GEODETIC MONITORING OF DISPLACEMENTS AND DEFORMATIONS FOR ASSESTMENT OF EFFECT FROM SUSPEND OF EXPLOITATION OF PERNIK MINES

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ABSTRACT

The Pernik Coal Basin is the oldest in Bulgaria - its operation starts on 17.08.1891. Depth of bedding of coal beds is small (10-130m). In the last years, after the mining operations were stopped on 2000, emergency situations occurred on the territory of the town of Pernik, which are directly related to the mining activity carried out in the Pernik basin. Risky and emergency situations potentially affect all types of engineering facilities on the terrain of the city of Pernik (buildings, streets, roads, railways, bridges, stadiums, other facilities) as well as elements of the underground engineering infrastructure (water mains, sewerage, cable routes, etc.). The main goal of the project is to carry out studies and analyses and to propose design solutions for the development of the geodetic network for surveying of the movements and deformations of the land surface and the mining mass with objects in order to organize specialized monitoring as a preventive measure for the purpose of conservation of objects and facilities from the harmful influence of the mining works and the consequences of stopping their operation in region of Pernik Mining. Different methods and instruments were applied for performing of precise geodetic measurements for deformation monitoring for last 9 years. Some results and conclusions are presented in the report based on collected 4D data base.

I. General information

A. *The object of interest*

The Pernik Coal Basin is the oldest in Bulgaria - its operation starts on 17.08.1891.

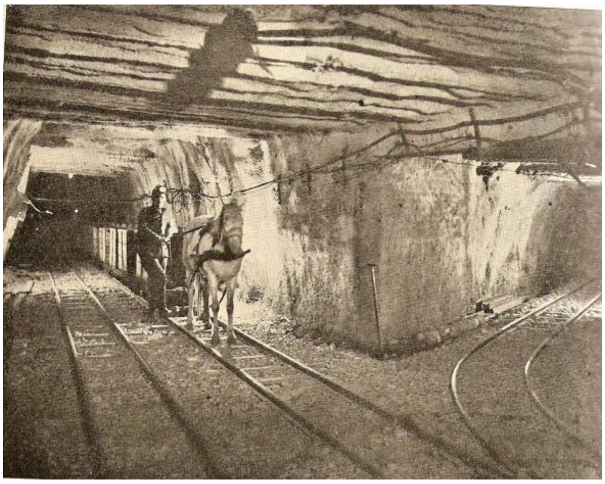

Figure 1. Galleries of Mini Pernik at the past

Depth of bedding of coal beds is small (10-130m). Seized underground spaces and burrows extend over a large part of the residential quarters and built engineering infrastructure of the town of Pernik.

In the last years, after the mining operations were stopped on 2000, emergency situations occurred on the territory of the town of Pernik, which are directly related to the mining activity carried out in the Pernik basin.

Independent of the type of used abutment, the present conditions of the underground mining galleries can be described as one of the following variants:

1) The abutments are not fully degraded yet, but in each next moments can change to Variant 3;
2) The gallery is repaired with complete disassembly of the fastening and breaking at the end of their existence. It is the better variant;
3) The abutment is already degraded on 90% and the top is ruined with a large cavity - a high vault above the top.

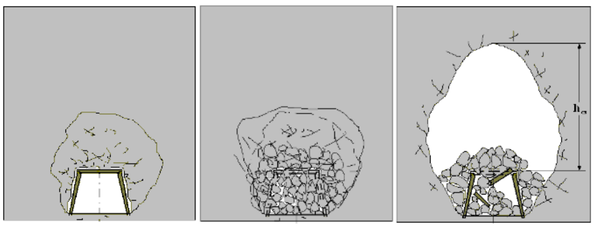

Figure 2. Variants of the conditions of the underground galleries

Risky and emergency situations potentially affect all types of engineering facilities on the terrain of the city of Pernik (buildings, streets, roads, railways, bridges, stadiums, other facilities) as well as elements of the underground engineering infrastructure (water mains, sewerage, cable routes, etc.).

B. *The project for geodetic monitoring for displacements and deformations*

The scope of the project is to design and develop a spatial network for geodetic monitoring of the ground surface, the rock massive and objects of engineering infrastructure on the ground and performing precis geodetic measurements for monitoring of displacements and deformations of the most threatened objects by interrupted underground mining activities of the Pernik Minings in the City of Pernik with a goal to control and prevent the structures from the harmful influence of the performed mining activities and aftereffect of stopping of their exploitation.

