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VERTICAL CRUSTAL MOVEMENTS IN SEISMIC ACTIVE REGIONS

This paper presents the measurements and certain vertical displacements of the Earth's crust in the seismic active area of the Skopje valley. The need for this activity was initiated by 16 earthquakes with Mw = 2.1 - 5.2 according to the EMSC that appeared in the period from 11.09 to 20.09 2016. Therefore, a precise levelling of high accuracy has been used on a part of the state levelling network from first order, which is located on the territory of the City of Skopje. In particular, height differences are determined between the benchmarks of the levelling line that pass through the blocks formed by intersection of the active faults in the area.

Key words: basic levelling network, precise levelling, geodynamics, vertical crustal movements.

1. INTRODUCTION

Since the formation of the Earth as a geological body till today, it has been constantly changing, with its individual parts being in a state of complex interactions with each other. Therefore, a modern definition of tectonic movements, as a fundamental concept of geotectonics, should be based on the assumption of the Earth as an unstable system in which the geological processes flow continuously, but unevenly with different intensity in time and space. Observations of the geodynamic processes and the determination of displacements and deformations of the Earth's crust based on geodetic measurements, is in fact examination of the time evolution of the reference system, that is, the geodetic reference networks, realized and materialized with appropriate markers on the physical surface of the Earth. [12]

Direct measurements are the basic source of information necessary to determine the character and genesis of a given geodynamic process and the phenomena associated with it. Given the nature of the methods of determining the mutual position between the points of the networks, the horizontal and vertical component of the displacements are determined by different measurements.

Therefore, in the geodetic terminology, the terms contemporary vertical movements of the Earth's crust (**CVMEC**) and contemporary horizontal movements of the Earth's crust (**CHMEC**) were imposed. [6]

The displacements are determined based on a minimum of two mutually comparable and independent measurements made over a different period of time. The differences in the positions of the points in both measurements represent the displacements in a horizontal or vertical sense, depending on the type of measurements.

In the particular case, it's a matter of precise geodetic measurements aimed at determining the vertical displacements of the Skopje valley. To this end, a precise levelling of high accuracy is applied, which is part of geometric levelling, which can provide the highest accuracy in determining height differences. The precise levelling is applied to one levelling line in the Skopje valley, where the benchmarks are located in different blocks formed by intersection of local faults: the Skopje-Kjustendil fault (which cuts the Skopje valley on the middle in east-west direction), then the Skopje-Crnogorski fault (stretching along the western slopes of the eponymous mountain) and other smaller faults.

Due to various internal and external factors over time, horizontal and/or vertical displacement of the blocks may occur, which usually last for a few seconds, known as an earthquake. The movement itself is from several millimeters to several centimeters. [7]

2. SEISMOTECTONICS, GEOLOGICAL PROCESSES AND STRUCTURES

Tectonic plates theory claims that the Earth's crust is divided into multiple plates, these plates are parts of the lithosphere that float on the subfluidic asthenosphere and move relatively one relative to another at a certain speed. [3] This constant movement of the plates is responsible for geological events such as volcanic activity, earthquakes, and the movement of continents.

The tectonic movements are manifested as deformations of the Earth's crust, these deformations are most common in the boundary zones between the plates or the blocks. These boundary zones are defined depending on the way of movement of the tectonic slabs. If two plates are moving towards one another, the collision is the boundary of convergence (***convergent zone***) these activities can cause the occurrence of earthquakes. In the case when the plates diverge, that is a boundary of separation (***divergence zone***) resulting in volcanic activities, whereas if the plates move horizontally along a vertical fault surface, that is boundary of slipping (***transformation zone***).

