Study of Deformation and Movements on the Earth's Crust, of Technogenic Character, Based on Repeated Geodetic Measurements

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Key words: Deformation measurement; GNSS/GPS; Risk management

SUMMARY

This study treats the methods of monitoring deformations based on repeatedly observed geodetic networks with emphasis on modeling, processing and evaluation of geodetic observations.

Local geodetic network is build around the salt body and is deployed for monitoring the crustal movements in the region. Precise geodetic measurements to determine in the deformation, in the area of the Mirovo Salt Deposit are made. Mathematical model for combined, three-dimensional adjustment of classical and GPS measurements for the adjustment are used, for several epochs of measurements, including: horizontal directions, distances, height differences and GPS observations. On the basis, of the estimated coordinates and covariation matrices, velocities for the control points are computed.

In the article are presented computation methods for determining the deformation components of spatially oriented triangles. A graphic analysis has been conducted, as well as a comparison of the results. Presented are also diagrams of the main axes of deformation, as well as the surfaces of the angular deformations. Conclusions are drawn about the of the deformation processes, their possible stage at present.

The necessity of regular monitoring of the geodynamic situation and surface subsidence are discussed. Results of the analyses of the geological and seismotectonic situation, assessment of the surface subsidence, analyses of the seismic regime variation are presented. The use of these analyses and their possible applications for the general stability assessment of the system are formulated.

РЕЗЮМЕ

За мониторинг на движенията и деформациите на земната кора в района на Мировското солно находище е изградена локална геодезическа мрежа. При обработката на данни за няколко епохи измервания е приложен математически модел за комбинирано изравнение на класически и GPS измервания, които включват: хоризонтални посоки, дължини, превишения, астрономични азимути и GPS наблюдения. На основата на получените оценки за координатите и ковариационните матрици са изчислени скоростите на преместване на точките.

Представени са методи за определяне на компонентите на деформация на пространствено ориентирани триъгълници. Определени са главните оси на деформация, както и ъглови, площни и срязващи деформации. Направен е графичен анализ и сравнение на получените резултатите и обосновка на необходимостта от редовно проследяване на геодинамичните процеси за контрол на повърхностните движения и изменения.

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1. INTRODUCTION

1.1 Provadiiska seismic zone

The Mirovo salt deposit is situated in NE Bulgaria. The mine has being exploited since 1956. Since 1980 several moderate earthquakes (M>4.0) are occurred in this region. This work is in connection with the observed higher seismic activity and probable manifestations of technogenic seismicity in the region.
Provadiiska seismic zone is characterized by a high indication of weak earthquakes, whose magnitude seldom exceeds 4.5.

