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Strain and stress fields of the Ignalina NPP area from GPS data and thin-shell finite element modelling, NE Lithuania

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Horizontal movements of the Earth's surface were measured in a GPS network in the Ignalina NPP area. The network consists of ten GPS sites established in 1998. It was designed according to the known tectonic framework. Two cycles were carried out in September 1998 and September 1999. The modelling of crustal deformations and stresses was performed using a thin-shell finite element modelling (FEM) technique (ANSYS). A significant tectonic strain was recognised in the Ignalina NPP area. The stress field shows variations in the network controlled by the large-scale Drūkšiai fault trending west–east. Three major blocks are defined in the area, showing differential movements as high as 10 mm/a. The defined tectonic stress level reasonably explains the earthquake activity in the Baltic region. The principal maximum stress in northeast Lithuania is suggested to be oriented NNE–SSW. The modelling results reasonably explain the earthquake activity potential of the Baltic area.

Key words: Ignalina NPP, finite element modelling, thin-shell, GPS, stress, strain, horizontal movements

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INTRODUCTION

The available evidences from the different regions, even the cratonic areas that are characterised by relative stability throughout geological periods, indicate that the Earth's crust is affected by tectonic stresses of different type. Tectonic stresses in the East European craton are scarcely studied, except the Fennoscandian shield showing an increased seismic activity which, in combination to well developed seismic network, allows a rather detailed mapping of the pattern of the stresses affecting the crust (Wahlostrom, Assinovskaya, 1998), while little is known on the pattern of tectonic stresses in the adjacent Baltic sedimentary basin (Grunthal, Stromeyer, 1996; Jarosinski, 1994a). Therefore, the recent geodynamic processes in the cratons remain poorly constrained, in contrast to a much better understanding of the processes involved in tectonically active zones.

Most information on the stress field in the lithosphere is derived from seismic observations (e.g., focal mechanism solution) (Zobeck, 1992). Direct measurements of a stress field are performed in boreholes and underground mines (Bell, Babcock, 1986; Jarosinski, 1994b; Epov, Morozova, 1999). In most cases they provide information on the direction of the principal stresses. Besides, some techniques (e.g., hydro-fracturing) allow estimation of the stress magnitudes.

GPS networks are being increasingly developed in different countries. They provide valuable information on the recent movements of the Earth's surface in the vertical and essentially horizontal directions (e.g., Scherneck et al., 1998; Pan, Sjoberg, 1999; Kharadze, Qamar, 1999; Grenerzcy et al., 2000). However, the encoding of the geodynamic information from those measurements is rather difficult, different alternatives are suggested in the literature (e.g., Golke et al., 1996). Surface movements are recorded in scarcely spaced GPS sites, while the movement trends remain unknown inbetween. While modelling the deformations of the Earth's crust, the strain pattern is determined using interpolation techniques (rectilinear interpolation in most cases) which have serious limitations, such as dependence of the results on the selected reference points considered to be stable in the model. When interpolating crustal movements between the geodetic points the mechanical properties of the deformed body are neglected.

Crustal movements associate with changes in the stress field and are functionally interrelated (Jaeger, 1969; Singiresu, 1999; Varadan, Bhaskar, 1999; Zadro, Braitenberg, 1999). The geodetic methods reveal strain changes for a given time span. Accordingly, they reflect changes in the stress field and do not determine the absolute stress values. A simple comparison of coordinates obtained during two measurement cycles provides an invariant solution. Accordingly, the calculation of the stress field is also invariant.

The finite element modelling technique is widely applied to model changes of strain and related stresses, seeking to obtain patterns of crustal deformations and stresses at a scale that provides a better linkage of measured data to the tectonic framework of the crust. This technique was applied in the present study to analyse data on horizontal movements of the Earth's surface, obtained in the Ignalina NPP GPS network. The inplane linear and shear deformations, changes in the normal and shear tectonic stresses, and the principal stresses were calculated for an isotropic shell model. It is aimed at a better understaning of the geodynamic processes in the periphery of the Baltic sedimentary basin and in cratonic areas in general.

IGNALINA GPS NETWORK

The geodynamic network is represented by ten GPS sites consisting of concrete pillars with a forced centring (Fig. 1) (Šliaupa, 1998, 1999; Zakarevičius, Stanionis, 2003; Aksamitauskas et al., 2005). It was established in 1998 to measure the horizontal movements of the Earth's crust in the Ignalina NPP area (Zakarevičius et al., 2003). To ensure stability, a concrete pillar is embedded as deep as 2 m, which is locally considered free of frost. Above the surface the pillar is supported by a 0.5–0.6 m concrete pipe approximately 40 cm in diameter. The pillar is strengthened by reinforcing steel (4–5 bars). During measurement, a correct horizontal position is obtained by mounting the tribrach. A correct height of the antenna is achieved by applying internal calipers (devices for measuring small distances with a high level of accuracy). The horizontal points are defined by the centre of the thread for the tribrach. The vertical point is defined by means of three marked points located on a steel plate spaced 120 degrees around the thread.

