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APPLICATION OF MONITORING RESULTS ON CONTEMPORARY VERTICAL MOVEMENTS OF THE EARTH'S CRUST IN THE SPITAK EARTHQUAKE REGION FOR FURTHER STUDIES

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Data on the Spitak earthquake from scientific studies conducted by specialists were analyzed and consolidated. The differences in the absolute heights of benchmarks, obtained during previous leveling works at the geodynamic polygon of the Spitak Region, were summarized, analyzed, and calculated. Based on these data, a map depicting modern vertical crustal movements in the Spitak earthquake zone was created for the period before the 1988 earthquake, and subsequently for the 1989–1990 period. Another map was generated for the period from 1989–1990 to 2002–2006, illustrating that the rate of crustal subsidence–measured at 9 to 12 *mm*/year – persisted until 2016. It is currently hypothesized that the Earth's crust in this region continues to subside at the same rate. This hypothesis is supported by data officially provided by the RA Ministry of Emergency Situations, as well as by a map of earthquake epicenters with magnitudes of $M \geq 2.5$ recorded in the Amasya, Ashotsk, and Bavra Regions between 01.01.2020–01.03.2022. It is recommended to initiate a project for comprehensive geodynamic monitoring in this region, involving the joint efforts of surveyors, geologists, geophysicists, and seismologists. The data obtained will help clarify the causes of crustal dynamics and their patterns in relation to the stresses resulting from energy accumulation in the Earth's subsurface.

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Keywords**:** earthquake, fault, crust, vertical displacement, geodynamic polygon, leveling, elevation mark.

Introduction. Survey works at the Spitak geodynamic polygon were conducted by the State Scientific and Production Complex "Geodesy and Cartography" of the Real Estate Cadastre Committee under the Government of the Republic of Armenia between 2013 and 2016.

The Spitak Region is characterized by several major faults, including the Pambak–Sevan, Akhuryan, Spitak, Javakhk, and Sarigamish faults (Fig. 1). The movement of these faults contribute to ongoing deformation of the Earth's crust,

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impacting the Arabian and Eurasian tectonic platforms, with significant effects in Armenia.

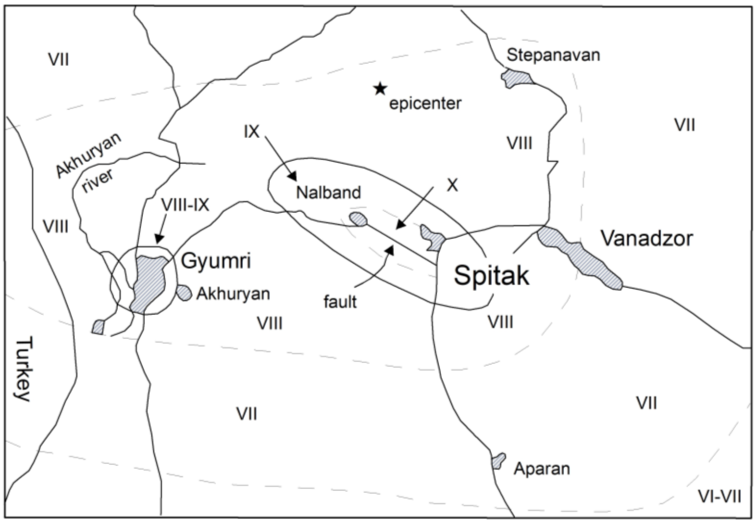

Fig. 1. The 1988 Spitak earthquake isoseismals.

The first high-precision measurements of crustal deformations in Armenia and adjacent territories were obtained in 1997 through a collaborative effort involving the Massachusetts Institute of Technology (MIT), the National Seismic Protection Survey of Armenia (NSSP), and the Institute of Geophysics of the Russian Academy of Sciences.

Deformations in different areas vary depending on the density of the rocks, as does the speed at which deformation limits are reached. The most deformed areas of the Earth's crust correspond to its weakest zones, i.e. faults. According to the World Statistics of Seismic Events, the strongest earthquakes occur along active fault lines.

The Spitak geodynamic polygon is situated in the northern part of the Republic of Armenia. The region's relief features a diverse topography, including mountain ranges, peninsulas, plateaus, and depressions. Absolute elevations range from 700 *m* (Debed River Valley) to 3100 *m* (Mount Tezh), with some peaks in the Bazum and Pambak ridges exceeding 3000 *m*. The ends of the mountain ranges are sharp, rocky, dome-shaped. The slopes of the mountain ranges are divided by deep gorges 50–150 *m* high. The southwestern part of the territory is divided by steep slopes of the Akhuryan and its tributaries, river valleys, so that it is often impossible to descend to the water of the river bed. The plains and plateaus have a wavy, sometimes hilly surface, dissected by river valleys and canals.

Now let's present the current vertical movements within the polygon in relation to the geological structure of the region.