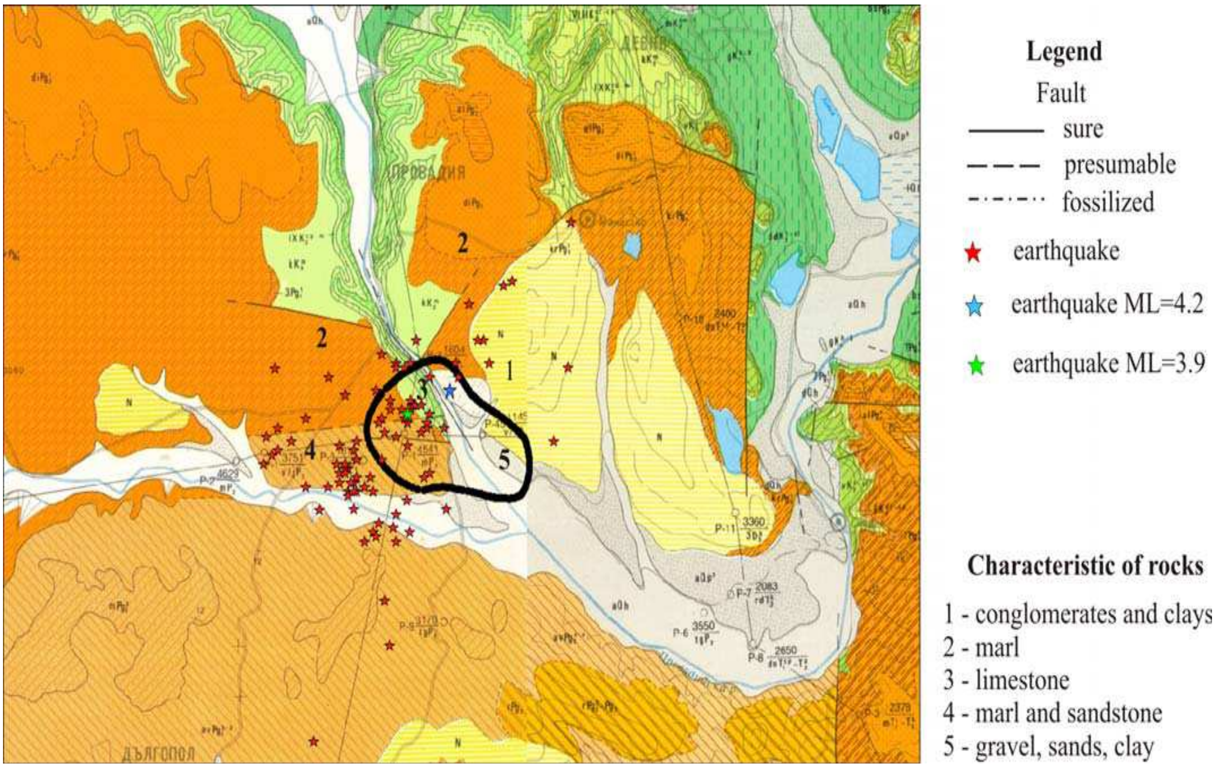

Figure 1 Epicenters of the weak earthquakes after 2006 related to the geology map 1:100,000 (Cheshitev et al., 1999). The black line delimited the salt deposit body at 2000 m depth level ((Dimitrov D et al., 2013).

This concentration of earthquakes are due to the intersection of several faults. Nature around the salt body, tensions arise from its movement to the ground and the stored energy is released by weak earthquakes. An additional factor for increasing the number of earthquakes over the last 30 years is the intensive exploitation of the salt by leaching and the formation of large underground chambers. For now there are no trends to stop the exploitation of salt. For better study of developing processes are created local seismic and geodetic networks in the region around the Provadia town.

The monitoring on the seismicity in the region is performed from the Local seismological network of four constant and two temporary stations, all equipped with modern broadband digital sensors and acquisition systems. Weak seismicity is observed on well-expressed and well-known fault structures in the region. The most active part is situated between the South Moesian subequatorial fault and North Supbalkan fault. The most of them are concentrated in the central part of the Provadia valley which is covered by the Mirovo salt deposit body. Significantly bigger number of earthquakes is realized in the region of the salt body and in 1 km distance from it in South West direction. The magnitude of the earthquakes varied reaches up to 3.1 as the depth of the earthquakes reaches 5 km. The Fig 1. shows the seismological and geological combined map (Dimitrov D et al., 2013).