While tectonic plates are interacting, a lot of pressure and stress is created that exceeds the upper limit of their mechanical strength, and during that deforming, tectonic forms, known as faults, occur. [12] With the creation of the fault structure, the formed wings (blocks) in the rocks move in a horizontal or vertical or combined direction. The basic form of vertical displacements is the faults; they are usually under different slopes in relation to the horizontal. In nature, shear faults occur most often. They are further divided into: gravity or **normal faults**, **reverse faults** and peelings, sleeves and **horizontal faults**. Of course, various combinations of movements are possible, compared to the basic groups.

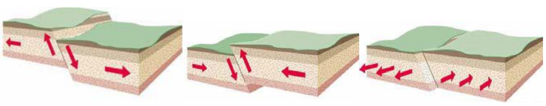

Figure 1. Normal fault (left), reverse fault (mid) and trans-current (horizontal) fault (right) [12]

2.1 TECTONICS AND NEOTECTONICS OF R. MACEDONIA

The territory of the Republic of Macedonia is located in the central part of Southeast Europe, in particular on the Balkan Peninsula. Nowadays the Balkan Peninsula lies in a collision zone between three major plates: Eurasian, African and Arabian, which are divided into smaller plates. The active tectonic processes in the eastern Mediterranean are most influenced by the following: subduction of the Adriatic micro plate under the Dinarides, subduction of the Ionian and Levant micro plains under the Hellenic trenches and the collision between the Eurasian and the Arabian plates, related to the North - Anatolian fault. [8]

From geological research, made by Dumurdjanov et al., 2005, active faults within Macedonia are summarized in Fig. 2. Three categories of faults are shown; 1) faults with evidence of active faulting, such as scarps or offset streams (red), 2) faults with well-developed morphological expression for active faulting, but without evidence for scarps (solid blue), and 3) faults with well-developed morphological expression for the modern topography and are only suspected to be active (dashed blue). [4]

In engineering, special attention is paid to the existence of so-called **active faults**.

They are structures where displacements occur and in modern days through their length there is release of seismic energy in the form of earthquakes.

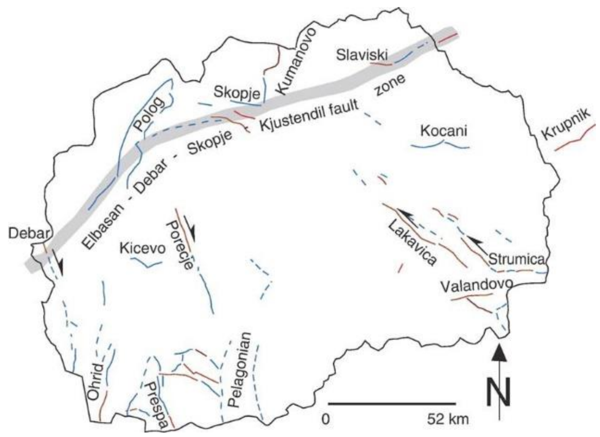

Figure 2. Active faults in Macedonia [4]

