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THE DISPERSION OF HORIZONTAL TECTONIC STRESSES IN THE EARTH'S CRUST IN THE BALTIC REGION

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Abstract. GPS measurements recorded within the period from1992 to 2003 were employed to investigate horizontal tectonic stresses in the Earth's crust in the Baltic region. To avoid the impact of discrepancies in the systems of coordinates upon the parameters of deformations, the method of tensor analysis was applied thus estimating parameters employing the method of finite elements. Computations were performed using the created algorithms and applying *ANSYS* code.
The values of tectonic stresses in the Earth's crust in the territory of the Baltic Sea region were calculated considering changes in maximum and minimum principal stresses. The value of change in maximum principal stress in the territory of the Baltic Sea region varies between –0.0013 MPa and +0.0032 MPa; the value of change in minimum principal stress varies between –0.0084 MPa and +0.0009 MPa. Positive values are dominating in directions of changes in maximum principal stresses (extension), whereas negative values – in directions of changes in minimum principal stresses (compression).

Keywords: finite element modelling, horizontal strains, tensor analysis, GPS, tectonic stresses.

1. Introduction

Horizontal deformations of the Earth's crust can be identified from changes in geodetic coordinates and other elements of the points of geodetic networks performing repeated geodetic measurements (Barba *et al.* 2010; Dwivedi and Hayashi 2010; Ponraj *et al.* 2010; Rontogianni 2010; Stanionis 2008; Zakarevičius 2003; Zakarevičius *et al.* 2009, 2010a, 2010b; Zakarevičius and Stanionis 2007; Zhu and Shi 2011). The carried out measurements appear as continuous and / or differential regimes.

Among the latest technologies for measuring a geodetic network, GPS is the most widely used approach. The repeated measurements of GPS networks enable a definition of horizontal stresses affected by the Earth's crust.

The objective of the present study is to evaluate the applicability of tensor analysis and finite element modelling approach dealing with horizontal stresses using geodetic measurements. Data on the geodetic network of the Baltic region were employed.

2. Data

Data on GPS campaigns organized within the period from 1992 and 2003 GPS were used in the performed analysis. The network consists of 354 triangles (Fig. 1) comprising 19 geodetic sites (Fig. 2).

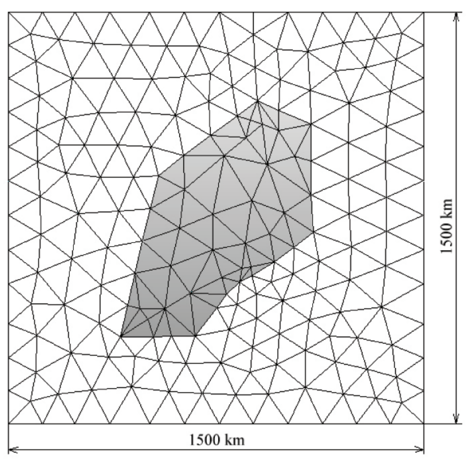

Fig. 1. Finite element meshing of the model

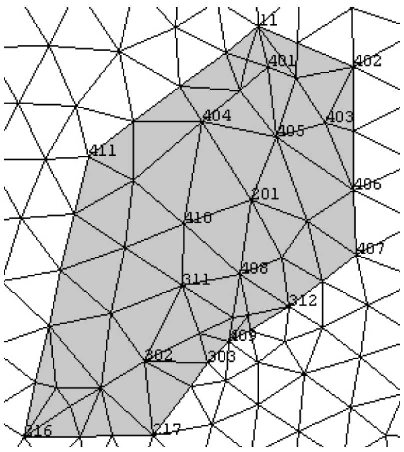

Fig. 2. GPS sites of the Baltic region

The EUREF-BAL´92 campaign was carried out from August 29 to September 4, 1992 (Ehrnsperger 1995; Madsen, F., Madsen, B. 1993). Each day, the morning and afternoon sessions of approximately 5 hours duration took place. The observations were made by Norwegian, Swedish, Finish and Danish geodesists using Ashtech dual frequency receivers. 24 geodetic sites were measured using 20 GPS receivers. The sites in Landskrone (401), Vaivara (402), Tartu (403), Ohtja (404) and Saarde (405) were measured in Estonia, the sites in Riga (201), Kaugari (406), Indra (407) and Arajas (410) – in Latvia and those in Akmeniskiai (311), Meskonys (312), Saseliai (408) and Dainavele (409) – in Lithuania. The EUREF network was tied to geodetic stations in Poland (Borowiec (216), Barowabora (217), Lamkowko (302), Masze (303), Germany (Wettzell (035), Karlsburg (313), Finland (Metsähovi (011), Sweden (Mårtsbo (013), Klinta (015), Visby (411) and Denmark (København (412). Stations 011, 013, 015, 035, 313, 412 were fixed with reference to EUREF-89 geodetic coordinates. Processing was performed as a traditional network densification of the original EUREF-89 campaign. TOPAS software was used for reducing observations and FILLNET – for vector adjustment.