1.2. Provadia geodynamic network

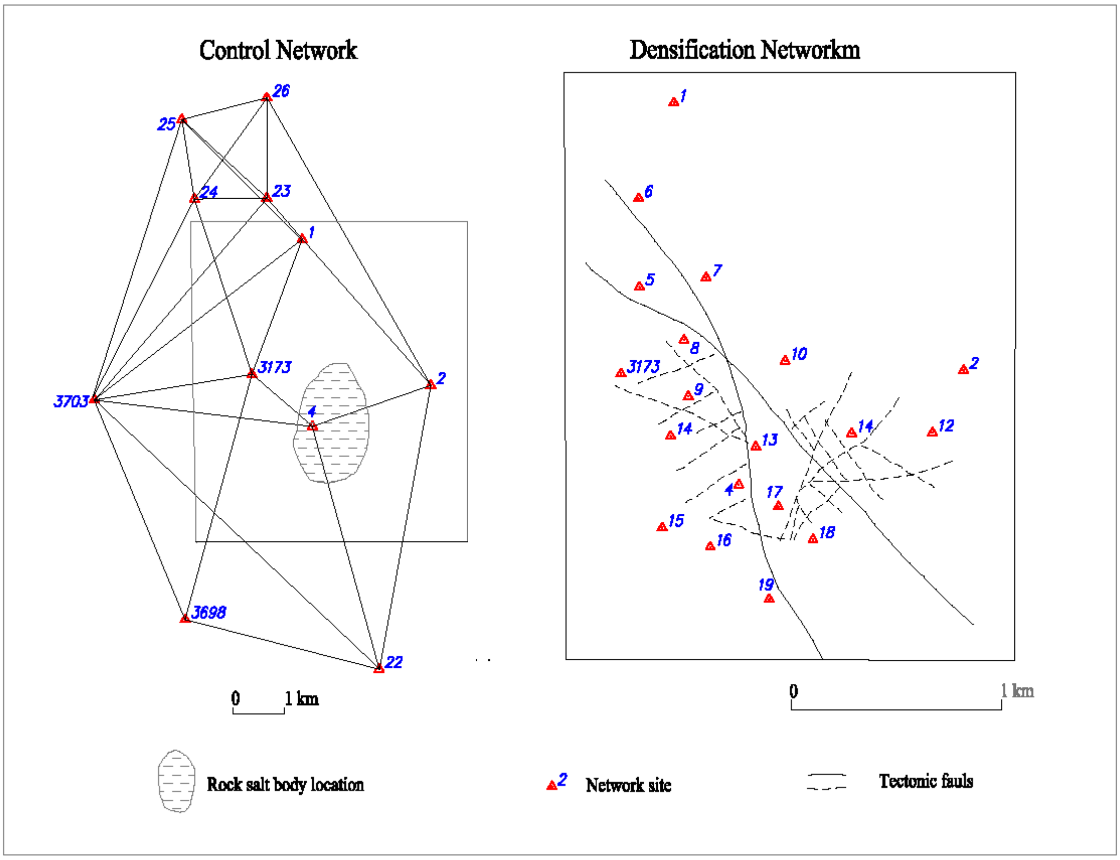

Figure 2 Provadia geodynamic network (Milev et. al., 1994)

Geodynamic project, which attracting researcher's interests is the Mirovo salt deposit near Provadia, NE Bulgaria, the above mentioned from me. The aim is to examine how far exploitation of rock-salt in connected to local seismic activity because recently earthquakes occur here more frequently and with increasing strength.

A network of 26 pillars and many leveling bench marks is designed and built-up especially to monitor movement and deformations in the deposit area using precise angular and distance measurements, spiritleveling and GPS. Part of the pillars was outside the central zone for control the detailed over the salt body (Figure. 2). GPS has been used to determine the controlling sites, once per year but recently, after having proven useful, it is regularly implemented far precise positioning of all the network sites. (Milev et. al., 1994). The initial observation is in 1990 from "Geoprecise engineering" Ltd.

Deformation measurements are an important part of engineering survey. The main tasks in deformation analysis are to describe crustal movements and the movements or the displacements of objects, such as landslides, buildings. For geological monitoring of the deformations in the region of the Mirovo salt deposit are used most precise and contemporary method for permanent monitoring of movements using GPS technology is applied. Besides precise GPS observations are carried out measurements of the horizontal directions, EDM distances, heights and astronomical azimuths.

For evaluation of the natural and technogenic risks in the Mirovo salt deposit the data from details geodesic monitoring of network of periodical (each year) precise measurments in the zone of Mirovo salt deposit are analyzed. Re-measured are longitudes between 24 points (fig. 2) by laser telemeter of the Mekometer ME5000 firm which guaranteed accuracy of the measured distances of the order of (0,2mm + 0,2ppm) and with periodical GPS measurements. Comparing the distances shows the relative movement between the location points which are situated in close proximity to and above the salt body. Thus for example points 4 and 11 have been got nearer to one another for the time of one year with 89.1 mm, points 4 and 10 – with 74.9 mm, points 11 and 8 – with 52.7 mm.

2. Determining the velocities of the stations of geodynamic network Mirovo Salt Deposit

Estimates of the coordinates of the points and their square errors are obtained by combined adjustment program Adjust [Milbert et al].

For basis point was selected station 3703, considerably distant from the deformation zone. On the basis of the adjustment of network by Least Squares Method for every epoch are received estimates of coordinates of points, their mean square errors and covariation matrices. From these estimates are derived velocities of the points and their mean square errors between the four cycles (1994, 2000, 2004, 2007) using formulas presented in [Atanasova, 2003]. In the table 2 are presented relative velocities and their mean square errors.