The design defined objects, which are subject to protection from harmful influence of the underground mining works. All objects, for which are received official complaints by citizens, ware included; the objects with social importance; buildings and constructions, which are above of "crosses" of mining galleries as potentially most dangerous places for occurrence of deformation processes; profile lines on the streets as infrastructural objects; buildings situated on or near to borders of seized spaces on the coal layers and near to profile lines on the streets. The configurations of the buildings, the number of floors, the occupied area, the construction, foundation and condition are taken into account during selection of the buildings and were included only the buildings with massive structure.

The defined groups of objects ware categorized in respect of „Instruction for protection of the objects and structures from harmful influence of the underground mining activities in coal basins" from 1983:

№ по ред	Категория	Общо описание на опазваните съоръжения и обекти	Допустими максимални деформации			
			Наклон i, mm/m	Кривина K, mm/m2	Радиус на кривина R, m	Хоризонтални деформации ε, mm/m
1	I	Пет етажни и по-високи жилищни и обществени сгради	4	0.2	5000	2
2	II	Детски ясли и градини, независимо от броя на етажите с дължина до 50 m; Мостове на ЖП линии с дължина до 20 m; 3,4 етажни обществени и жилищни сгради с дължина над 40m.	8	0.4	2500	3
3	III	Едноетажни сгради с дължина над 20 m; Двуетажни жилищни и обществени сгради с дължина до 40 m; Едноетажни складове с дължина над 40 m; ЖП линия.	12	0.6	1700	6
4	IV	Едноетажни сгради с дължина до 20 m; Всички пътища в обхвата на проекта.	20	0.8	-	10

Figure 3. Categorization of the objects and structures for monitoring of deformations with limits of values of maximum parameters of deformations

On the base of preliminary investigations were defined the boundaries and the coverage of the territory under the project - about 213ha, including 7 residential areas in the centre of City of Pernik:

Figure 4. The boundaries and coverage of the territory under of the project

The basic principal for the choice of the type of monitored movements and deformations for different type of objects are adopted the following:

- For all buildings, bridges and other structures the vertical displacements and deformations of their bases and foundations are measuring;
- For all streets, roads and railways the vertical and horizontal displacements and deformations are measuring.

The following tree types of geodetic marks for stabilization of the points, included in spatial geodetic network, are used – deep levelling benchmarks, wall benchmarks, combined land marks for horizontal and vertical measurements.

The positions of the geodetic marks are determined on the base of the existing information from the planes of underground galleries and cadastral map of the city. The geodetic network included about 362 combined land marks, 708 controlled wall benchmarks and 27 deep levelling benchmarks now.

On the results of analysis of existing geodetic base in the area of interest the reference points were selected

– 6 existing ground benchmarks and 2 existing points from State Geodetic Network with known coordinates.

The methodology and technology for performing of precise geodetic measurements ware well-founded. To ensure the necessary accuracy of the observed vertical displacements and deformations, the absolute heights above sea level of the controlled benchmarks are determined by precise geometric levelling II-nd class with standard deviation of ≤ 0.70 mm on 1km double run distance. The levelling is performed by set of high-precise digital levels and invar levelling staffs.

The horizontal displacements and deformations of the objects above underground mining galleries in this project are determined from measured coordinates by using combination of GNSS and trigonometrical methods. The accuracy of determined bases between points by each two GNSS receivers is in the limits of m_S=2.5-5mm. The angular and distance measurements are performed by tri stative method with electronical total station with standard deviation of measured angle $m_\beta \leq \pm 2''$ and for measured distance $m_S \leq \pm$(2-3mm+2ppm):

Figure 5. Examples of used precise geodetic instruments

The period between of the measurement campaigns was accepted by 6 months and additional measurements in cases of force major events such earthquakes, water floods and appearing of visible disruptions of the constructions. For the period of past 8 years of organized observations such kind of exceptional measurements were not performed nevertheless that on 2012 was a huge earthquake in Pernik region.

II. Geodetic measurements

The last 14 campaign of geodetic measurements for monitoring of displacements and deformations were performed August - September 2018. At the moment is realizing the next campaign.

