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FEM MODELLING OF HORIZONTAL TECTONIC STRESS PATTERN IN THE BALTIC REGION

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Abstract. GPS measurements of the years 1992 and 2003 were employed to investigate horizontal tectonic stresses of the Earth's crust in the Baltic region. To avoid the impact of the discrepancy of the systems of coordinates upon the parameters of the deformations, the method of tensor analysis was applied by estimating the parameters by the method of finite elements. Computations were performed by using created algorithms and applying *ANSYS* code.
Tectonic stresses affecting the Baltic Sea Region were modelled. The changes of maximum and minimum principal stresses were calculated. The modelling indicates that the horizontal extension predominates in the west, while compressional regime is suggested in the eastern part of the Baltic region.
The knowledge of tectonic stresses of the Earth's crust is important for interpretation of recent movements of the Earth's crust and seismic hazard assessment of the Baltic Sea region.

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

1. Introduction

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

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

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

2. Data

Data of GPS campaigns of 1992 and 2003 GPS were used in analysis. The network consists of 354 triangles (Fig 1) comprising 19 geodetic sites (Fig 2).

The EUREF-BAL´92 campaign was carried out from August 29 to September 4, 1992 (Ehrnsperger 1995; Madsen, F. and Madsen, B. 1993). Each day the morning and afternoon sessions of approximately 5 hours duration were performed. The observations were performed by Norwegian, Swedish, Finish, and Danish geodesists using Ashtech dual frequency receivers. 24 geodetic sites were measured using 20 GPS receivers. In Estonia the sites Landskrone (401), Vaivara (402), Tartu (403), Ohtja (404) and Saarde (405) were measured; in Latvia – Riga (201), Kaugari (406), Indra (407), Arajas (410); in Lithuania – Akmeniskiai (311), Meskonys (312), Saseliai (408), Dainavele (409). The to 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)), Denmark (København (412). Stations 011, 013, 015, 035, 313, 412 were fixed at EUREF-89 geodetic coordinates. The processing was performed as a traditional network densification of the original EUREF- 89 campaign. The TOPAS software was used for the reduction of the observations, and the FILLNET – for the vector adjustment.

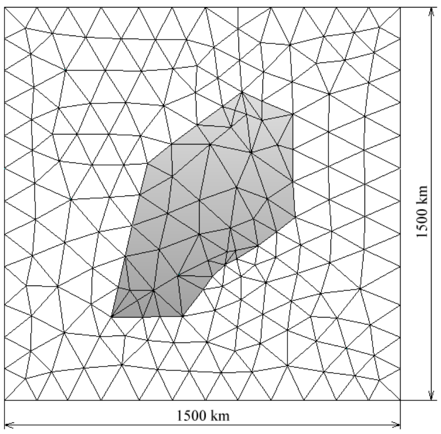

Fig 1. Finite element meshing of the model

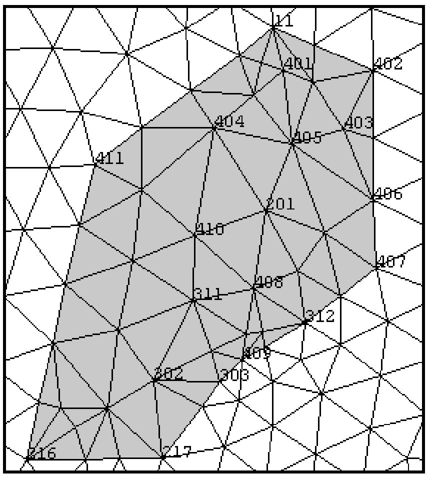

Fig 2. GPS sites of the Baltic region

EUREF-POL´2001 GPS campaign was carried out in September 2001 (Jaworski *et al.* 2002). Five 24 hour-duration sessions were performed for a 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 of sites 302 and 303 were used for the strains analysis of the geodetic network.