Table 2. Relative velocities and their mean square errors between epochs 96-07

№	v^x	σ_{v^x}	v^y	σ_{v^y}	v	α
	[mm/yr]	[mm/yr]	[mm/yr]	[mm/yr]	[mm/yr]	[g]
1	4.73	0.5	-6.13	0.5	7.74	341.8431
2	1.30	0.5	-4.67	0.4	4.84	317.2959
3173	0.46	0.5	6.06	0.4	6.08	95.1125
4	12.13	0.4	14.06	0.4	18.57	54.6892
5	-0.43	0.4	3.63	0.4	3.65	106.9805
6	0.76	0.4	2.03	0.4	2.17	77.0456
7	-0.87	0.4	4.33	0.4	0.44	112.5666
8	-3.27	0.4	3.33	0.4	4.66	149.357
9	-1.70	0.4	11.89	0.5	11.13	109.7614
10	-6.92	0.4	-0.53	0.5	6.92	204.9110
11	-1.61	0.4	-13.58	0.5	13.59	292.4899
12	2.42	0.5	-6.83	0.5	7.24	321.5025
13	-2.57	0.4	5.11	0.5	5.70	129.6829
14	-3.57	0.4	14.53	0.4	14.96	115.3207
15	8.33	0.4	4.59	0.4	9.47	31.5211
16	12.53	0.4	-1.81	0.4	12.66	390.9191
17	15.50	0.5	-4.00	0.4	16.01	383.9219
18	11.16	0.4	-6.14	0.4	12.72	368.1707
19	9.26	0.4	1.23	0.4	9.34	408.1984
3698	6.13	0.4	-1.97	0.4	6.44	380.2460
3703	0	0	0	0	0	0
22	-0.27	0.4	-3.03	0.5	3.04	294.4177
23	2.83	0.4	0.23	0.4	2.84	5.2309
24	5.20	0.4	-1.07	0.4	5.30	387.1198

Geodetic network located the area of the salt body, constantly alters its configuration and position of the points, as the area is exposed to various anthropogenic, tectonic, seismic attracting acting mixed with different intensity.

Displayed horizontal displacement speeds give an idea of the nature and direction of motion of the points. The values of horizontal velocity vectors are shown graphically in Figure 3. This diagram clearly shows a tendency to move the items to the center of the salt body established by [Valev G., 2000]