A. *Precise geometric levelling*

The precise geometric levelling was realized by high-precise digital levels LEICA NA3003 and LEICA DNA03 with set of twins of invar barcode levelling staffs. The method BFFB (Back-Fore-Fore-Back) was used for measuring of the height differences between stations of the instruments. Double-run measurements (in one and opposite directions) were performed for whole levelled lines.

The total length of double run levelled lines in the network is 54 253 m. The number of double run levelled height differences is 1115 (2230 measured differences in total) and the total number of included benchmarks (fixed and controlled) is 938:

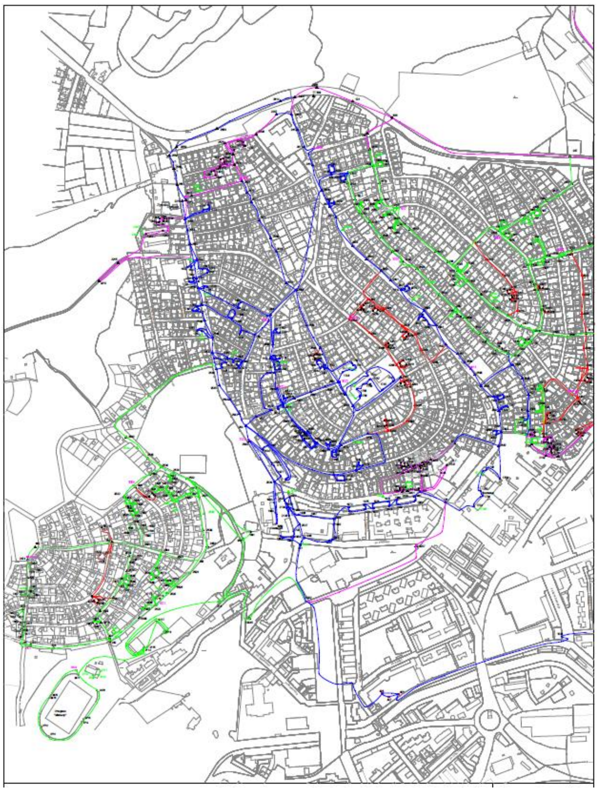

Figure 6. A part of the schema of the precise levelling geodetic network

B. *GNSS observations*

To connect the network of controlled points for geodetic measurements of horizontal displacements and deformations with reference points from the State Geodetic Network the precise GNSS observations were performed.

The observations were realized by professional geodetic GNSS receivers LEICA GPS SYSTEM 530 (5 items), SOKKIA RADIAN-IS (4 items) и CHC HUACE X91/X900 (3 items) in set with standard accessories for mount the antennas on wooden tripods and centric with optical plummets.

The total number of the points, which coordinates were determined by GNSS observations, is 145. The total number of the determined spatial vectors in the network is 436 (1308 coordinate differences). Because of the large number of simultaneously used GNSS receivers not only vectors between reference base stations and new points were determined, but a large number of vectors between rovers new points also were determined.

C. *Precise polygonometry (angle – distance) measurements*

Due to the fact, that a big part of the controlled points for monitoring of horizontal displacements and deformations are situated in the city canyon of Pernik, where conditions for GNSS observations are not good, in these regions of the plane network were performed additional geodetic measurements by conventional technology. This decision is based on the main goal to receive reliable end results for coordinates of the controlled points, which were situated on specific places according existing underground galleries. The places of controlled points were fixed by the needs of the monitored objects and cannot move them because of limits of used technologies for measurements.

The measurements were performed by two precise total stations LEICA TC1610 (angular accuracy of 5^{cc} and distance accuracy of 3mm+2ppm) with standard set of accessories for mount the instruments and reflectors on wooden tripods and centric by optical plummet.

The total number of points, which coordinates were determined by polygonometry, is 300. For the calculations were used as reference 85 points, determined by GNSS observations. The total number of angle-distance measurements, used in calculations of the network, is 917 per each.