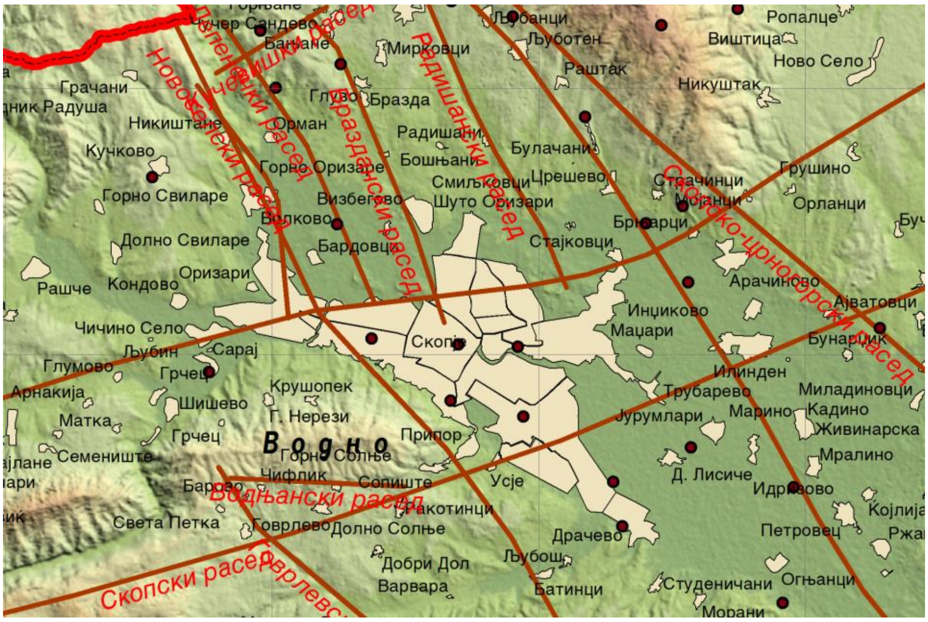

Figure 3. Neotectonic faults in the Skopje valley [3]

When it comes to active faults, that is, reactivated pre-neotectonic faults, it should be emphasized the fault that is considered to have the most significant role for the appearance of most of the earthquakes in the territory of the Skopje valley. It is about the Skopje fault, which represents a connection between the Debar-Kriva Palanka transversal dislocation in Macedonia. This dislocation starts from the city of Elbasan in the Republic of Albania through Debar, Mavrovo, Skopje, Kriva Palanka and Kyustendil in the Republic of Bulgaria. [3]

Neotectonic longitudinal faults are a special characteristic of the Skopje valley. They are concentrated in two areas, and are limited by the Skopje dislocation, that is, the Skopje fault. The division was made in the northern and southern regions defined in relation to the Skopje fault. In the northern region that have a direct impact on the Skopje valley, there are five fault structures: Radishanski, Brazdanski, Lepenicki, Novoselski and Svilarski fault. [3] Most of the above-mentioned faults cross into nodes with the most expressed potential lability (instability).

2.2 SEISMIC ACTIVITY ON THE TERRITORY OF R. MACEDONIA

The Skopje valley has large seismicity, like the majority on the territory of the Republic of Macedonia, which belongs to the central active seismic part of the Balkan Peninsula. In this region, there is often occurrence of catastrophic earthquakes, which reached epicentre intensity to X MSK-64 and magnitude to 7.8 degrees (which is the highest observed magnitude on the Balkan Peninsula), is the Pehchevo-Kresna earthquake of April 4, 1904, with a magnitude from 7.8 degrees on Richter scale.

The Vardar seismogenic zone is one of the weakest tectonic units with particularly expressed seismicity in the areas of crossing of reactivated old faults in a Vardar direction with neotectonic faults that predominantly stretch in a transverse direction.

The **Skopje epicenter area** - related to the contemporary tectonic activity of the Skopje depression, which represent a neotectonic depression. According to the morphological characteristics it is divided into three segments: a modern Skopje field, areas built of neogene sediments and surrounding mountain terrains.[8]

When it comes to instrumental data on earthquakes in this area, it should be noted that such data exist since 1900. According to these data, two earthquakes were registered on the territory of the Skopje epicentre region, followed with human casualties and material damage. One of them happened on 10.08.1921, on the northern slopes of the mountain range Skopska Crna Gora with a magnitude M_L = 6.2 degrees on the Richter scale and with a depth of 20km. The second earthquake is the famous Skopje earthquake of July 26, 1963, with a magnitude of M_L = 6.1 degrees on the Richter scale and with a depth of 5km of the hypocentre in which a large number of human lives were lost and created great material damage.