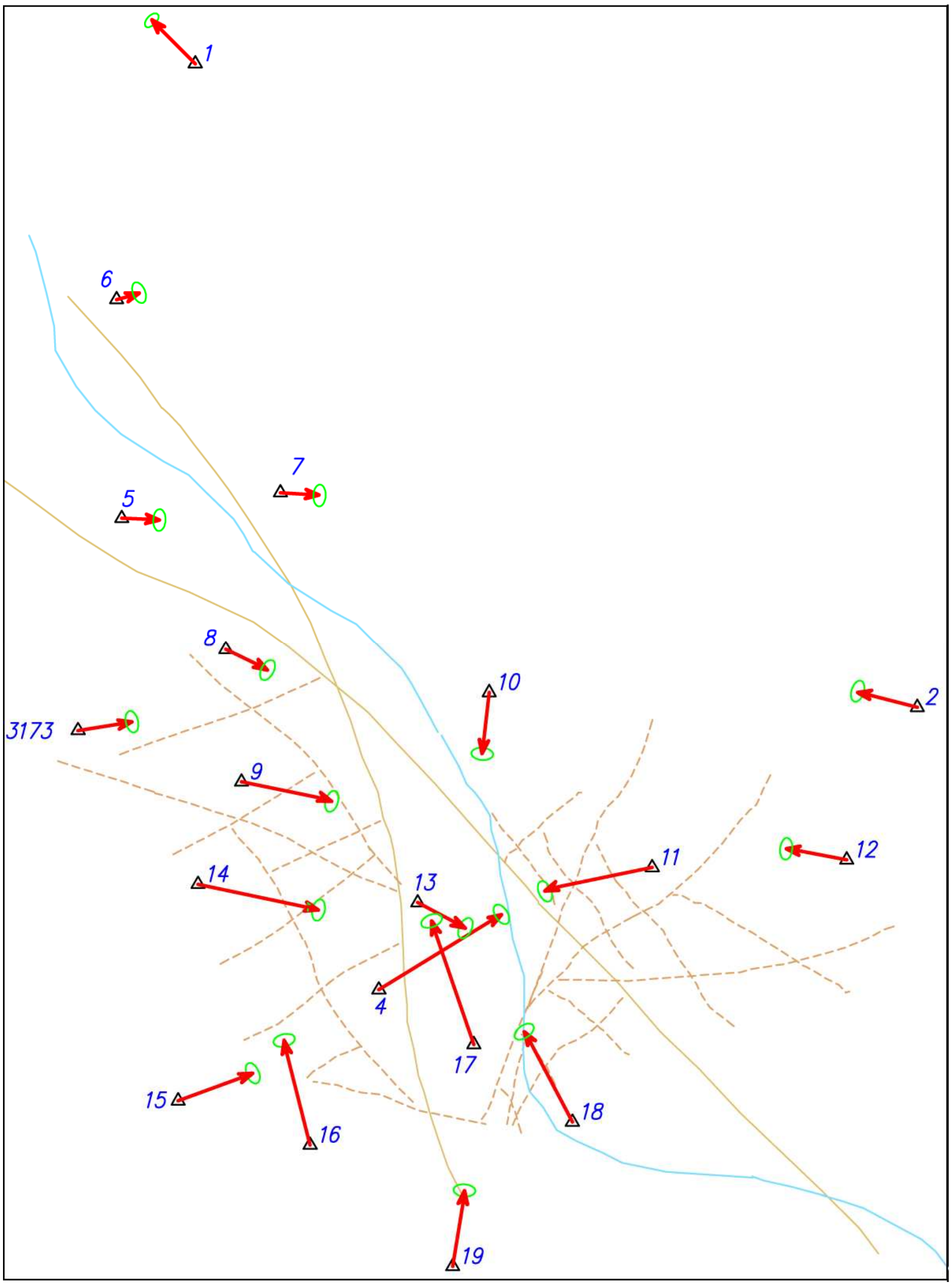

Figure 3 Relative velocities in the region of Mirovo salt depot

Seasonal movements are observed being registered during more than the 20 years permanent measurements. On the basis of these observations conclusion might be drawn that probably the observed seismicity in the Rrovadia region is induced seismicity resulting from intense exploitation of salt mining in the near by (3-4 km) Mirovo salt deposit.

Stations 4,11,14,16,17,18 are that which shows maximum velocities from 12.6-18.5 mm/year direction and maximum significant subsidence for point 13 with velocities of – 24.3 mm/year.(fig 4)