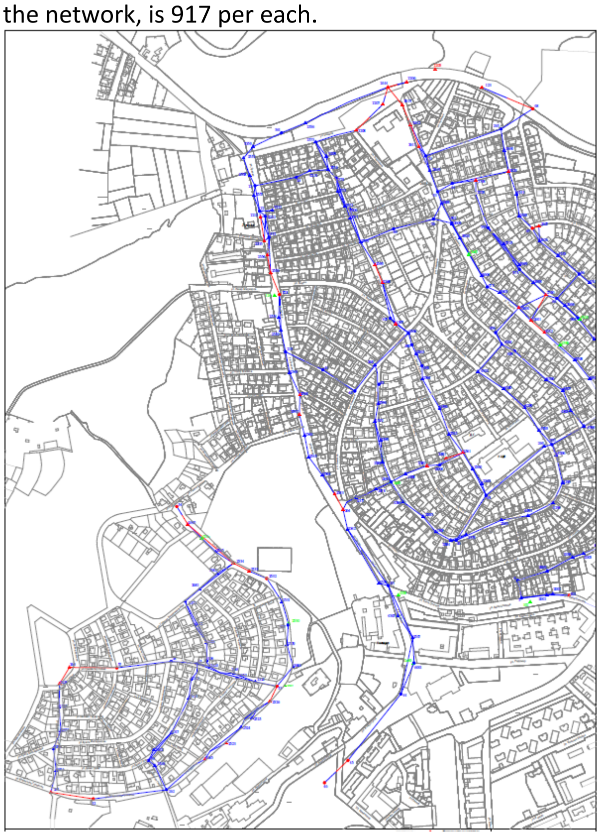

Figure 7. A part of the schema of the precise polygonometry and GNSS geodetic network

III. Processing the geodetic measurements

A. *Processing the precise geometric levelling measurements*

The processing of collected data from performed levelling measurements is realized by specialized software DigitalLeveling - our own application, developed especially for big geodetic networks as in case of Pernik Minings. A preliminary asset of the measured height differences and distances in the levelling network was performed by closed loops. The determined values of the measured height differences were adjusted by strict parametrical adjustment by Least Square Method (LSM). The results from this adjustment shows that, the highest value of standard deviation of adjusted elevation is 0.99mm. The standard deviation for measurement with weight equal one for whole network is Me=0.3mm, which correspond with a priory value of the standard deviation of the used instruments (0.4mm).

B. *Processing the GNSS observations*

The processing of GNSS observations was realized in the environment of specialized software Leica Geo Office. All spatial vectors between occupied points were calculated by the GNSS measurements. During these calculations were determined the errors (standard deviations) of the coordinate differences dX, dY, dZ, formed each vector, on the base of multiply measurements. The maximum value of the standard deviation of the adjusted coordinates is 3.5mm.

C. *Processing of the linear-angular measurements*

The processing of performed angle-distance measurements was realized in the environment of specialized software WIN TPLAN. A preliminary asset of the measured angles and distances in the polygonometry network by closed loops. The received values of measured angles and distances in the network were adjusted by strict parametrical adjustment by LSM. The results from this adjustment processing shows that the maximum value of the standard deviation of adjusted coordinates is m_s=7.98mm. The standard deviation for measurement with weight equal one for whole network is Me=5.7^{CC}, which is corresponding with the accuracy of the used total station.

IV. Comparative analysis of the results from the campaigns of geodetic measurements

All results from performed campaigns of geodetic measurements are collected in specialized data base, created for the project in the GIS environment and analyzed by GIS functionality and office software.

A. *Analysis of the vertical displacement data*

In order to perform comparative analysis of the data, collected by campaigns of measurements, the vertical displacements were calculated from determined elevations of controlled benchmarks in different campaigns. The absolute displacements were calculated for the period from the date of first to date of last campaigns and relative displacements were calculated for the period from date of the previous to date of the last campaigns. Annual displacements and velocities of the movements were calculated also. Results from these calculations were presented in tables as following:

Репери по обекти в участък			Абсолютни вертикални премествания , mm												№ на репер
№ на репер	Тип обект	Местонахождение	11-0 29.03.2017г.		Средна скорост mm/месец	12-0 29.09.2017г.		Средна скорост mm/месец	13-0 30.03.2018г.		Средна скорост mm/месец	14-0 30.09.2018г.		Средна скорост mm/месец	
1354	Сграда	Сграда на Пътя за Дивотино				-2.5			0.7		0.0	0.5	↑	0.0	1354
2216	Път	Път за Дивотино	7.8	↑	0.1	4.4	↑	0.1	8.2	↑	0.1	5.5	↑	0.1	2216
2217	Път	Път за Дивотино	10.4	↑	0.1	9.2	↑	0.1	12.5	↑	0.2	10.9	↑	0.1	2217
2218	Път	Път за Дивотино	11.3	↑	0.2	10.9	↑	0.1	13.5	↑	0.2	11.7	↑	0.1	2218
131	Път	Път за Дивотино													131
132	Път	Път за Дивотино	-0.1	↓	0.0	-2.0	↓	0.0	7.3	↑	0.1	6.7	↑	0.1	132
141	Път	Път за Дивотино													141
142	Път	Път за Дивотино	-14.5	↓	-0.2	-61.7	↓	-0.8	5.3	↑	0.1	-14.0	↓	-0.2	142
151	Път	Път за Дивотино	-0.6	↓	0.0	-3.6	↓	0.0	3.6	↑	0.0	2.8	↑	0.0	151
152	Път	Път за Дивотино	20.3	↑	0.3										152
153	Път	Път за Дивотино	25.7	↑	0.4	20.2	↑	0.3	27.1	↑	0.3	26.9	↑	0.3	153
154	Път	Път за Дивотино	15.0	↑	0.2	3.1	↑	0.0	16.1	↑	0.2	2.4	↑	0.0	154
1019	Път	Път за Дивотино	-5.6	↓	-0.1	-9.8	↓	-0.1	0.6	↑	0.0	1.7	↑	0.0	1019
1020	Път	Път за Дивотино	-17.6	↓	-0.3	-27.2	↓	-0.4	-12.4	↓	-0.2	-14.3	↓	-0.2	1020
2401	Път	Път за Дивотино	5.9	↑	0.1	-14.7	↓	-0.2	8.4	↑	0.1	2.7	↑	0.0	2401
2402	Път	Път за Дивотино	-9.7	↓	-0.1	-22.1	↓	-0.3	-9.5	↓	-0.1	-17.7	↓	-0.2	2402
2501	Път	Път за Дивотино	14.6	↑	0.2	15.4	↑	0.2	20.1	↑	0.2	21.8	↑	0.2	2501
2502	Път	Път за Дивотино	25.5	↑	0.4	24.1	↑	0.3	28.9	↑	0.4	30.1	↑	0.3	2502
2503	Път	Път за Дивотино	18.5	↑	0.3	18.7	↑	0.2	21.6	↑	0.3	23.1	↑	0.3	2503
2504	Път	Път за Дивотино													2504
2505	Път	Път за Дивотино													2505
2506	Път	Път за Дивотино	24.9	↑	0.4	-1.4	↓	0.0	26.9	↑	0.3	10.2	↑	0.1	2506
2507	Път	Път за Дивотино	14.1	↑	0.2	4.4	↑	0.1	16.8	↑	0.2	15.1	↑	0.2	2507
2625	ЖП линия	ЖП линия Перник-Волуяк	-30.5	↓	-0.7	-46.2	↓	-0.9	-45.0	↓	-0.8	-47.0	↓	-0.7	2625
2624	ЖП линия	ЖП линия Перник-Волуяк	-54.2	↓	-1.2	-66.8	↓	-1.3	-69.4	↓	-1.2	-79.6	↓	-1.2	2624
2574	ЖП линия	ЖП линия Перник-Волуяк	-5.1	↓	-0.1	-9.5	↓	-0.2	-1.7	↓	0.0	-4.7	↓	-0.1	2574
1361	ЖП линия	ЖП линия Перник-Волуяк	-5.4	↓	-0.1	-23.7	↓	-0.3	-4.5	↓	-0.1	-10.9	↓	-0.1	1361
1362	ЖП линия	ЖП линия Перник-Волуяк	-10.6	↓	-0.2	-42.5	↓	-0.6	-13.1	↓	-0.2	-19.9	↓	-0.2	1362
1363	ЖП линия	ЖП линия Перник-Волуяк	-11.4	↓	-0.2	-49.4	↓	-0.7	-10.2	↓	-0.1	-23.5	↓	-0.3	1363
1364	ЖП линия	ЖП линия Перник-Волуяк	-1.5	↓	0.0	-8.2	↓	-0.1	-0.5	↓	0.0				1364
1365	ЖП линия	ЖП линия Перник-Волуяк													1365
1366	ЖП линия	ЖП линия Перник-Волуяк	0.5	↑	0.0	-0.7	↓	0.0							1366
1367	ЖП линия	ЖП линия Перник-Волуяк	-5.2	↓	-0.1	-5.4	↓	-0.1	-2.9	↓	0.0	-5.1	↓	-0.1	1367
2313	ЖП линия	ЖП линия Перник-Волуяк	-44.7	↓	-0.6	-63.5	↓	-0.8	-49.3	↓	-0.6	-56.1	↓	-0.6	2313
2314	ЖП линия	ЖП линия Перник-Волуяк	-27.5	↓	-0.4	-53.6	↓	-0.7	-30.0	↓	-0.4	-35.6	↓	-0.4	2314
2315	ЖП линия	ЖП линия Перник-Волуяк	-26.2	↓	-0.4	-45.8	↓	-0.6	-25.3	↓	-0.3	-32.6	↓	-0.4	2315
2316	ЖП линия	ЖП линия Перник-Волуяк	-1.7	↓	0.0	-33.6	↓	-0.4	1.7	↑	0.0	-20.8	↓	-0.2	2316
2317	ЖП линия	ЖП линия Перник-Волуяк	-12.6	↓	-0.2	-11.3	↓	-0.1	-9.0	↓	-0.1	-11.3	↓	-0.1	2317
2318	ЖП линия	ЖП линия Перник-Волуяк	-49.0	↓	-0.7	-91.2	↓	-1.2	-52.1	↓	-0.6	-70.6	↓	-0.8	2318