The GPS sites were positioned according to the known tectonic framework of the Ignalina NPP area, defined by Marcinkevičius et al. (1995, unpublished report). Four points (Nos. 1–4) were established close to the nuclear power plant in order to determine the present tectonic activity of the area (Fig. 2). The southern part of the GPS network represents the South Drūkšiai block (sites 1–5) separated from the North Zarasai structural terrace (sites 8, 9) by the Drūkšiai depression (sites 7, 10) confined to the large-scale fault zone. The western part of the network characterises a block separated from the eastern blocks by a north-south trending fault. Some smaller-scale faults and lineaments separate individual GPS sites, the shift of which should have unravelled the activity of those tectonic features.

The most distinct fault zone in the Ignalina NPP area is represented by the west-east striking Drūkšiai zone. It intersects with another large-scale north-east trending fault zone in the Lake Drūkšiai area. These two zones are well documented by geophysical and geological data. Also, these zones are most active in terms of vertical movements, as shown by precise levelling data (111 sites levelling network) (Zakarevičius, 2003).

MEASUREMETNS OF GPS NETWORK OF IGNALINA NPP

Two measurement campaigns were performed in September 1998 and September 1999 (Stanionis, 2005; Za-

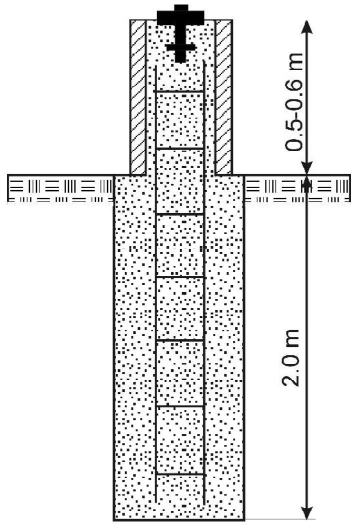

Fig. 1. Scheme of the GPS site of Ignalina NPP network
1 pav. Ignalinos AE poligono GPS punkto schema

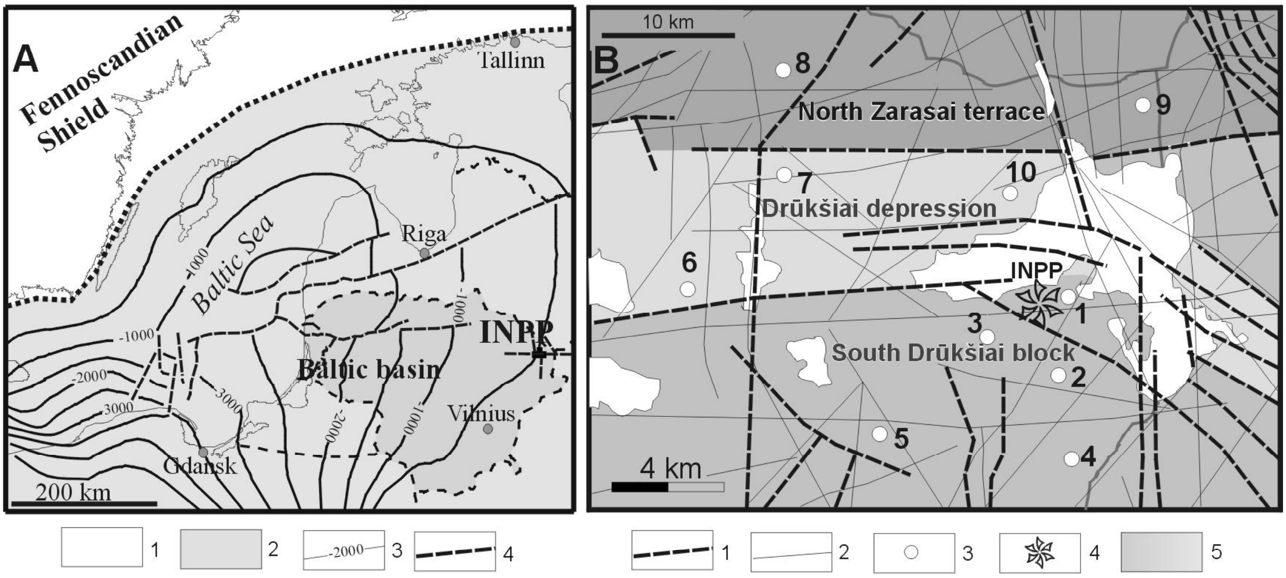

Fig. 2. *A* – structural situation of Ignalina NPP: *1* – exposed Precambrian crystalline basement; *2* – Baltic basin sediments; *3* – depth of the crystalline basement; *4* – major faults. Lithuanian territory is highlighted. *B* – tectonic structures of the Ignalina NPP. Dashed lines indicate major faults identified by geological and geophysical methods, thin lines show neotectonic lineaments modified according to an unpublished report (Marcinkevičius et al., 1995). GPS sites and numbers are indicated. Major lakes and location of Ignalina NPP are shown