For our research, very important is probably the centennial seismic cycle that struck Skopje and

its surroundings in 2016 from 11 to 14 September, which was located 3.5-7.0 km east from the seismic hotspot from 1963. In the cycle, a total of 16 earthquakes occurred with M_w = 2.1 - 5.2. The first strong earthquake occurred on 11 September at 6 am and 58 minutes, the hotspot is about 10 km northeast of the centre of Skopje, between the village of Arachinovo and the village of Creshevo, with a depth of about 5 km, a magnitude of 4.1 degrees, and the intensity around the V- VI degrees by EMS (European macroseismic scale, also known as EMS-98). The second strong earthquake occurred again on **September 11 at 3 pm and 10 minutes**, with a stronger intensity of **5.2 -5.3** degrees or about 15 times the energy of the first quake. The hotspot of this earthquake was several kilometres east of the centre of Skopje, at a depth of about 10 km. This earthquake is the strongest in the group of earthquakes. The last earthquake occurred on September 14 at 1 pm and 32 minutes, with a magnitude of 3.1 degrees and a depth of 3 km. Such strong earthquakes in the Skopje region, according to data from the seismological observatory at PMF in Skopje, appear on average once every 100 years. It is believed that the strongest expected or occurring earthquake in the Skopje's seismic region can reach magnitude to 6.5 degrees, something slightly stronger than that of the great earthquake in 1963 (6.1 degrees). The probability of an earthquake with magnitude greater than 6 degrees is once in 500 years. [7]

Date	Time UTC	Latitude	Longitude	Depth	Magnitude Type	Magnitude
11.09.2016	04:58:01	42	21.51	4	mb	4.2
11.09.2016	05:00:05	41.99	21.49	3	ML	2.8
11.09.2016	13:10:07	41.98	21.5	4	mb	5.2

Table 1. Official data from EMSC (European Mediterranean Seismological Centre) [7]

The earthquakes of September 11-14 occurred just beside the faults juncture, where the Skopje-Kustendil and the Skopje-Crnogorski fault intersect, at a depth of about 5-10 km and in a diameter of about 5 km along the fault structures. Along the two faults, the Skopska Crna Gora block is moving vertically and in the west direction, as evidenced is the turning of the valleys of rivers descending from the mountain. [7]

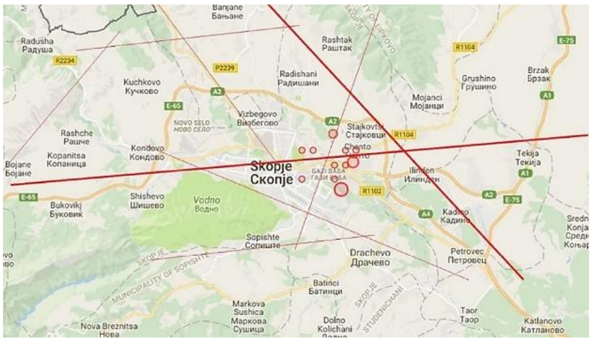

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Figure 4. Epicentres of the earthquakes from 11 to 14 September 2016 stronger than 2.5 M (circles) and the main fault cracks [7]

3. THE NEW LEVELLING NETWORK OF THE R.MACEDONIA

The basic levelling network is a part of geodetic networks, which serves as the altimetric base for preforming of all height surveys in the Republic of Macedonia, as well as for realization of important scientific engineering and technical tasks. It is divided into several ranks, of which **I** and **II** rank, are of the highest accuracy and used for scientific research in determining the figure of the Earth and the vertical movements of the Earth's crust, as well as the differences in the levels of seas and oceans.

The new levelling network with high accuracy (NVT3) is consisting of 1098 levelling points (benchmarks) connected with 49 levelling lines and 19 polygons, plus 12 lines for connection with neighbouring countries. The total length of levelling traverses is 2189 km, with an average distance of 1800 m between benchmarks and average perimeter of the polygons with 166 km. It is consisting 28 fundamental benchmarks and 31 nodal points. [9]

