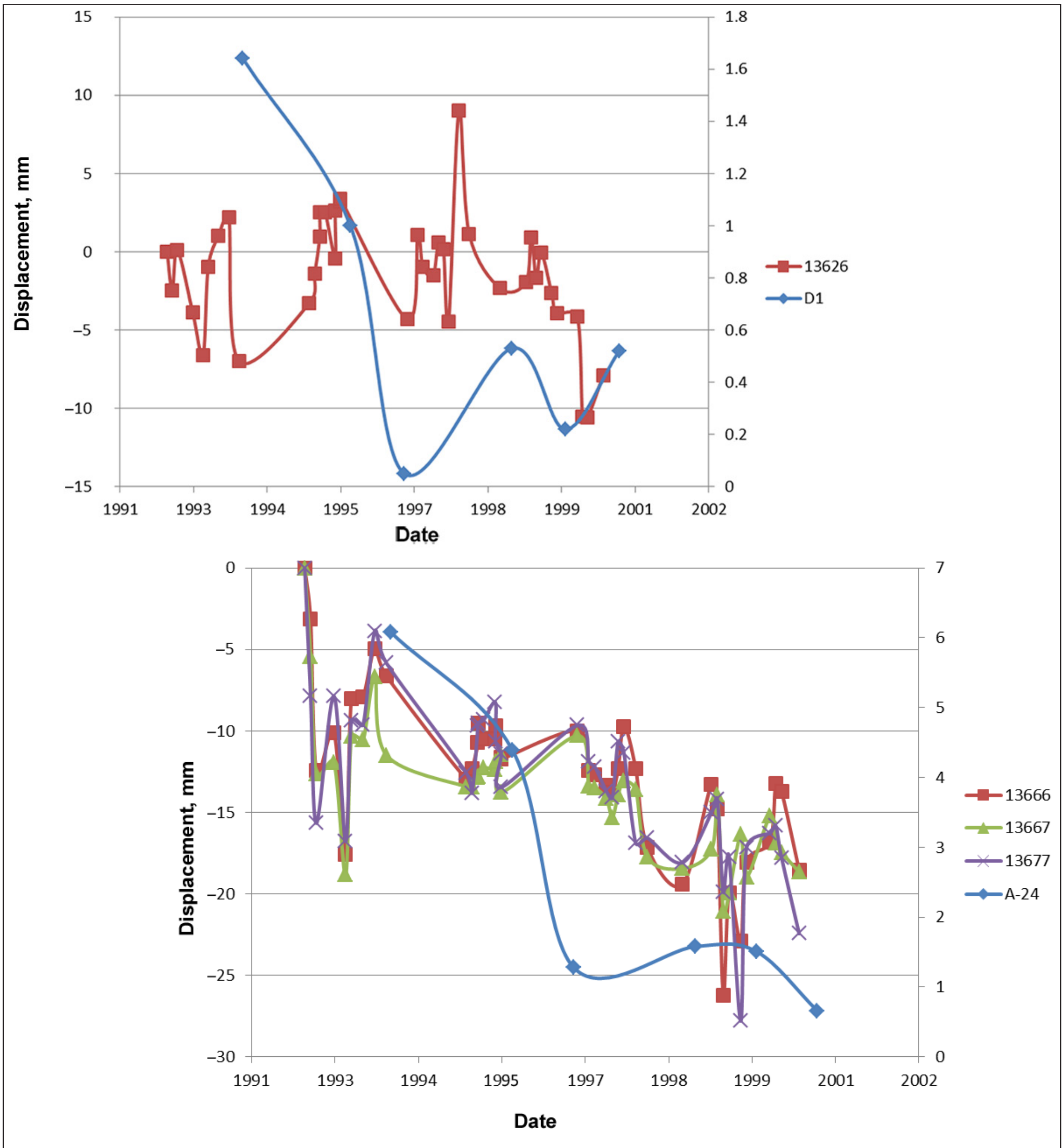

Fig. 15. Comparison of PSI data with displacement measurements (left axis – PSI results from the reference point, right axis – displacement results (mm) from the local reference point)
15 pav. PSI taškų ir poslinkių stebėjimo palyginimas (kairė ašis – PSI rezultatai nuo atskaitos taško, dešinė ašis – pokyčių reikšmės nuo vietinio atskaitos taško)