The EUREF-POL´2001 GPS campaign was carried out in September 2001 (Jaworski *et al.* 2002). Five 24 hour-duration sessions were performed for the quality assurance of the Polish part of the EUREF-POL´1992 campaign (Zielinski *et al.* 1994). The solution was computed in ITRF 2000 epoch 2001.74 and then transformed to ETRS89. Data on sites 302 and 303 were used for analyzing strains on the geodetic network.

The 2003 GPS campaign under the framework of the Nordic Geodetic Commission (NKG) was carried out in GPS-week 1238 (28 September to 4 October 2003) (Jivall *et al.* 2005a, 2005b, 2007). The campaign mainly covered permanent GPS stations in the Nordic and Baltic areas as well as Island, Greenland and Svalbard. The geodetic points of ETRS 89 were also included in Latvia, Lithuania and Denmark. Processing the NKG GPS 2003 campaign was performed in four centres of analysis using three different software packages (Bernese version 4.2, version 5.0, Gamit/Globk, Gipsy/Oasis II). The final solution to ITRF 2000 epoch 2003.75 is the average of four solutions after aligning them all to the average of two global solutions (Gipsy and Gamit). The estimated accuracy at a level of 95% is 0.5–1 cm for horizontal components and 1–2 cm for the vertical ones. New ETRS 89 coordinates based on the NKG 2003 campaign have been calculated.

Finally, all coordinates were converted to the plane coordinates of Transverse Mercator projection (Table 1).

Table 1. Plane rectangular coordinates of GPS sites and their changes

GPS sites	x_{1992} (m)	y_{1992} (m)	x_{2003} (m)	y_{2003} (m)	Δx (m)	Δy (m)
11	6677031.9509	521909.1789	6677031.9342	521909.1805	–0.0167	0.0016
201	6312913.3231	503565.2750	6312913.3052	503565.2747	–0.0179	–0.0003
216	5815531.6150	27711.9353	5815531.6046	27711.9271	–0.0104	–0.0082
217	5819167.2339	298609.6680	5819167.2225	298609.6586	–0.0114	–0.0094
302	5977885.3672	281147.2077	5977885.3597	281147.1945	–0.0075	–0.0132
303	5972821.0726	414581.4432	5972821.0609	414581.4523	–0.0117	0.0091
311	6133606.0460	362420.3672	6133606.0354	362420.3593	–0.0106	–0.0079
312	6089118.3447	584389.8085	6089118.3320	584389.7969	–0.0127	–0.0116
401	6590192.0115	541864.6581	6590192.0041	541864.6568	–0.0074	–0.0013
402	6589613.4649	718703.8336	6589613.4522	718703.8348	–0.0127	0.0012
403	6475325.8898	658701.1614	6475325.8732	658701.1584	–0.0166	–0.0030
404	6478886.3818	404611.4777	6478886.3672	404611.4691	–0.0146	–0.0086
405	6444302.5676	559477.0009	6444302.5600	559476.9926	–0.0076	–0.0083
406	6334917.5992	717738.2104	6334917.5771	717738.2073	–0.0221	–0.0031
407	6199760.1464	725911.0411	6199760.1608	725910.9935	0.0144	–0.0476
408	6156799.5186	481318.6422	6156799.4958	481318.6496	–0.0228	0.0074
409	6015165.7893	460745.2649	6015165.7673	460745.2578	–0.0220	–0.0071
410	6264461.9294	363483.8445	6264461.9091	363483.8345	–0.0203	–0.0100
411	6405424.0359	164014.3807	6405424.0153	164014.3760	–0.0206	–0.0047

3. Strain and Stress Field Determination

Strains ε_{xx}, ε_{yy}, ε_{xy} are linked to shifts u and v and are calculated by three geometric (Koshi) equations in a horizontal plane at a point of the deformed body (Atkočiūnas and Nagevičius 2004; Zakarevičius and Stanionis 2004b):

$$\begin{cases} \varepsilon_{xx} = \dfrac{\partial u}{\partial x}, \\ \varepsilon_{yy} = \dfrac{\partial v}{\partial y}, \\ \varepsilon_{xy} = \dfrac{\partial u}{\partial y} + \dfrac{\partial v}{\partial x}. \end{cases} \tag{1}$$