Figure 5. Fundamental Benchmark Skopje

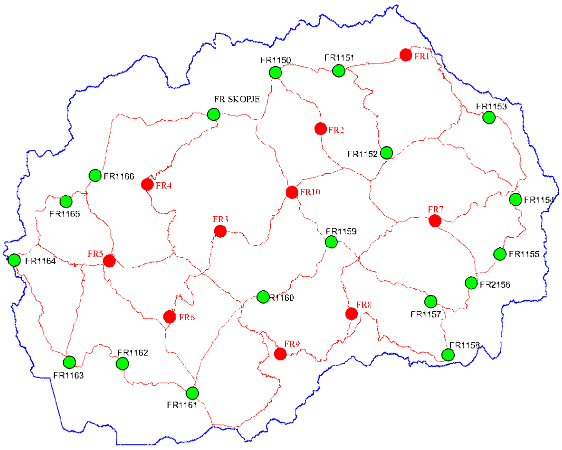

Figure 6. Location of the fundamental benchmarks of the new levelling network

3.1 GRAVIMETRIC NETWORK

Gravimetric measurements were carried out on the entire territory of the Republic of Macedonia for the purpose of defining different physical height systems.

Rank	Zero	First	Second
Year of measure-ment	2010	2013	2014
Number of points	3	25	2310
Accuracy	3 µGal	13 µGal	< 60 µGal

Table 2. Basic data for the gravimetric network of RM

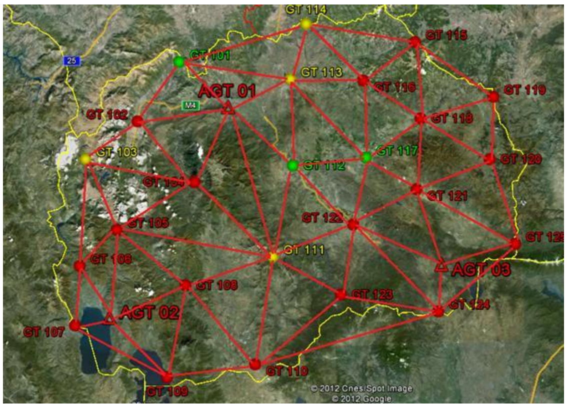

Figure 7. Gravimetric network of the first order

4. PRACTICAL MEASUREMENTS

First, an analysis of the location of the faults in the Skopje valley was made and their expansion in relation to the levelling traverses from the state levelling network of the first rank, in order to get an idea of which levelling traverses have benchmarks that are located on different blocks formed from the intersections along the fault structures.

Parts from the levelling traverses V2 and L17 are selected, from which is formed levelling traverse with total length of 9.2km, which consists of five levelling sides.