Figure 8. Table with results of comparative analysis of vertical displacements

The vertical displacements were showed graphically by linear changes of elevations of controlled benchmarks on profiles and objects in time and regression analysis for forecasting of the movements:

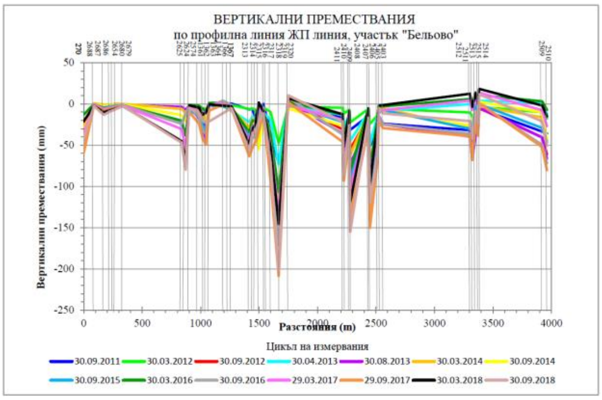

Figure 9. Graph of linear changes of vertical displacements by profiles in time

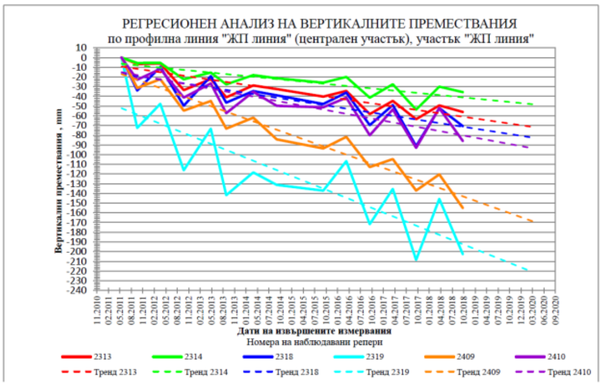

Figure 10. Graph of linear changes of vertical displacements of benchmarks in time and regression analisys

It has been found that for most of the controlled benchmarks, the values of the observed vertical displacements are significantly greater than the accuracy of the method used to determine the elevations. This gives a high degree of credibility to claim that there have actually been vertical displacements in the controlled benchmarks and objects.

The vertical deformations were calculated on the base of the vertical displacements. The results were shown in tables with calculated values of the main deformation parameters according Instruction for the protection of the facilities and structure from the harmful influence of the underground mining works in the coal basins, issued by Ministry of Energy, Sofia 1983 – the inclination i (mm/m), curvature (mm/m²) and radius of the curvature R (m) for applied cases of objects (on buildings and linear objects – roads and railways).

B. *Analysis of the data for horizontal displacements*

The values of calculated coordinate differences dX, dY for the periods between dates of first and next campaigns of measurements and between consecutive campaigns were presented in table forms. By these coordinate differences were calculated the values of properties of the vectors of horizontal displacements – the length dS and bearing anlge α, as the velocity of the the rate of horizontal displacements. The values of horizontal deformations ε (mm/m), calculated according Instruction, were presented in tables also.