Site No. 6: The negative velocity PS is located in the Ignalina NPP area. The PSI dataset was compared with available alternative services and information sources, such as observations of deformations in the Ignalina NPP. These observations of deformations in the period between 1993 and 2000 were performed inside the buildings. Overall 8 points were measured (Fig. 14). The comparison of these data and the PSI dataset was made. The general similarities can be seen in the charts (Figs. 15, 16, 17). The detected motions of deformation are very close to the motions detected by PSI except, maybe, D-26, D2 versus

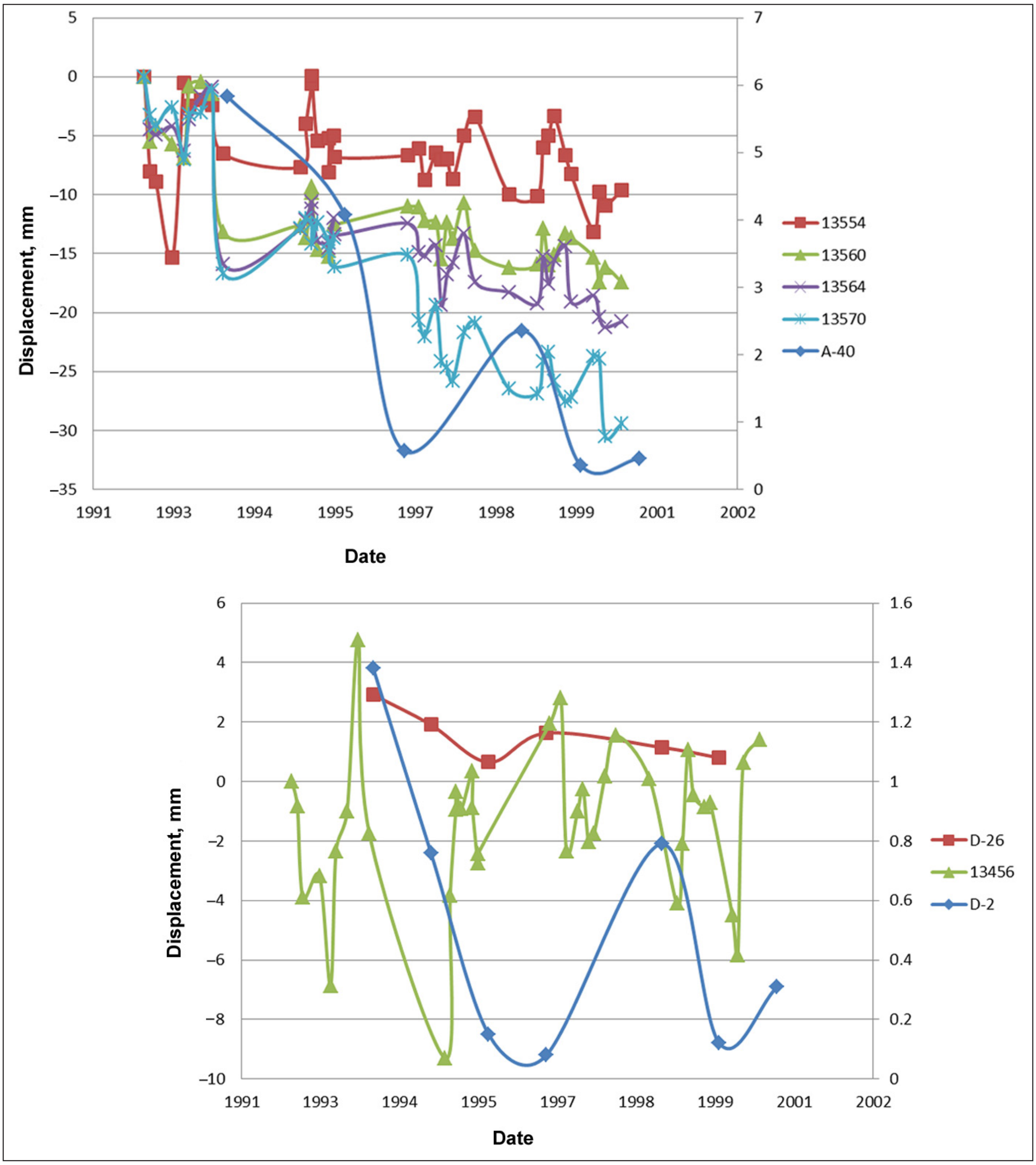

Fig. 16. Comparison of PSI data with displacement measurements (left axis – PSI results from the reference point, right axis – displacement results (mm) from the local reference point)