2 pav. *A* – Ignalinos AE struktūrinė stiuacija: *1* – atsidengiančios kristalinio pamato uolienos; *2* – Baltijos basieno nuosėdinės uolienos; *3* – kristalinio pamato gylis; *4* – pagrindiniai lūžiai (Lietuvos teritorija paryškinta). *B* – Ignalinos AE ploto tektoninės struktūros. Brūkšninės linijos rodo pagrindinius lūžius, išskirtus geologiniais ir geofiziniais metodais, plonos linijos – neotektoninius lineamentus (pagal Marcinkevičius ir kt., 1995). Parodyti GPS punktai, jų numeriai, Ignalinos AE vieta ir pagrindiniai ežerai

karevičius, Stanionis, 2003). Measurements were carried out by VGTU and the Danish company "Nellemann & Bjørnkjær" using eight GPS ASHTECH Z-Surveyor and Z-12 tools. The measurement survey consists of four sessions. The duration of one session is 24 hours. All four sessions were carried out at GPS sites 1, 2, 4, 6, 9, 10, whereas only two sessions were performed in GPS sites 3, 5, 7 and 8.

The data were processed at the Geodesy Institute of VGTU and at the "Nellemann & Bjørnkjær" using the GPPS and FILLNET program packages.

The average quadratic error of measurements is in the range of 0.3–2.4 mm (Zakarevičius et al., 2005; Zakarevičius, Stanionis, 2005b). The standard deviations of point coordinates are less than 0.8 mm (Ignalina Control Network, 1998). The coordinates of GPS sites and their shifts in the period from September 1998 till September 1999 are presented in Table 1.

MEASUREMENT RESULTS

The measured sites indicate a rather considerable scatter in the magnitude of the horizontal movements of the surface – from 0 mm in site No. 1 to 14 mm in site Nos. 2, 5; the direction of the movements also show some scatter, though the dominating NNE orientation is evident (Fig. 3). In a plan view, a regular pattern of the horizontal movements is recognised (Fig. 4). Three areas are distinguished. The northern sites (Nos. 7, 9, 10) indicate a persistent shift to the NNE, the rates

Table 1. **Coordinates and measured coordinate shifts of GPS sites**
1 Lentelė. **GPS punktų koordinatės ir išmatuoti koordinačių pokyčiai**

GPS site	x_{98} (m)	y_{98} (m)	x_{99} (m)	y_{99} (m)	Δx (m)	Δy (m)
1	66373.772	62793.511	66373.772	62793.511	0.000	0.000
2	63911.515	62186.465	63911.528	62186.469	0.013	0.004
3	64276.247	57780.546	64276.255	57780.555	0.008	0.009
4	61073.407	62485.044	61073.417	62485.044	0.010	0.000
5	60745.917	55036.724	60745.930	55036.728	0.013	0.004
6	66983.435	47762.041	66983.429	47762.049	–0.006	0.008
7	71076.298	50898.683	71076.301	50898.685	0.003	0.002
8	75083.175	52536.489	75083.165	52536.487	–0.010	–0.002
9	72475.732	65068.225	72475.736	65068.226	0.004	0.001
10	71040.621	61144.137	71040.626	61144.137	0.005	0.000

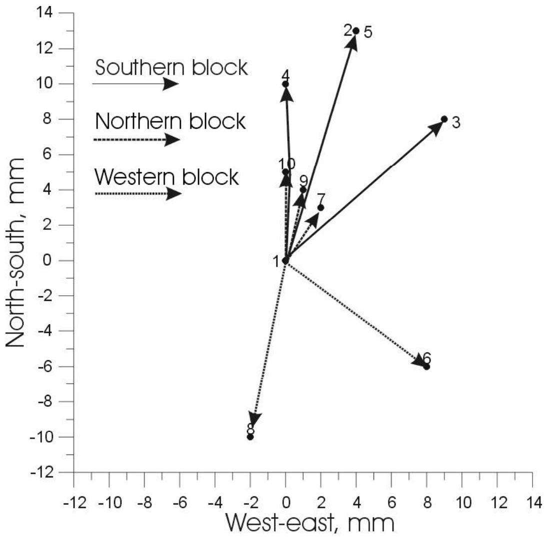

Fig. 3. X and Y shifts of GPS sites N 1–10 of Ignalina NPP network

3 pav. Ignalinos AE poligono GPS punktų pasislinkimo X ir Y grafikas

being in the range of 2–3 mm. The southern sites (Nos. 2, 3, 4, 5) reveal the same trend, but distinctly different magnitudes of the horizontal movements – within 11–14 mm. Two sites of the western part of the network (Nos. 6, 8) indicate the inverse direction of movements to the south and southeast at the rate of 8–11 mm. Only site No. 1 does not show any discernable shift in its coordinates.