In an operational matrix form, Koshi geometric equations are (Atkočiūnas and Nagevičius 2004; Zakarevičius and Stanionis 2004b):

$$\varepsilon = \nabla^T \cdot \boldsymbol{u}, \tag{2}$$

$$\varepsilon = [\varepsilon_{xx} \quad \varepsilon_{yy} \quad \varepsilon_{xy}]^T, \tag{3}$$

$$\boldsymbol{u} = [u \quad v]^T, \tag{4}$$

where ε is the vector of horizontal strains, $\boldsymbol{u}$ is the vector of shifts, ∇^T is transposed Hamilton operator.

Strains on plane stress state $\varepsilon_{xz} = 0$, $\varepsilon_{yz} = 0$, $\varepsilon_{zz} \neq 0$ (Zakarevičius *et al.* 2005):

$$\varepsilon_{zz} = -\frac{v}{(1-v)} \cdot (\varepsilon_{xx} + \varepsilon_{yy}), \tag{5}$$

where v – Poisson's ratio (0,25), ε_{xz} and ε_{yz} – relative shear strains, ε_{zz} – relative linear strain.

When horizontal relative linear and shear strains are calculated, it is possible to evaluate change in tectonic stress (for certain time span).

The inverse Hooke's Law may be applied to model tectonic stresses in the horizontal plane ($\sigma_{xz} = 0$, $\sigma_{yz} = 0$, $\sigma_{zz} = 0$) (Atkočiūnas and Nagevičius 2004; Zakarevičius *et al.* 2005; Zakarevičius and Stanionis 2004a):

$$\begin{cases} \sigma_{xx} = \dfrac{E}{1-v^2} \cdot \left(\varepsilon_{xx} + v \cdot \varepsilon_{yy}\right), \\ \sigma_{yy} = \dfrac{E}{1-v^2} \cdot \left(\varepsilon_{yy} + v \cdot \varepsilon_{xx}\right), \\ \sigma_{xy} = G \cdot \varepsilon_{xy} = \dfrac{E}{2 \cdot (1+v)} \cdot \varepsilon_{xy}, \end{cases} \tag{6}$$

where G is shear modulus, E is Young's modulus $\left(7 \cdot 10^{10} \ \dfrac{\text{N}}{\text{m}^2}\right)$, σ_{xx}, σ_{yy}, σ_{zz} – normal stresses, σ_{xy}, σ_{xz}, σ_{yz} – shear stresses.

Physical relationships (6) can be written in a matrix form (Zakarevičius *et al.* 2005; Zakarevičius and Stanionis 2004a):

$$\boldsymbol{\sigma} = K \cdot \boldsymbol{\varepsilon}, \tag{7}$$

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{yy} & \sigma_{xy} \end{bmatrix}^T, \tag{8}$$

$$K = \frac{E}{1-v^2} \cdot \begin{bmatrix} 1 & v & 0 \\ v & 1 & 0 \\ 0 & 0 & \dfrac{1-v}{2} \end{bmatrix}, \tag{9}$$

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{yy} & \varepsilon_{xy} \end{bmatrix}^T, \tag{10}$$

where σ is the vector of tectonic stress, ε – the vector of horizontal strains, K is - stiffness matrix.

Following the law of shear stress duality, $\sigma_{xy} = \sigma_{yx}$. Accordingly, tectonic stress state in a horizontal plane is defined by the symmetric stress tensor (Atkočiūnas and Nagevičius 2004):

$$\tilde{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{bmatrix}. \tag{11}$$

The second rank stress tensor $\tilde{\sigma}$ does not depend on the selected coordinate system.

Principal tectonic stresses are calculated as a quadratic equation (Atkočiūnas and Nagevičius 2004; Zakarevičius *et al.* 2005):

$$\sigma^2 - I_1 \cdot \sigma + I_2 = 0, \tag{12}$$

that is obtained by extending the determinant:

$$\det \begin{bmatrix} \sigma_{xx} - \sigma & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} - \sigma \end{bmatrix} = \begin{vmatrix} \sigma_{xx} - \sigma & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} - \sigma \end{vmatrix} = 0, \tag{13}$$

$$I_1 = \sigma_{xx} + \sigma_{yy}, \tag{14}$$

$$I_2 = \begin{vmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{vmatrix}, \tag{15}$$

where σ is – principal stresses, I_1, I_2 – stress tensor invariants.