16 pav. PSI taškų ir poslinkių stebėjimo palyginimas (kairė ašis – PSI rezultatai nuo atskaitos taško, dešinė ašis – pokyčių reikšmės nuo vietinio atskaitos taško)

13456. The received results show that the PSI technique can be used to monitor light settlements, i. e. perform some of geotechnical monitoring tasks. It is good enough to detect light settlements and help to avoid structural damages of the buildings.

DISCUSSION AND RECOMMENDATIONS

Based on the results of the performed studies, it could be concluded that the PSI technique is a valuable and powerful tool for surface deformation

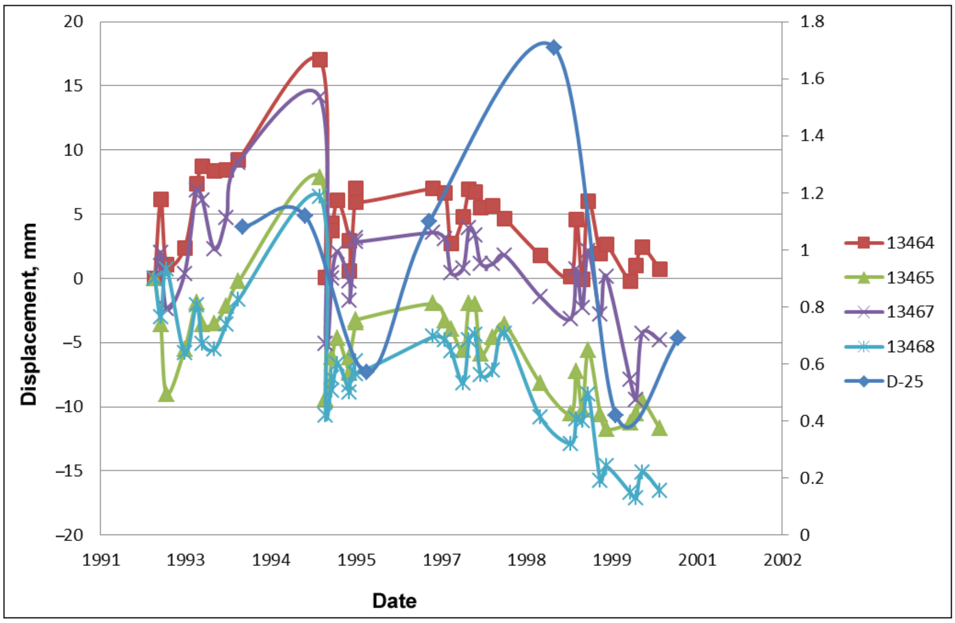

Fig. 17. Comparison of PSI data with displacement measurements (left axis – PSI results from the reference point, right axis – displacement results (mm) from the local reference point)
17 pav. PSI taškų ir poslinkių stebėjimo palyginimas (kairė ašis – PSI rezultatai nuo atskaitos taško, dešinė ašis – pokyčių reikšmės nuo vietinio atskaitos taško)

monitoring, as it is characterized by high accuracy, wide area coverage, non-invasiveness and cost-effectiveness. The PSI technique can be used to monitor light settlements, i. e. perform some of geotechnical monitoring tasks. It is good enough to detect light settlements and help to avoid structural damages of the buildings. The advantage of the PSI technique for geotechnical monitoring compared with other monitoring techniques is a dense network of PS measurements and permanent (each month) observation.

However, the performed activities also suffered from intrinsic problems due to low density of PS points in Visaginas area. The limitation of SAR PSI points has been related to the vegetation and seasonal weather conditions such as snow cover. This causes lack of reflecting surfaces. Also some doubts are concerned with suitability to use the received SAR data for understanding the (neo) tectonic activity of the area due to the limited time scale of available PSI data. In general, the (neo) tectonic movements could have low rates, therefore larger time scale information could improve confidence in the results. To understand the (neo) tectonic processes, their rate and influence on Quaternary sediments, (neo)tectonic structures and movements, further complex of studies and services should be used. The basic studies of the sub-Quaternary relief, Quaternary succession, modern relief and drainage system, and their comparison with DInSAR data from different satellites, the GPS campaigns and traditional geodetic levelling data could help properly understand the recent tectonic activity and seismic potential of a region, and to assess the associated hazards.