FEM MODELLING OF CRUSTAL DEFORMATIONS AND TECTONIC STRESSES

Horizontal deformations of the Earth's crust can be defined from at least two cycles of measurements of geodetic network (Kaiser et al., 2005; Ruiz et al., 2003; Sue et al., 2000; Vigny et al., 2002), as changes in the position (coordinates) of the GPS sites, recording the horizontal movements of the Earth's surface, associate with changes in the stress field. Tensor analysis has been shown to be highly effective in unravelling the distribution of strain and stresses within the PGS network (Zakarevičius, 2003; Zakarevičius, Stanionis, 2002).

The FEM has been widely used to investigate crustal deformations associated with different tectonic structures, such as extensional or convergent. Advantages of the FEM over analytical methods are presented in most FEM books (Zienkiewicz, Taylor, 2000; Smith, Griffiths, 1998). For the Ignalina NPP area, the horizontal strains and stresses of the Earth's crust were modelled using FEM tgechniques. The shell model was applied in a two-dimensional space assuming that geometric elements (triangles) of limited size deform isotropically. Zero movements at the model boundaries define boundary conditions. The model incorporates four fixed points and nine mobile GPS sites. The area of the model is larger than that of the Ignalina NPP network; it consists

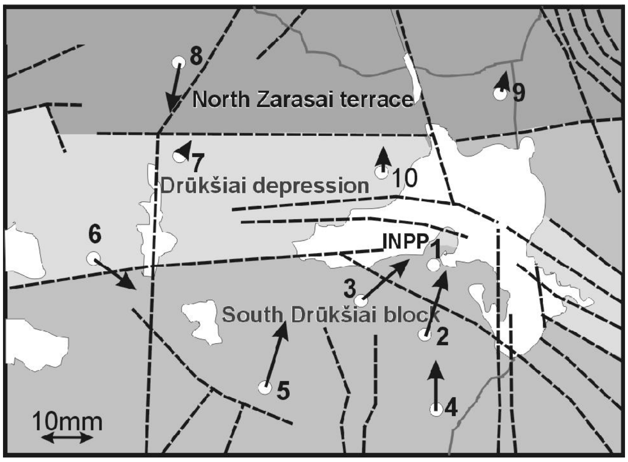

Fig. 4. Scheme showing the shift of GPS sites in Ignalina NPP area. The arrows' length is scaled (see left lower corner)

4 pav. GPS stočių poslinkių Ignalinos AR rajone schema. Rodyklių ilgis yra proporcingas poslinkio dydžiui (parodyta kairiajame apatiniame kampe)

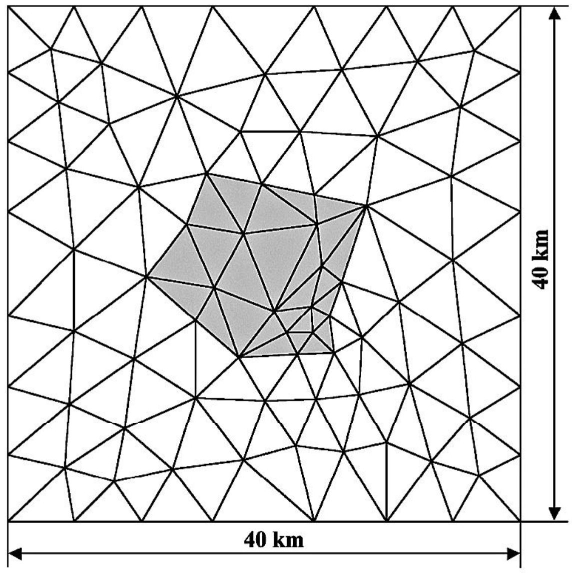

Fig. 5. Finite element mesh of the model (Ignalina NPP area is shaded)

5 pav. Baigtinių elementų tinklo modelis (Ignalinos atominės elektrinės rajonas)

of 146 finite elements (triangles), of which 26 cover the Ignalina NPP area (Fig. 5). This kind of expansion of the model with respect to the Ignalina NPP area is necessary to avoid the artefacts (if any) at the model boundaries.