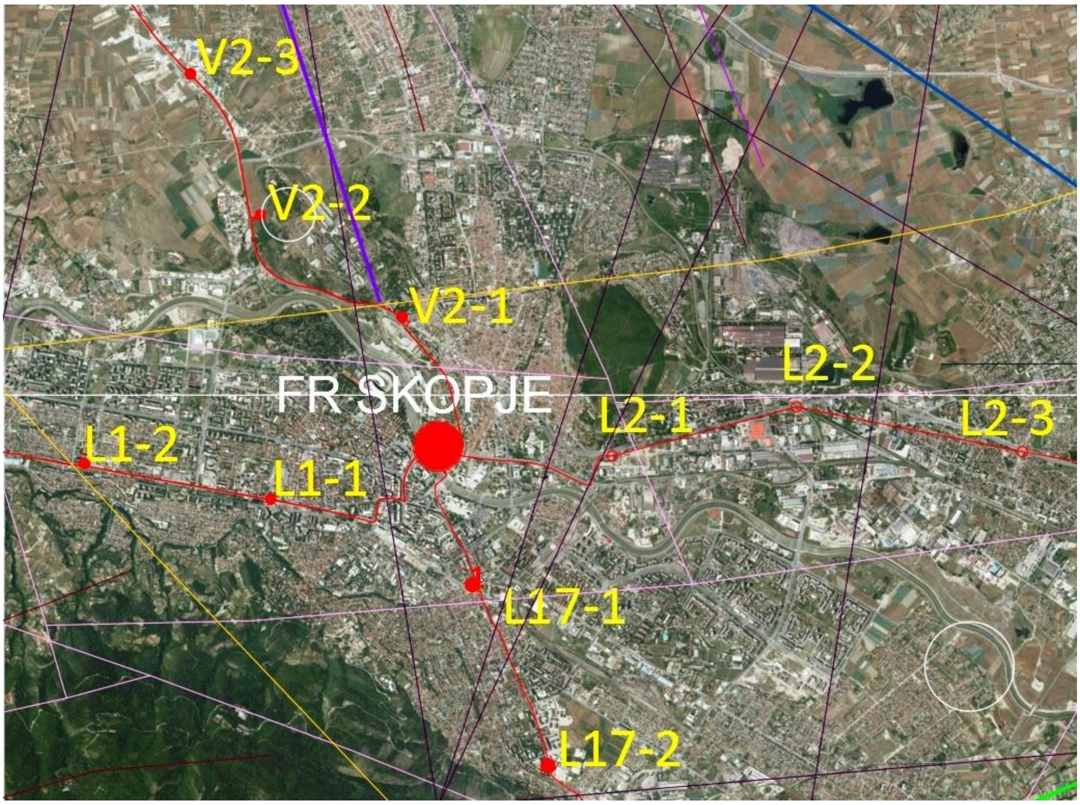

Figure 8. The location of the faults in the Skopje valley and their expansion in relation to the levelling traverses from the state levelling network of the first order

Field activities were carried out in the period from 16 to 20 July 2018. While planning the measurement schedule and after the organized field inspection, it was ascertained that the R_2 benchmark from the levelling line V2 was destroyed, in order to meet the criterion for distance between two successive first-order benchmarks, a new auxiliary benchmark Rp_2 was placed near the old benchmark R_2.

4.1 GEOGRAPHICAL AND GEOLOGICAL DESCRIPTION OF THE LEVELLING ROUTES

The V2 line extends geographically in the north-west direction, from the Skopje exit passes through the industrial zone of Vizbegovo, goes along the national road which is in good condition, but not very wide for the frequency of the traffic that passes through it.

From the beginning of the route, until the connection to the main road for the Blace border crossing, the terrain from geological aspect is built of Miocene sediments, composed of jackals, sands, marls and clays.[1]

The line L17 starts from the fundamental FR-SK benchmark under the fortress in Skopje, near the Goce Delchev Bridge, geographically extends in the north-west direction along the regional road Skopje-Sopiste. The route of the line L17 from the starting point crosses the river Vardar to the square "Macedonia" then, passing through the main access roads continues through the city Skopje to the exit from Skopje near Kisela Voda at the foothills of Vodno.

The whole terrain through which the route of the levelling line crosses is built from quaternary sediments represented as lower river terraces and alluvial sediments formed around the river Vardar. These sediments are products of the youngest erosion processes, which last even today. They are composed of various granulated, unsorted gravel, sands and clays, which originate from the rocks of the watershed of the river Vardar and its tributaries in the Skopje valley. [1]

4.2 MEASUREMENT OF HEIGHT DIFFERENCES

Measurement of height differences was made in accordance with the recommendations of the technical specification with appropriate instruments, equipment and observation procedures, the required accuracy was fully met. The precise digital level used is **Leica**

DNA 03, equipped with two three metre barcoded levelling rods with invar tape, with original holders and metal slippers. The instrument has a declared accuracy of **0.3 mm/km.** During the measurement, readings and registration of the temperature values were performed. At a certain time interval of 2 hours on three different places, the lower, middle and upper part of the Invar rods with the help of an appropriate instrument.