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

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

3. Horizontal stresses of the Earth's crust in the Baltic region

3.1. Strain and stress field determination

The 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 the point of deformed body (Atkočiūnas and Nagevičius 2004; Zakarevičius and Stanionis 2004b):

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

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

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

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

where

$$
\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{yy} & \varepsilon_{xy} \end{bmatrix}^T , \tag{3}
$$

$$
\boldsymbol{u} = \begin{bmatrix} u & v \end{bmatrix}^T , \tag{4}
$$

here $\boldsymbol{\varepsilon}$ is the vector of the horizontal strains, $\boldsymbol{u}$ is the shifts vector, ∇ is the Hamilton operator.

The transposed Hamilton operator is:

$$
\nabla^T = \begin{bmatrix} \dfrac{\partial}{\partial x} & 0 \\ 0 & \dfrac{\partial}{\partial y} \\ \dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial x} \end{bmatrix} . \tag{5}
$$

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

$$
\varepsilon_{zz} = -\frac{v}{(1-v)} \cdot \left(\varepsilon_{xx} + \varepsilon_{yy} \right) , \tag{6}
$$

here v – Poisson's ratio (0,25), ε_{xz}, ε_{yz} are the relative shear strains, ε_{zz} is the relative linear strain.

When horizontal relative linear and shear strains are calculated, it is possible to evaluate the change in the 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):

$$
\begin{cases}
\sigma_{xx} = \dfrac{E}{1-v^2} \cdot \left(\varepsilon_{xx} + v \cdot \varepsilon_{yy} \right) , \\
\sigma_{yy} = \dfrac{E}{1-v^2} \cdot \left(\varepsilon_{yy} + v \cdot \varepsilon_{xx} \right) , \\
\sigma_{xy} = G \cdot \varepsilon_{xy} = \dfrac{E}{2 \cdot (1+v)} \cdot \varepsilon_{xy} ,
\end{cases} \tag{7}
$$

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

Physical relationships (7) can be written in a matrix form (Zakarevičius *et al.* 2005; Zakarevičius and Stanionis 2004a):

$$
\boldsymbol{\sigma} = K \cdot \boldsymbol{\varepsilon} , \tag{8}
$$

here

$$
\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{yy} & \sigma_{xy} \end{bmatrix}^T , \tag{9}
$$

$$
K = \frac{E}{1-v^2} \cdot \begin{bmatrix} 1 & v & 0 \\ v & 1 & 0 \\ 0 & 0 & \dfrac{1-v}{2} \end{bmatrix} , \tag{10}
$$

$$
\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{yy} & \varepsilon_{xy} \end{bmatrix}^T , \tag{11}
$$

here $\boldsymbol{\sigma}$ is the tectonic stress vector, $\boldsymbol{\varepsilon}$ is the vector of the horizontal strains, K is the stiffness matrix.

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

$$
\tilde{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{bmatrix} . \tag{12}
$$

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

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

$$
\sigma^2 - I_1 \cdot \sigma + I_2 = 0 , \tag{13}
$$

that is obtained by extending the determinant:

$$\det\begin{bmatrix} \sigma_{xx}-\sigma & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy}-\sigma \end{bmatrix} = \qquad (14)$$

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

$$I_1 = \sigma_{xx} + \sigma_{yy}, \qquad (15)$$

$$I_2 = \begin{vmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{vmatrix}, \qquad (16)$$

here σ is the principal stresses, I_1, I_2 are the stress tensor invariants.

By solving a quadratic equation (13), two actual roots σ_1, σ_2 $(\sigma_1 \geq \sigma_2)$ are obtained, i.e. σ_1 is the maximum principal stress, σ_2 is the minimum principal stress.

3.2. 2-D finite element modelling of tectonic stresses

GPS sites are rather regularly spaced (Fig 2). Data of 19 GPS marks were used in analysis. The measurements in the Baltic Sea region were carried out in 1992 and in 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 approach described above for calculation of horizontal stresses, the two-dimensional (2-D) thin-shell body was modelled to define the horizontal stresses affecting the Baltic region. The finite element approach was applied assuming that geometric elements (triangles) of 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; it consists of 354 finite elements (triangles), of which 68 elements cover the Baltic region area (Figs 1, 2). The increase in the model area is required to avoid the artifacts (if any) at the model edges.

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).