The modelling was carried out using the ANSYS code (ANSYS Theory Reference, 1998; Bada et al., 1998). When calculating shifts of nodes, the obtained mechanical model of isotropic body deformations is estimated according to the information of initial points. The finite element is described by six nodes. Each node of the triangle has two degrees of freedom (north and east shifts). Shape functions are described by ANSYS Theory Reference, 1998; Zienkiewicz, Taylor, 2000.

It should be noted that it is impossible to determine the state of stress of the Earth's crust from the geodetic measurements; they only provide information on changes in the stress field (Zakarevičius, Stanionis, 2005b).

GEODYNAMIC IMPLICATIONS

The measurements of the horizontal shift in the coordinates of GPS sites reveal quite a regular pattern which matches the general tectonic framework of the Ignalina NPP area. Basically, three major blocks are identified.

The northern block, bounded in the south by the Drūkšiai fault zone oriented west-east, indicates the low-rate movement to the NNE and NE (2–3 mm/a), while the block in the south is moving roughly in the same direction but at much higher rates (11–14 mm/a). Site No. 1 actually marks the position of this tectonic boundary, which is very close to the Ignalina NPP. The difference between the shift of those two blocks is about 10 mm/a, i. e. an order higher than that of the vertical movements (about 1 mm/a). A similar (10 mm/a) differentiated shift has been identified for the western block with respect to the eastern area separated by the north--east trending fault. In general, the shift of most of the GPS sites in the Ignalina NPP area to the northeast correlates with the overall drift of the East European plate. The rate of the plate drift is assessed to be as high as 21–24 mm/a (Grenerczy et al., 2000). The magnitude of movements defined in the Ignalina NPP area is considerably lower, that implying activity of the local tectonic movements.

The high values of the differentiated horizontal movements imply high strains in the Earth's crust in the Ignalina NPP area. The modeling results are presented in Table 2. The linear strain changes ε_{xx} range from $-0.95 \cdot 10^{-6}$ to $0.36 \cdot 10^{-6}$, ε_{yy} vary from $-0.83 \cdot 10^{-6}$ to $0.65 \cdot 10^{-6}$, and ε_{zz} is in the range of 0.0210^{-6} to $0.37 \cdot 10^{-6}$. The relative shear strain ε_{xy} changes from $-1.6 \cdot 10^{-6}$ to $2.2 \cdot 10^{-6}$. Shear stresses change from –0.045 to 0.062 MPa, the maximum principal stress σ_1 changing from –0.086 MPa to –0.024 MPa (compression) and the medium principal stress σ_2 varying from –0.025 MPa to 0.056 MPa (extension and compression).

It is much higher than can be expected in the cratonic Baltic basin. It should be, however, noted that unexpectedly high strains were identified also in the Fennoscandian part of the East European Craton. In Finland, the strain rate calculated from GPS measurements is of the order of 0.5 μstrain/a (Kakkuri, 1997). The strain rates exceeding the modeled values by two orders were reported also from the Swedish SWEPOS GPS network (Scherneck et al., 1998).

The modelled pattern of the principal stresses shows a rather regular distribution. South of the Ignalina NPP the NW–SE direction of the principle maximum stress (compression) is identified. It changes to NNW-SSE and NNE–SSW directions to the north (Fig. 6). Moreover, the medium principle stress is predominantly negative (i.e. shortening) to the west, whereas negative values (extension) are modelled in the east. The boundary between these two provinces is sharp. It is confined to the west-east striking the Drūškiai fault zone. The southern

Table 2. **Horizontal strains and tectonic stresses**
2 lentelė. **Horizontaliosios deformacijos ir tektoniniai įtempiai**