To illustrate the comparative analysis of the results of the geodetic measurements, the combined schemes were presented, which containing:

- Positions of the elements of engineering infrastructure on the ground surface situated on the cadastral map of the City of Pernik;
- Positions of underground mines and fields;
- Positions of benchmarks and geodetic points;
- The calculated horizontal and vertical displacements on controlled points.

The horizontal displacements were presented graphically by trajectories of movements, by applying colour according to the period of their occurrence between the campaigns performed.

The colorized of vertical displacements are also used, depending on their size. An example of such a combined scheme is given in the following figure:

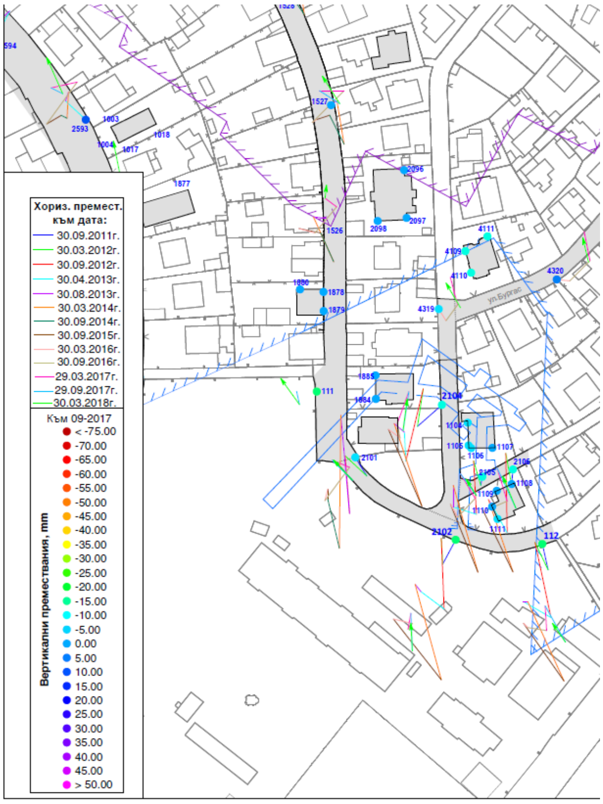

Figure 11. A part of combined schema for graphical representation of changes of vertical and horizontal displacements

C. *Conclusions and recommendations*

For each measurement campaign, a detailed analysis of the observed displacements, deformations and rate of change is made, taking into account the location of the controlled points, the initial moment the observations, the type of the observed object, etc.

As a result, the correlation between the magnitude of vertical and horizontal displacements was found, i.e. in areas with more significant absolute shrinkage, higher values of horizontal displacements are also found.

There is a clear trend towards the horizontal displacement vector directions, which generally follow the direction of the terrain slope and the underground layers - an expected result that confirms the correctness of the observed data for horizontal movements. Particularly clear is the trend of horizontal displacements for the points on the railway line - the vectors have directions perpendicular to the axis of the line, depending on the position of the points in relation to the axis in opposite directions to the fall of the line embankment. It is noteworthy the cyclical nature of a diametrical change of direction of the horizontal displacement vectors with more significant values, the trajectory showing seasonal variations of the controlled points around the initial position, which coincide with the oscillations of the vertical displacements.

In result of provided data from geodetic monitoring for deformation processes occurring in sections of the railway structure, the responsible authority made decision to design and execute reinforcement activities to protect and prevent construction of this important object.

The developed GIS data base with collected actual geodetic data for the progress of deformation processes will be useful tool for the further design of strengthening measures for the prevention of the residential areas of the town of Pernik.

Executing the largest object for geodetic monitoring of displacements and deformations in Bulgaria for last 9 years our team acquired and further developed its professional qualifications and expand the practical and theoretical experience in this very specialized field of the geodetic science and practice.

This experience was base for development of other projects for geodetic monitoring of important objects on territory of Bulgaria as following:

- National Disposal Facility of State Enterprise “Radioactive Waste” (SE RAW) Radiana site for Low and Intermediate Level Short-Lived Radioactive Waste;
- Tailing repositories;
- Oil reservoirs in petroleum basec of OMV Bulgaria.