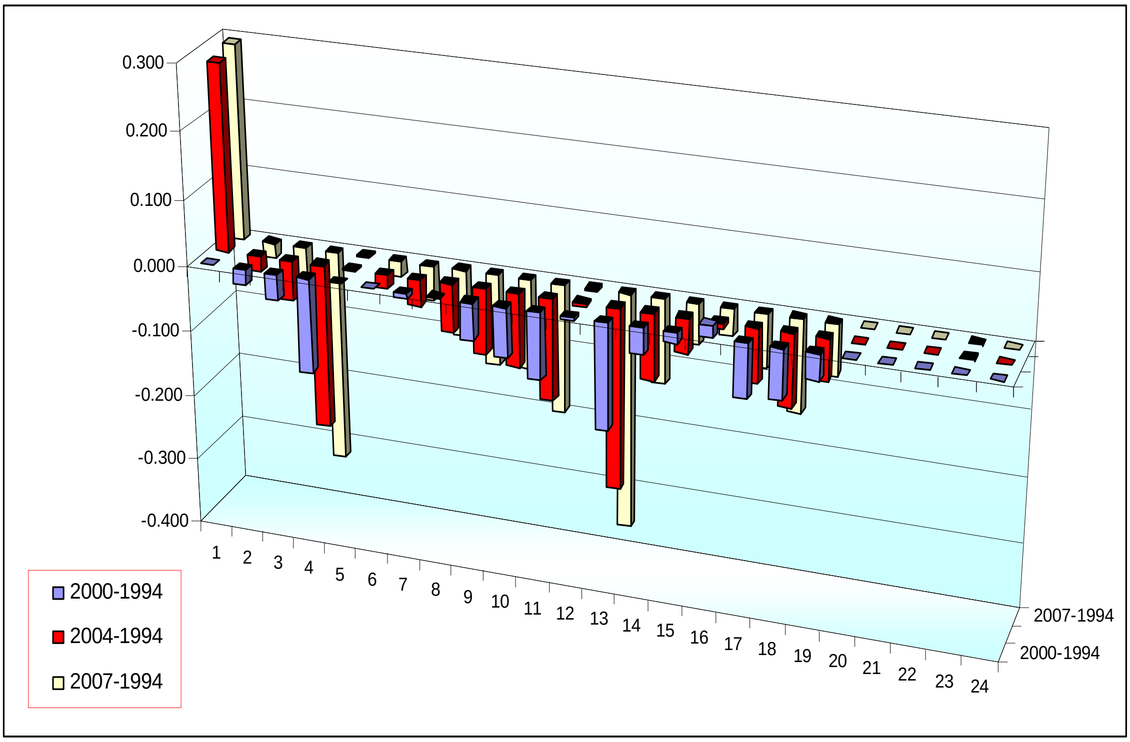

Figure 4. Change of vertical position of the points of the Provadia network between epochs (1994, 2000, 2004 and 2007). Subsidence

3. Calculating the components of the deformation in the region of Mirovo salt deposit

This is considered a possibility to study the deformation processes through the use of measured parameters – spatial chords based on geodetic measurements carried out based on the theory of deformations and Finite Element Method (FEM). Used the results of GPS-measurements for the epochs 1994, 2000, 2004 and 2007 on basis of which the calculated spatial chords (Table 2) between the points cover the main tectonic structures in the area of experimental geodynamic area.

Calculated are the components of deformation in the region of Mirovo salt depot using results periodic measurements. The basis for calculation is used famous formula [Toshev B. 1967], giving relationships between the components of deformation tensor and linear deformation of a section of a deformation environment.

For each of the triangles is composed and determined system of three equations as a result of which received tensor components of a "pure" deformation.Calculated are the major axes of relative deformation to the median's center of the triangle (table 2) All these elements characterizing the deformation processes, reduced to the plane of the respective triangle. Graphical presentation of the major axes of deformation given in Figure 5..

Table2 Deformations calculated by the method of "finite elements" between epochs 94-00

Ttriangle			Relative deformation at the distances $[*e^{-5}]$			Major axes of relative deformation $[*e^{-5}]$		
A	**B**	**C**	**AB**	**AC**	**BC**	**a**	**b**	**alfa [g]**
1	23	24	1.61	-0.18	-0.46	3.36	-0.52	197.64
1	2	7	-1.65	0.2	-4.11	0.25	-6.1	183.46
1	6	7	-0.95	0.2	0.19	0.37	-2.33	172.97
1	7	10	0.2	2.74	2.3	3.22	-16.75	163.26
1	2	10	-1.65	2.74	-3.83	6.77	-4.18	14.68
1	3703	5	-0.67	0.29	0.38	5.61	-0.86	138.95
1	11	12	-1.47	-2.13	7.41	14.15	-2.16	54.8
2	10	11	-3.83	7.49	-15.43	9.29	-15.44	51.28
2	7	10	-4.11	-3.83	2.3	19.15	-4.45	13.59
4	9	14	-10.69	-9.33	-6.7	-4.63	-10.7	67.08
4	9	13	-10.69	-48.14	-1.96	-1.79	-48.67	135.98
4	14	15	-9.33	8.55	-7.29	8.55	-14.96	68.12
4	15	16	8.55	6.67	-8.46	10.01	-13.22	52.17
4	16	17	6.67	-38.7	-7.14	6.71	-38.97	29.24
4	13	17	-48.14	-38.7	-38.04	-36.84	-50.79	157.89
5	6	7	1.77	-2.99	0.19	1.78	-3.01	195.85
8	9	10	1.4	-10.22	-15.18	2.59	-15.22	176.66
8	7	10	-1.95	-10.22	2.3	6.93	-15.73	179.37
8	5	7	3.85	-1.95	-2.99	3.84	-4.81	161.45
8	5	3173	3.82	3.73	-2.42	8.17	-2.42	114
8	9	3173	1.4	3.73	7.65	7.65	0.11	120.47
9	10	13	-15.18	-1.96	-10.88	-0.09	-16.42	161.92
10	11	13	-15.43	-10.88	-27.35	-7.62	-27.44	195.66
11	12	18	7.41	-15.37	-6.26	7.95	-16.25	108.74
11	13	17	-27.35	-26.29	-38.04	-25.54	-38.34	66.98
11	17	18	-26.29	-15.37	2.49	4.69	-27.3	162.77
16	17	19	-7.14	-9.75	3.35	3.39	-14.75	11.2
17	18	19	2.49	3.35	-10.71	8.47	-16.59	178.36
14	15	3173	-7.29	8.41	-3.23	25.4	-7.29	107.13
22	18	19	1.63	2.23	-10.71	2.25	-12.44	168.48
22	2	18	-1.09	1.63	-4.1	4.04	-4.1	144.99
3703	5	6	0.38	-0.26	1.77	5.39	-0.54	142.03
3703	3173	5	1.43	0.38	-2.42	3.01	-2.43	116.79
3703	3698	22	0.16	-0.03	-0.34	0.18	-0.44	180.12
3703	3173	15	1.43	2.8	-3.23	2.8	-4.29	109.45
3703	3698	3173	0.16	1.43	-0.62	1.84	-0.63	107.29
3703	1	24	-0.67	-0.12	-0.18	0.62	-0.82	170.25
3173	9	14	7.65	8.41	-6.7	9.54	-7.56	141.78