Corner node	$\varepsilon_{xx} \cdot 10^{-6}$	$\varepsilon_{yy} \cdot 10^{-6}$	$\varepsilon_{zz} \cdot 10^{-6}$	$\varepsilon_{xy} \cdot 10^{-6}$	σ_{xx}, MPa	σ_{yy}, MPa	σ_{xy}, MPa	σ_2, MPa	σ_1, MPa
1	0.108	–0.364	0.085	–0.503	0.001	–0.025	–0.014	0.007	–0.031
2	0.113	–0.555	0.147	0.090	–0.002	–0.039	0.003	–0.002	–0.040
6	–0.531	–0.196	0.242	–0.012	–0.043	–0.025	0.000	–0.025	–0.043
7	–0.036	–0.097	0.044	0.632	–0.005	–0.008	0.018	0.012	–0.024
8	0.364	–0.829	0.155	–0.816	0.012	–0.055	–0.023	0.019	–0.062
9	0.143	–0.631	0.162	0.132	–0.001	–0.044	0.004	–0.001	–0.045
11	–0.436	0.091	0.115	0.560	–0.031	–0.001	0.016	0.005	–0.038
12	–0.750	0.646	0.035	0.538	–0.044	0.034	0.015	0.037	–0.047
13	0.053	–0.116	0.021	0.746	0.002	–0.008	0.021	0.018	–0.024
21	0.005	–0.456	0.150	–0.112	–0.008	–0.034	–0.003	–0.008	–0.034
23	0.045	–0.447	0.134	–0.072	–0.005	–0.033	–0.002	–0.005	–0.033
29	–0.185	–0.577	0.254	–1.603	–0.025	–0.047	–0.045	0.011	–0.082
32	–0.394	0.336	0.019	1.013	–0.023	0.018	0.028	0.032	–0.038
35	–0.001	–0.310	0.104	1.340	–0.006	–0.023	0.038	0.024	–0.053
45	–0.260	–0.295	0.185	0.831	–0.025	–0.027	0.023	–0.003	–0.049
46	0.080	–0.479	0.133	0.138	–0.003	–0.034	0.004	–0.002	–0.035
61	–0.953	–0.163	0.372	0.935	–0.074	–0.030	0.026	–0.018	–0.086
62	–0.447	0.245	0.067	2.227	–0.029	0.010	0.062	0.056	–0.075
63	–0.609	0.235	0.125	1.216	–0.041	0.006	0.034	0.024	–0.059
64	0.086	–0.714	0.209	–0.654	–0.007	–0.052	–0.018	0.000	–0.058

Note: Minus indicates shortening and plus expansion of the element.

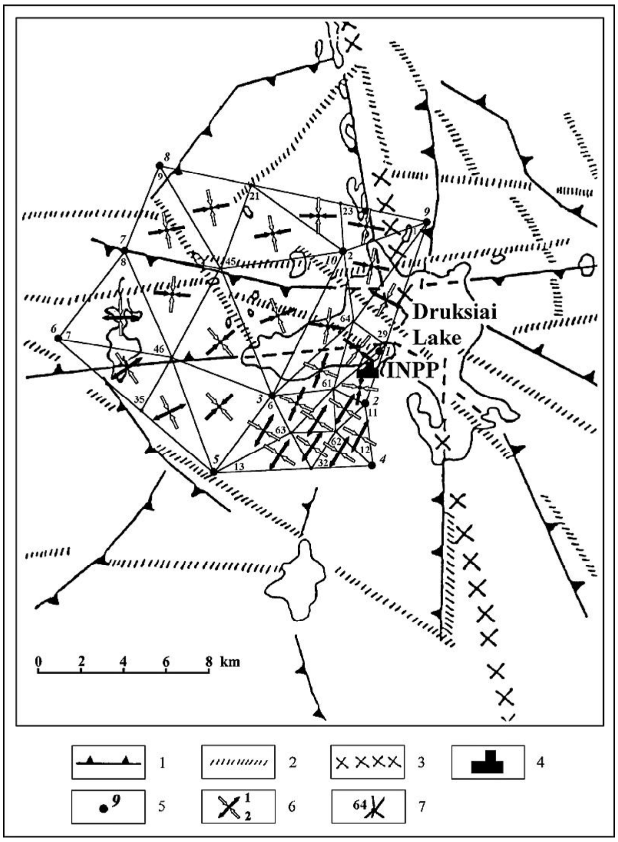

Fig. 6. Pattern of principal tectonic stresses in INPP area. Some major tectonic features are shown (modified according to unpublished report by Marcinkevičius et al., 1995). Faults defined from: *1* – seismic survey, *2* – aeromagnetic survey, *3* – morphostructural analysis. Others: *4* – Ignalina Nuclear Power Plant, *5* – GPS site, *6* – principal stresses (1 – σ_1, 2 – σ_2), *7* – corner node

6 pav. Svarbiausių tektoninių įtempių kryptys Ignalinos atominės elektrinės teritorijoje. Tektoniniai lūžiai (pagal Marcinkevičius ir kt., 1995) nustatyti pagal: *1* – seisminius tyrinėjimus, *2* – aeromagnetinius tyrinėjimus, *3* – morfostruktūrinę analizę; *4* – Ignalinos atominė elektrinė, *5* – GPS punktas, *6* – svarbiausieji įtempiai (1 – σ_1, 2 – σ_2), *7* – mazginis taškas

block is divided by some smaller scale north-south trending fault which affects the distribution of the medium principle stress, though alternatively it may reflect the impact of the general stress rotation. It should be noted that this structural control on the stress field rotation is less distinct in the west, suggesting that the activity of the Drūkšiai fault decreases in this direction. On the other hand, it can be related to the controlling position of GPS site No. 1 in the model. The stress rotation is a characteristic feature of large-scale fault zones (e.g., Du, Aydin, 1996).