Figure 9. Measuring the temperature of the Invar rod

Conditions that are met while measuring the height differences:

- Before starting the measurements, the instrument and the invar rods are acclimatized to external conditions for half an hour;
- The values of the angle "*i*" are determined. The values for the angle "*i*" are not included in the instrument in the form of corrections in the measurement of the height differences, but they are recorded in separate files. The absolute value of the angle "*i*" does not exceed 15 '';
- Double measurements were made by changing the height of the instrument;
- The measurements of each station are made from the middle where the difference between the front and rear sight distance is not greater than 3m, also attention is paid on the change of the position of the tripod legs when changing the stations;
- The number of stations in the precise levelling of the height difference between two benchmarks is even;
- The wind speed did not exceed 3 m / s, and when sighting the conditions of the front and rear invar rods were approximately the same;
- The length of the sight does not exceed 30m, while the height of the sight reading is not less than 0.5m or greater than 2.5m.

The results of the measurements of the height differences on the levelling sides are shown in the levelling field book, and from the field book a table is prepared containing the data for the mean values of the height differences of the levelling sides and the deviations from the front and back levelling.

Nº BM	lm between BM, S, km	Height difference, m		d=II - I mm	Average value of height differences
		I	II		
FRSK V2-R1	2.01	28.53262	-28.53317	-0.55	28.53290
V2-R1 V2-R2p	2.18	20.9649	-20.96575	-0.85	20.96533
V2-R2p V2-R3	1.36	-14.1584	14.15921	0.84	-14.15879
FRSK L17-R1	1.65	-4.51362	4.51348	-0.14	-4.51355
L17-R1 L17-R2	1.95	-2.69487	2.69573	0.86	-2.69530

Table 3. Measured height differences

From the data in the field books, the following basic characteristics of the measurements can be noted:

- Minimum distance instrument-invar rod occurs in the level-side V2-FR-V2-R1 and is 5.85 meters;
- The maximum distance of the instrument-invar rod occurs in the level-side V2-FR-V2-R1 and is 29.77 meters;
- The minimum number of levelling stations occurs on the level-side V2-R3-V2-R2p and is 28;
- The maximum number of levelling stations occurs on the level-side V2-FR-V2-R1 and is 54;

4.3 QUALITY CONTROL OF THE MEASUREMENTS

Levelling results are checked before further processing:

- By calculating the values for the height differences measured back and forth;
- By creating differences from the height differences between the front and back levelling;
- By comparing with the criteria defined for the realization of the measurements.

The basic criteria of the accuracy for performing the measurements are defined through:

Allowed deviation of the dual height difference (forward-backward):

$$\Delta_{\Delta H}(mm) = 2\sqrt{s} \qquad (1)$$

s - length of the levelling line in km.

Allowed deviation of closing of the polygons:

$$\Delta_{P}(mm) = 4\sqrt{s} \qquad (2)$$

s - length of closed polygon in km.

From the analysis of the difference between the height differences in the levelling sides (forward-back) and the allowed deviations, it can be noted that all the height differences fulfil the condition of accuracy.

4.4 DETERMINATION OF VERTICAL MOVEMENTS

Vertical shifts in the Earth's crust are determined by comparing measured height differences from the current epoch 2018 and the initial measurements after the establishment of the new levelling network from first order, realized in 2013.

From	To	Distance [m]	Dh-2013	Dh-2018	Dh [m]
FRSK	**V2-R1**	2014.37	28.53066	28.53290	**-0.00223**
V2-R1	**V2-R3**	3545.00	6.807685	6.806535	**0.00115**
FRSK	**L17-R1**	1654.71	4.512605	4.51355	**-0.00095**
L17-R1	**L17-R2**	1951.91	2.690815	2.69530	**-0.00449**