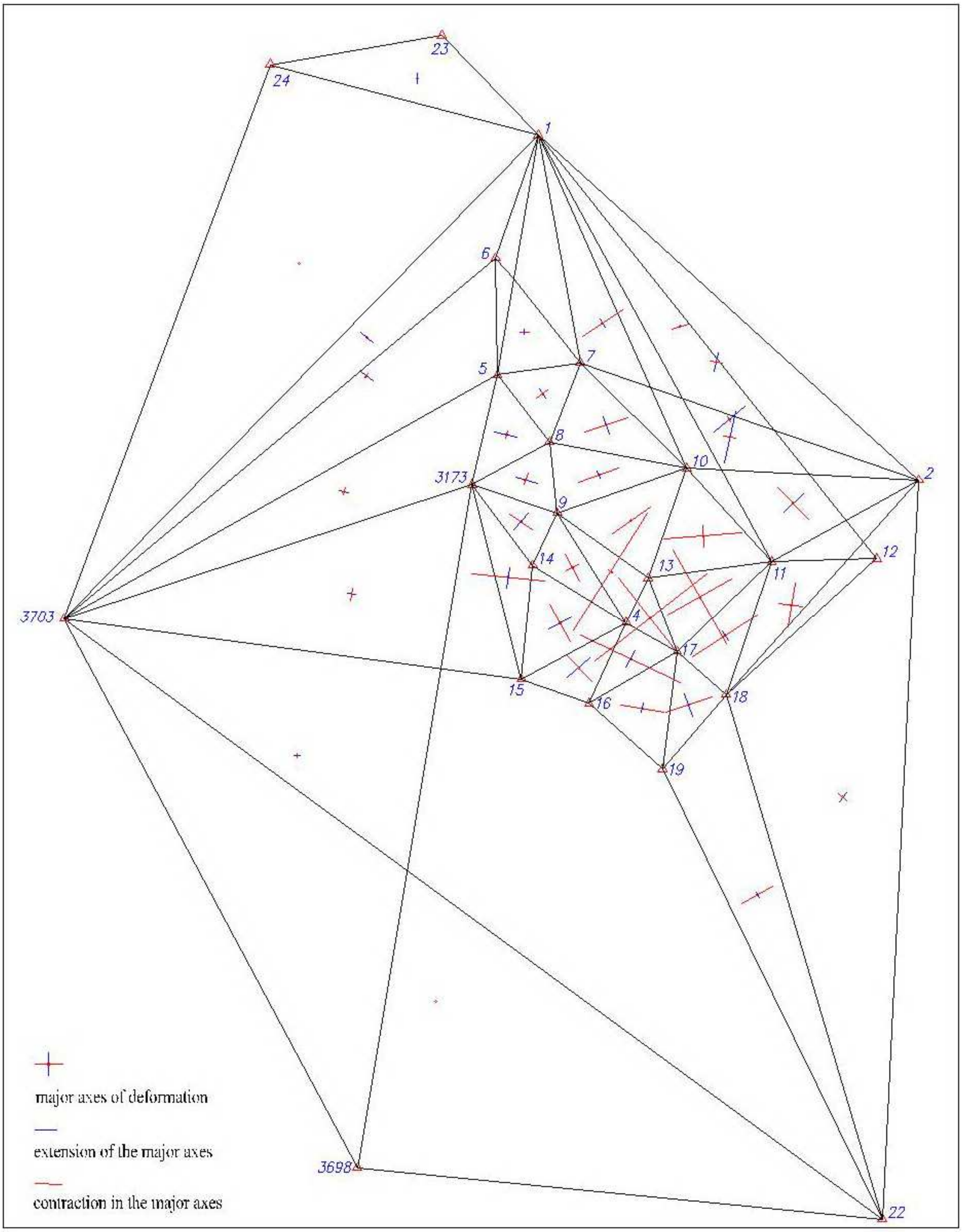

Figure 5 .Main axes of relative deformation to the median's center of the triangles