Based on the aforementioned evidences, we conclude that the Ignalina nuclear power plant is located close to an active fault which is large enough to disturb the regional stress field. The second important tectonic feature is related to the north-south trending fault crossing the network in the west. The other faults identified in the study area, except the smaller scale north-south trending fault crossing the southern block, do not show any discernable impact on the horizontal movements of the surface.

The influence of the fault tectonics inhibits consistent regional-scale implications on the stress field in this part of Lithuania. So far, no instrumental measurements of the stress field have been available in Lithuania, except in one well studied by the FMS method in west Lithuania, which shows a NW–SE direction of the principle compression (Šliaupa, Zakarevičius, 2000). Furthermore, a comparison of the triangulation network with the GPS network of Lithuania revealed two stress provinces (Zakarevičius, 2003). The western half of Lithuania is affected by a NW–SE tectonic compression, whereas the direction of the maximum principle stress in the Lithuania is directed NNE–SSW. It is in concert with the stress field pattern identified by geomorphological (lineament) metods (Sim, Sergejev, 1995).

In the INPP area, the principal horizontal compression is oriented NW–SE on the southern flank of the fault, whereas the NNW-SSE to NNE–SSW direction dominates the northern flank (Fig. 7). Assuming that the eastern part of the northern block is the best to reflect the regional situation, the orientation of the regional principle maximum stress is NNE–SSW which is in concert to previous studies.

The interpretation of the GPS data provides a considerable insight into the seismic activity of the faults (e.g., Kharadze et al., 1998). The stress drop of the recent Kaliningrad earthquakes (21.09.2004) of $M_L = 4.3$ and $M_L = 5$ was evaluated as high as 16 and 37 MPa respectively. Taking into consideration the stress changes obtained in the Ignalina NPP model, the recurrence of earthquakes of this level can be predicted as 10^2–10^3 years, in case there is no aseismic stress relaxation by small-scale shifts of blocks along the faults. It reasonably explains the recurrence and magnitudes of strong earthquakes in the Baltic region, reported by historical sources.

It should be noted that the proposed model represents a strongly approximated crust. It does not account

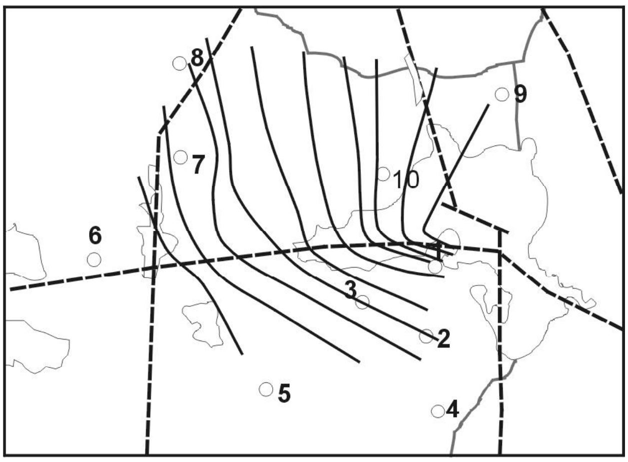

Fig. 7. Directions of maximum principal stress

7 pav. Pagrindinės maksimalios įtampos orientacijos schema for the inhomogeneities of the mechanical properties of the crust that have a considerable impact on the distribution of stress field and strain localization (e.g., Zhao et al., 2004). Furthermore, it considers a continuous shell, whereas the faults are important elements controlling the crustal mechanics. However, the model results reflect well the rate of the recent geodynamic processes in the Baltic basin.

CONCLUSIONS

Measurements in the Ignalina GPS geodynamic network indicate rather intense differential horizontal movements of the Earth's surface, suggesting a rather high activity of the recent geodynamic processes. Several major blocks, bounded by different-scale faults, are identified (Fig. 8).

Strain and stress changes in the Earth's crust have been defined by the FEN technique and show significant variations across the network. The west-east trending Drūkšiai fault zone significantly disturbs the local stress field, essentially in the east close to the Ignalina NPP, thus proving the previous suggestions about the highest order of this zone in the study area. The northern block overrides the southern block. In general, the NNE–SSW orientation of the maximum principle stress is suggested, which is compatible to the regional stress field reported from east Lithuania.

The annual stress changes (1998–1999) are identified to range from –0,024 MPa to –0,086 MPa for the horizontal principal compression, with σ_2 varying from –0,025 MPa to +0,056 MPa per year (compression / extension). In case there is no permanent stress relaxation along the faults, the earthquakes as strong as the Kaliningrad earthquake of 2004 (34 MPa) can occur once in 10^3 years, which reasonably explains the seismic activity reported from the Baltic region.

The obtained high values of strain rate in the Ignalina NPP urge to continue the studies, essentially by regularly performing the measurements of GPS site coor-dinate shifts in order to construct a more consistent geodynamic model of the area and a prognosis of earthquakes and surface deformation activities. The proposed model can be considered as the first approach to studying the recent tectonic activity in the Ignalina NPP area.