Table 4. Display of the vertical shifts

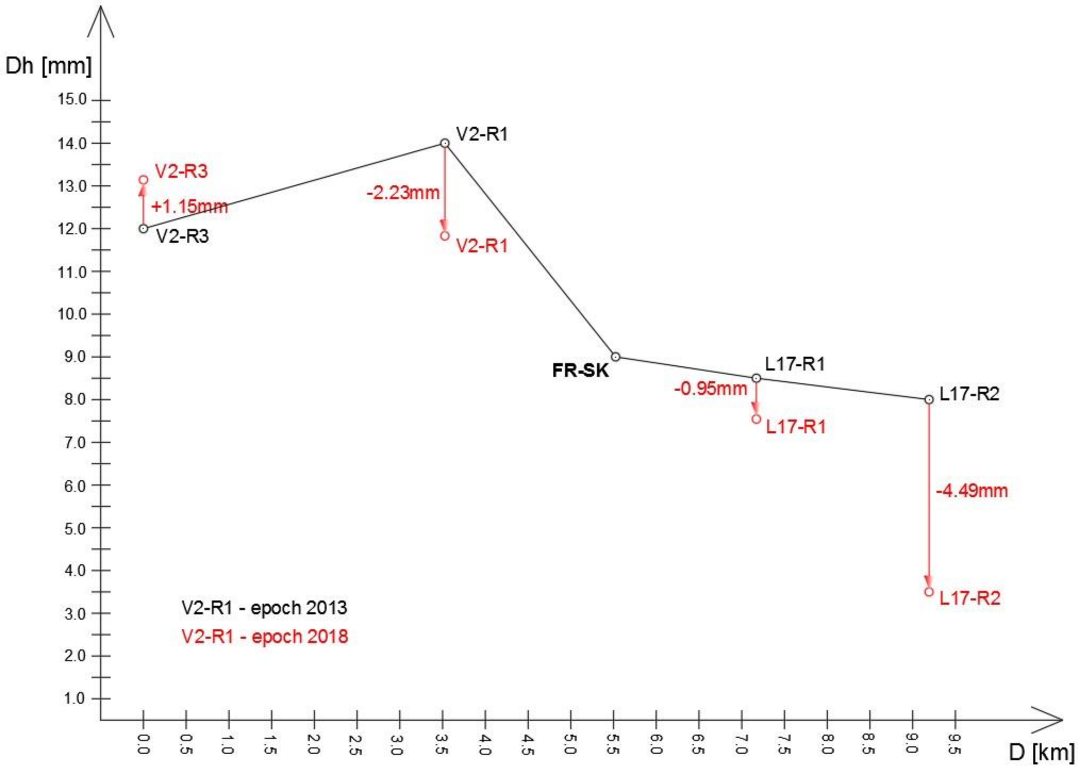

Figure 10. Graphic display of vertical displacements

5. CONCLUSIONS

Due to the movement of the lithospheric plates, the geodetic coordinates of the points on the surface area of the plates change their values over time, which makes them dependent on the epoch in which the observations were made. Geometric levelling is the oldest and only geodetic method that, with the accuracy it provides, meets the high accuracy criteria for determining the vertical component for exploration of seismic and tectonic processes.

When interpreting the results for the purposes of geodynamics, it should be borne in mind that the obtained data refer to the differences between uncorrected directly measured height differences between the benchmarks in both epochs. In order to obtain the definite heights of the benchmarks, it is necessary to realize and process two types of measurements, the basic precise levelling measurements, and additionally perform gravimetric and GNSS measurements of the benchmarks of the levelling network, as well as measurements and registration of temperature, humidity and pressure.

The data processing itself includes:

- First of all, the quality control of the measurements which was made in this paper and it was concluded that all levelling measurements were performed in accordance with the defined criteria for control and monitoring of the measurements, namely: stations, levelling sides and levelling traverses from the network;
- Next, the results of the levelling measurements should be corrected with geometric corrections;
- To perform a transformation of directly measured height differences in different physically defined height systems;
- Adjustment of the levelling network of high accuracy;
- And in the end conducting statistical tests and assessment of accuracy.

Figure 11. Level station at the Stone Bridge Skopje

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