Table 3 Deformations (shear, angular and area) between epochs 00-07

Ttriangle			**Deformations**		
A	**B**	**C**	shear [$*e^{-5}$]	angular [$*e^{-5}$]	area [$*e^{-5}$]
1	23	24	-1.66	-0.68	1.48
1	2	7	-3.44	-1.01	-2.63
1	6	7	-1.3	0.71	-0.02
1	7	10	-4.72	-8.47	-6.43
1	2	10	-5.56	2.95	1.54
1	3703	5	0.45	-3.41	2.99
1	11	12	0.63	9.98	7.27
2	10	11	0.15	13.51	-3.07
2	7	10	-11.32	5.38	7.52
4	9	14	1.66	0.45	-10.69
4	9	13	8.67	-25.48	-30.79
4	14	15	7.5	10.64	-4.08
4	15	16	2.74	9.25	-0.32
4	16	17	-15.67	18.07	-19.02
4	13	17	-3.38	-10.51	-50
5	6	7	-3.25	-0.48	-1.59
8	9	10	-7.89	-6.62	-7.07
8	7	10	-10.48	-6.91	-4.78
8	5	7	-3.02	-4.15	-0.88
8	5	3173	3.64	-2.07	2.84
8	9	3173	2.54	-2.66	3.94
9	10	13	-5.25	-7.05	-8.93
10	11	13	-11.39	-0.42	-17.89
11	12	18	11.72	-2.59	-3.5
11	13	17	3.71	5.54	-34.02
11	17	18	-9.36	-15.88	-12.04
14	15	3173	20.22	-1.7	10.98
16	17	19	-9.27	2.82	-8.88
17	18	19	-11.1	-11.13	-7.1
22	18	19	-3.64	-10.1	-7.22
22	2	18	1.6	-3.84	0.59
23	24	25	-0.22	-0.22	-0.02
3703	3173	15	4.64	-0.44	-2.12
3703	3698	3173	1.26	-0.42	0.64
3703	1	24	-0.32	-0.73	0.3
3703	5	6	1.08	-3.4	2.64
3703	3173	5	1.78	-2.11	1.18
3703	3698	22	0.06	0.55	0.76
3173	9	14	3.71	-10.05	-1.39

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6. CONCLUSION

The results are compared with multi-year repeated results from geodetic measurements of the Mirovo geodynamic network.
The results of study showed, that have activity on the Earth's crust in the area and confirmed, that the methods are appropriate for determining the technogenic movements of the earth crust.There have been several major conclusions about the nature of the deformation processes and the possible stage of their development
The results form the geodetic monitoring of the deformation in the Mirovo salt deposit region allow for the conclusion to be made that in and above the exploitation area of the salt deposit take place significant local deformations of the earth surface. These deformation processes could be explained with concentration of the epicenters of different in strength earthquakes in the region. The question stays open whether local movements and the induced anthropogenic regional seismicity to lead to activation of seismogenic faults which could lead to earthquake with higher intensities. For clarifying this issue is needed new profound and complex estimates and that is the need for a modern interpretation of the results using the geological and seismological data research.
I am grateful to "Geoprecise Engineering" Ltd for kindly providing the data for geodynamic network Provadia. Based on their measurements and research I made this studies and article.

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BIOGRAPHICAL NOTES

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Since 1998 I study the global and local coordinate systems and coordinate transformations for the Bulgarian territory. In October 2013 I obtained a PhD degree on thesis "Transformations models in contemporary geodetic coordinate systems". My studies are focused on application of GPS technology in geodesy and geodynamics. This includes determination of plate motions, deformation analysis and GPS data processing. Up to now I have 20 publications Since 2010 I am visiting assistant lecturer at the University of Architecture, Civil Engineering and Geodesy, Sofia.

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