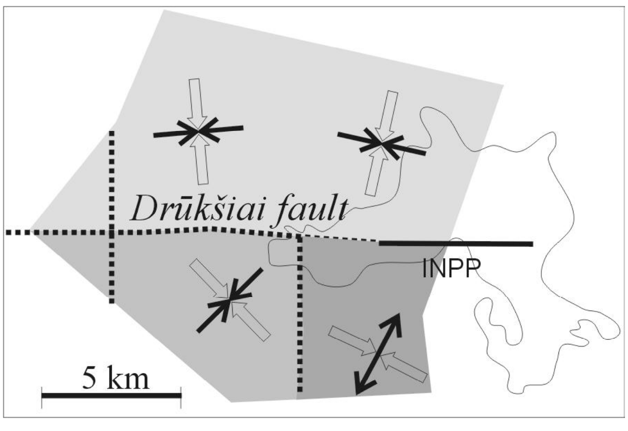

Fig. 8. Stress-field zoning and controlling faults
8 pav. Įtampų lauko rajonavimo schema ir kontroliuojantys lūžiai

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IGNALINOS AE REGIONO TEKTONINĖS ĮTAMPOS IR DEFORMACIJOS GPS DUOMENIMIS NAUDOJANT PLONOS PLOKŠTELĖS BAIGTINIŲ ELEMENTŲ MODELIAVIMĄ (ŠR LIETUVA)

Santrauka

1998 m. buvo įsteigtas GPS tinklas aplink Ignalinos AE. Atlikti du matavimo ciklai parodė intensyvius horizontalius Žemės plutos blokų judesius. Išskirti trys blokai skirtingomis horizontalių judesių kryptimis ir greičiu. Šiaurinis ir pietinis blokai, atskirti platuminės Drūkšių lūžių zonos, juda ŠŠR ir ŠR kryptimi, tačiau skirtingu greičiu – atitinkamai 11–14 ir 2–3 mm/m. Vakarinis blokas, apribotas meridianinio lūžio, juda į pietryčius 6–8 mm/m greičiu. Tai rodo aukštas blokų diferencijuotų horizontalių judesių reikšmes, siekiančias apie 10 mm/m, ir tai dešimt kartų viršija vertikalius judesius. Plonos plokštės baigtinių elementų programa ANSYS atliktas modeliavimas atskleidė tektoninių įtampų ir horizontalių deformacijų pasiskirstymą Žemės plutoje, Ignalinos AE regione. Skaičiavimai rodo aiškią Drūkšių lūžio įtaką įtampų laukui, t. y. stebima tektoninių įtampų rotacija, būdinga stambioms lūžių zonoms. Nepaisant didelio įtampų lauko sukimo, galima prognozuoti ŠŠR–PPV krypties regioninį įtampų lauką (maksimalus spaudimas), ir tai atitinka Rytų Lietuvos duomenis. Įtampų kaita siekia 0,024–0,086 MPa per metus (pagrindinis spaudimas). Tai gerai paaiškina stebimą vidutinių Žemės drebėjimų pasikartojimą Baltijos regione, taip pat ir Kaliningrado Žemės drebėjimą.

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ТЕКТОНИЧЕСКИЕ НАПРЯЖЕНИЯ И ДЕФОРМАЦИИ В РАЙОНЕ ИГНАЛИНСКОЙ АЭС ПО ДАННЫМ GPS, ПОЛУЧЕННЫМ МОДЕЛИРОВАНИЕМ ТОНКИХ ПЛАСТИН ИСХОДНЫХ ЭЛЕМЕНТОВ, СВ ЛИТВА

Резюме

В 1998 г. была создана сеть GPS вокруг Игналинской АЭС. Выполнены два цикла измерений, которые показали интенсивные горизонтальные движения блоков Земной коры. Выделены три блока, для которых характерны различные направления и скорости горизонтальных движений. Северный и южный блоки, разделенные широтной Друкшяйской зоной разломов, движутся в ССВ и СВ направлениях, но с различной скоростью: 11–14 мм/г и 2–3 мм/г соответственно. Западный блок, ограниченный меридианальным разломом, движется в ЮВ направлении со скоростью 6–8 мм/г. Выполнено моделирование тонких пластин исходных элементов с использованием программы ANSYS, которое выявило распределение тектонических напряжений и горизонтальных деформаций в Земной коре. Прогнозируется тектоническое давление ССВ и ЮЮЗ направлений, что соответствует имеющимся данным по Восточной Литве. Изменения напряжений достигают 0,024–0,086 МПа в год. Это хорошо объясняет наблюдаемые повторные средние землетрясения в Балтийском регионе, в частности Калининградское.