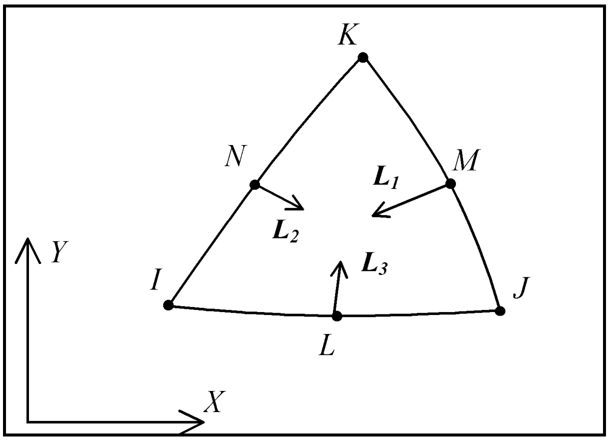

Fig 3. Geometry of the finite element

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

$$u_i = u_I(2L_1-1)L_1 + u_J(2L_2-1)L_2 + + u_K(2L_3-1)L_3 + u_L(4L_1L_2) + + u_M(4L_2L_3) + u_N(4L_3L_1) \ , \qquad (15)$$

$$v_i = v_I(2L_1-1)L_1 + v_J(2L_2-1)L_2 + + v_K(2L_3-1)L_3 + v_L(4L_1L_2) + + v_M(4L_2L_3) + v_N(4L_3L_1) \ , \qquad (16)$$

here 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 the shifts of node coordinates; L_1, L_2, L_3 are the normalized coordinates (the range from 0 to 1 in the finite element).

The shift of nodes of the finite elements was calculated using *Ansys* code. It should be stressed 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.

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

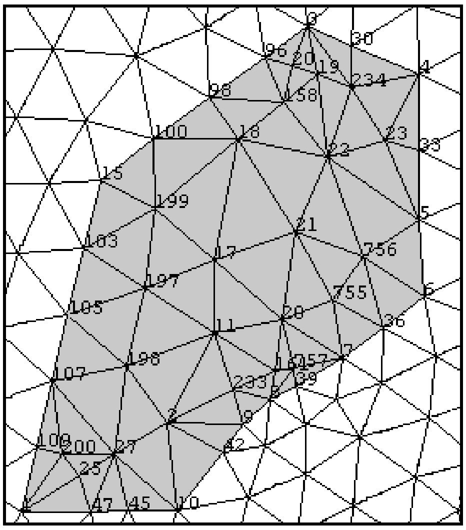

Fig 4. Stress field of the Baltic region defined from GPS

Table 2. Calculated changes of the 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

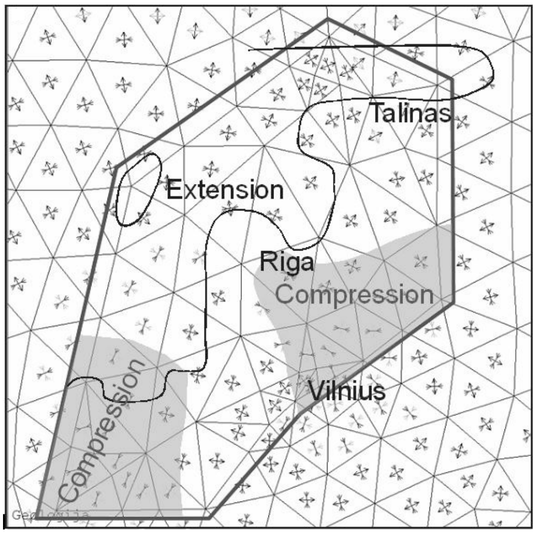

Fig 5. The modelled stress field of the Baltic region defined from GPS network.

4. Geodynamic interpretation

The modeling of GPS network reveals significant changes in the horizontal tectonic stress affecting the Baltic region. The region is 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 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 the GPS data from Fennsocandia that is accounted to post-glacial updoming 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 the distribution of the parameters of horizontal deformation from geodetic networks is important for understanding seismic processes in the Baltic region.

5. Conclusions

1. Modelling of changes in GPS sites is effective tool for recognition of tectonic horizontal stresses.
2. The tectonic stresses of the Earth's crust in the Baltic region are dominated by horizontal extension, while eastern part of the region is subject to tectonic compression.
3. It implies different geodynamic mechanisms involved in the Baltic area.

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