By solving the quadratic equation (12), two actual roots σ_1 and σ_2 $(\sigma_1 \geq \sigma_2)$ are obtained, i.e. σ_1 is maximum principal stress and σ_2 is minimum principal stress.

4. 2-D Finite Element Modelling of Tectonic Stresses

GPS sites are rather regularly spaced (Fig. 2). Data on 19 GPS marks were used in the conducted analysis. Measurements in the Baltic Sea region were carried out in 1992 and 2003. The coordinates of GPS marks of two measurement cycles are presented in Table 1. The relative errors of the network chords (zero class) do not exceed $\approx 0.1 \cdot 10^{-6}$.

Following the above described approach for calculating horizontal stresses, the two-dimensional (2-D) thin-shell body was modelled to define horizontal stresses affecting the Baltic region. The finite element approach was applied assuming that the geometric elements (triangles) of the limited size deform isotropically. Zero movements of a model contour define boundary conditions. The model incorporates four fixed points and 19 mobile GPS sites. The area of the model is larger than that of the Baltic region and consists of 354 finite elements (triangles), 68 of which cover the Baltic Region area (Figs 1, 2). An increase in the model area is required to avoid artifacts (if any) at the edges of the model.

The finite element is described by six nodes: I, J, K, L, M and N (Fig. 3). Each node of the triangle has two degrees of freedom (north and east shifts).

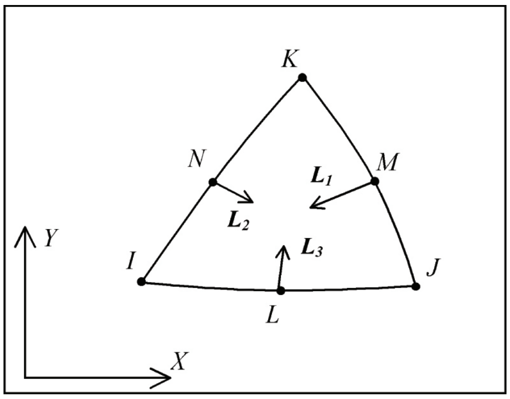

Fig. 3. The geometry of the finite element

A deformation of the finite element is described by (Ansys Theory Reference 1998):

$$u_i = u_I(2L_1 - 1)L_1 + u_J(2L_2 - 1)L_2 + u_K(2L_3 - 1)L_3 + u_L(4L_1L_2) + u_M(4L_2L_3) + u_N(4L_3L_1), \quad (16)$$

$$v_i = v_I(2L_1 - 1)L_1 + v_J(2L_2 - 1)L_2 + v_K(2L_3 - 1)L_3 + v_L(4L_1L_2) + v_M(4L_2L_3) + v_N(4L_3L_1), \quad (17)$$

where u_I, u_J, u_K, u_L, u_M, u_N, v_I, v_J, v_K, v_L, v_M, v_N are shifts of node coordinates; L_1, L_2, L_3 are normalized coordinates (range from 0 to 1 in the finite element).

The shift of the nodes of the finite elements was calculated using *Ansys* code. It should be stressed that it is impossible to determine the state of the stress of the Earth's crust taking into account geodetic measurements as they only provide information on changes in the stress field.

Changes in principal stresses were estimated for the finite element nodes (Fig. 4). The value of change in maximum principal stress in the territory of the Baltic Sea region varies between –0.0013 MPa and +0.0032 MPa, whereas the value of minimum principal stress change is between –0.0084 MPa and +0.0009 Mpa (Table 2). The calculated principal stress directions are presented in Fig. 5.