CONCLUSIONS

• The standard InSAR PSI data has been applied in order to investigate surface movements and to determine different crustal blocks of the studied Visaginas area.

• There is no visible spatial or linear trend of PS, which could provide some evidence of a possible relation between ground motions and tectonic or neotectonic activity of the studied area. The previously predicted / interpreted location of tectonic faults and PSI points shows that there are no evidences of active tectonic movements in the studied area.

• Although the PSI results did not reveal any obvious spatial or linear deformation trends, some areas present coherent groups of PS characterized by downward displacements. These areas as well as the site of the PS reference point were checked during the field reconnaissance and the local significance of the PS motion data is discussed.

• The groundwater levels of the Visaginas wellfield do not correlate with the PSI observed subsidence (uprising), however, a general tendency of head rise and PSI points positive motion rate has been defined.

• The review of the PS dataset has enabled to identify several sites within the Visaginas area characterized by spatially consistent concentrations (especially negative) of the PS. These localities were checked during the field reconnaissance. The examples of movements detected by PSI examined in the site included subsidence linked to the compaction of organic or weak soils, location and deformation of engineering constructions (pipelines, railway, and temporary buildings).

• The range of the PSI registered ground motions is close to the values obtained from the displacement geodetic measurements of the Ignalina NPP buildings.

• PSI technique is a valuable and powerful tool for surface deformation monitoring, as it is characterized by high accuracy, wide area coverage, non-invasiveness and cost-effectiveness. Also it can be useful for observation of deformations during operation of new NPP as well as in post-operational phases of nuclear related objects such as repositories of radioactive waste.

• It is recommended to carry out the basic studies of the of sub-Quaternary relief, Quaternary succession, modern relief and drainage system, and their comparison with DInSAR data from different satellites, the GPS campaigns and traditional geodetic levelling data that could help in understanding the recent tectonic activity and seismic potential, and to assess the associated hazards.

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NAUJAI PLANUOJAMOS VISAGINO ATOMINĖS ELEKTRINĖS APYLINKIŲ INTERFEROMETRINIŲ MATAVIMŲ DUOMENŲ ANALIZĖS REZULTATAI

Santrauka

Žemės paviršiaus pokyčius sukelia nuošliaužos, žemės drebėjimai, potvyniai, kranto erozija, gruntų poslinkis dėl požeminio vandens išsiurbimo ir požeminės naudingųjų iškasenų eksploatacijos, požeminių karstinių tuštumų įgriuvų ir kitų priežasčių. Duomenys apie žemės paviršiaus pokyčius tam tikroje vietoje, gauti iš satelitinių stebėjimų, kartu su geologiniais ir geomorfologiniais duomenimis apie tiriamąją vietovę gali padėti nustatyti žemės paviršiaus grimzdimo reiškinius. Lietuvoje žemės paviršiaus pokyčius daugiausia sukelia nuošliaužos ir karstinės įgriuvos, dažnai sugriaudamos pastatus ir komunikacijas. Straipsnis skirtas naujai planuojamos Visagino atominės elektrinės apylinkių satelitinės interferometrijos (SAR) duomenų analizei ir problemoms, su kuriomis teko susidurti interpretuojant šiuos duomenis, aptarti. Preliminari duomenų analizė rodo, kad Visagino apylinkių žemės paviršius gana stabilus, kasmet žemės paviršiaus judesių greitis svyruoja nuo –1,5 iki +1,5 mm/metus. Atskirose Visagino apylinkių teritorijose stebimos ir anomalinės neigiamos grimzdimo reikšmės. Šių reikšmių padėtis buvo patikslinta vietovėje lauko darbų metu, o tyrimo rezultatai išsamiai aprašyti šiame straipsnyje.

Raktažodžiai: satelitinis stebėjimas, sintetinis apertūrinis radaras, interferometrija, atominė elektrinė, Lietuva