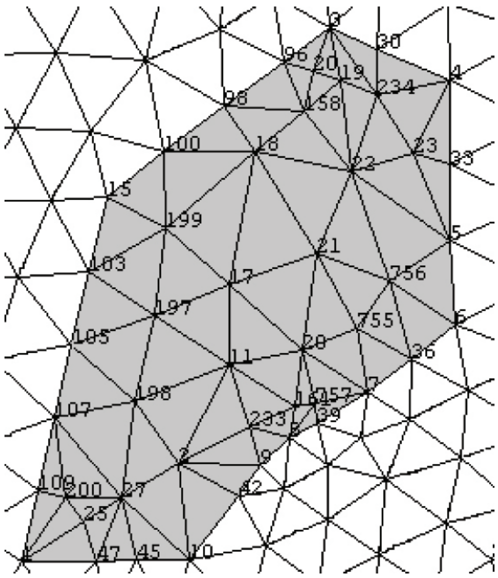

Fig. 4. The stress field of the Baltic region defined from GPS

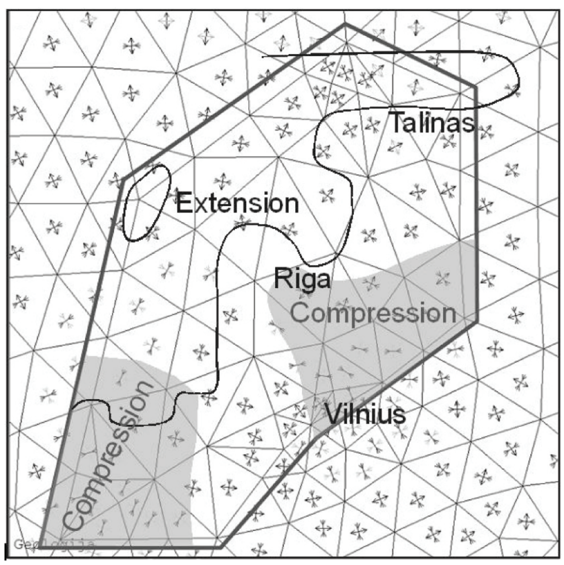

Fig. 5. The modelled stress field of the Baltic region defined from the GPS network

Table 2. Calculated changes in principal stresses

Corner node	σ_1, MPa	σ_2, MPa
1	–0.00033	–0.00063
2	0.00259	–0.00165
3	0.00135	–0.00172
4	0.00215	–0.00012
5	0.00129	–0.00291
6	0.00031	–0.00294
7	–0.00111	–0.00363
8	0.00151	–0.00430
9	0.00013	–0.00459
10	–0.00003	–0.00062
11	0.00166	–0.00063
15	0.00075	–0.00051
17	0.00045	–0.00107
18	0.00200	–0.00058
19	0.00223	–0.00144
20	–0.00002	–0.00430
21	0.00272	–0.00417
22	0.00162	–0.00122
23	0.00076	0.00035
25	–0.00022	–0.00125
27	0.00024	–0.00145
30	0.00120	–0.00042
33	0.00244	–0.00118
36	–0.00125	–0.00482
39	0.00085	–0.00318
42	0.00249	0.00075
45	–0.00029	–0.00146
47	–0.00004	–0.00130
96	0.00178	–0.00016
98	0.00173	–0.00026
100	0.00150	–0.00007
103	0.00018	–0.00195
105	–0.00027	–0.00126
107	–0.00034	–0.00123
109	0.00008	–0.00125
158	0.00317	–0.00047
161	0.00140	–0.00293
197	–0.00041	–0.00125
198	0.00022	–0.00166
199	0.00019	–0.00038
200	–0.00040	–0.00087
201	0.00112	–0.00036
233	0.00080	–0.00034
234	0.00156	0.00085
755	0.00046	–0.00754
756	0.00187	–0.00839
757	–0.00111	–0.00258

5. Geodynamic Interpretation

Modeling a GPS network reveals significant changes in horizontal tectonic stress affecting the Baltic region subject to horizontal extension the direction of which rotates from NNE-SSW in the south and west to NW-SE in the north and east (Fig. 5). The eastern part of Lithuania and Latvia and the northern part of central Poland are subject to predominating horizontal compression of respectively N-S and NW-E direction.

The identified low-rate strain rates are compatible to those obtained from other cratonic areas (e.g. Fennsocandian Shield, North America, and India). Furthermore, the domination of extensional deformations in the western and northern parts of the Baltic region correlate with GPS data obtained from Fennsocandia that is accounted to the post-glacial up-doming of the lithosphere induced by glacial isostasy. It may explain higher seismic activity of the extension-dominated area of the Baltic region (Latvia and Estonia).

The inferred pattern of distributing parameters of horizontal deformation from geodetic networks is important for understanding seismic processes in the Baltic region.

6. Conclusions

1. Tectonic stresses in the Earth's crust in the Baltic region were calculated. Positive values of stresses are prevailing in the direction of maximum principal stress; the values of minimum principal stress are negative within the whole territory (except three nodes).
2. Three different provinces were identified, which shows different stress regimes. It implies different geodynamic mechanisms involved in the Baltic area. The obtained stresses are compatible to other cratonic regions.

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