From a geological perspective, Spitak and Vanadzor are situated along river-beds in areas characterized by mountainous relief. The topography surrounding Spitak is less rugged compared to Vanadzor. In both cities, most areas are located on river shelf formations, which are up to tens of meters thick, consisting of thin soil layers or formations derived from the surrounding mountains. In Vanadzor, buildings are predominantly constructed on rocky ground, providing relatively stable foundations. Gyumri, by contrast, lies on a wide alluvial plain. Regional geological studies reveal that Gyumri is located in a basin filled with sedimentary formations extending to depths of 3 *km* to 4 *km*. Near the surface, geological sections in much of Gyumri exhibit strong layers of alluvial soils, including sand, clay, gravel, sandy loam, and lake sediments. Furthermore, Vanadzor occupies a narrow valley flanked by high mountains, whereas Gyumri is situated in a broad basin [1]. Most seismologists believe that the geological features of these cities significantly impaced the seismic resistance of their buildings. Among modern high-rise structures within the earthquake zone, 87% in Spitak, 52% in Gyumri, and 24% in Vanadzor either collapsed or sustained serious damage. The extensive destruction in Spitak is primarily attributed to its proximity to the fault zone (epicenter). Notably, Vanadzor experienced less damage than Gyumri, even though Gyumri is farther from the fault zone.

Materials and Methods. According to research conducted by Japanese specialists using modern ultra-sensitive measuring equipment, the prevailing soil vibration periods are as follows: 0.5–0.6 *s* in Gyumri, 0.2–0.3 *s* in Spitak, and 0.2–0.4 *s* in Vanadzor [2–4]. These values indicate that resonance phenomena significantly contributed to building destruction during the earthquake.

Using real data recorded during the first 30 *s* of body and surface waves from numerous teleseismic stations, American seismologists Eastbrook, Panchenko, and Nabelek confirmed that the main event on December 7, 1988, was a multiplet. During this period, at least three aftershocks occurred, with intervals of 4 *s* and 10 *s* [5]. According to their interpretation, the first shock originated near Spitak, the second occurred 4 *s* later, 15 *km* East of the first shock's epicenter, and the third occurred 10 *s* after the first shock, 30 *km* to the west. Thus, one of the reasons for the extensive destruction in Gyumri was that the third main shock of the earthquake occurred just 10 *km* from Gyumri, whereas it was about 40 *km* from Vanadzor, not 25 *km* as previously assumed [6]. There was also considerable debate regarding the layout of the isoseismals of the Spitak earthquake. Fig. 1 presents a preliminary version of the isoseismals proposed by a group of Soviet and foreign specialists shortly after the earthquake [6].

To study the dynamics of the Earth's crust in 1989–1990, geodetic work was conducted throughout the earthquake zone. However, following the collapse of the USSR, this work was not continued due to a lack of funding.

Results and Discussion. Given the advancements in technological development, it is now possible to determine the dynamics of the Earth crust with high accuracy and to obtain detailed data on tectonic and seismotectonic active faults in the Spitak Region. The results of previous studies can be utilized for scientific research and analysis, particularly when compared with newly obtained data.

At the Spitak Geodynamic Test Site, Class I leveling works were conducted, covering a total distance of 723.5 *km*. The details of the leveling work are as follows:

- in 2014, 267.7 *km* were covered in Stage I;
- in 2015, 344.7 *km* were covered in Stage II;
- in 2016, 111.1 *km* were covered in Stage III.

Class I leveling was performed using two lines in both forward and reverse directions, with a change in the leveling horizon. Line I corresponds to the direction before changing the horizon, while Line II corresponds to the direction after the change. The work adhered to the requirements outlined in [7–9].

The Class I grid consists of six nodes and ten rows, resulting in four closed polygons. Class I leveling was carried out using previously installed Class I and II lines, and in 2013, a new Vardaghbyur–Saralanj line was added.

To study the vertical movements of the Earth's crust during the Soviet period, Class I and II leveling works were conducted at the White Region Geodynamic Test Site. The data from these works are presented in Tab. 1, with the corresponding diagram shown in Fig. 1. The physical condition and presence of benchmarks and stamps involved in these works were inspected on-site. Damaged benchmarks were repaired, and new ones were installed in place of the destroyed ones.

Table 1

Part of the data on elevation marks, levels, stamps, and their vertical movements in the Spitak Region for the period 1979–2015

Names of points	Features					Differences of elevations, *mm*			
	Volume, *V*	Aghstafa – Fantan	Earth-quake zone	State height network	Spitak geo-polygon				
	1979	1987–1988	1989–1990	2002–2006	2014–2016				
	Altitudes, *m*					5–3	5–4	6–5	7–5
417 RP	1614.982	1614.892	1614.892	1614.745	1614.778	–90.1	0.0	–147.4	–113.9
050 Stamp	–	–	1670.798	1670.646	1670.691	–	–	–151.1	–106.5
7505 Rock RP	–	1692.928	1692.921	1692.771	1692.816	–	–6.7	–150.3	–105.2
9406 Rock RP	–	1736.032	1736.012	–	–	–	–20.4	–	–
112 Ground RP	1739.102	1738.991	1738.975	1738.822	1738.864	–127.5	–16.9	–152.3	–110.1
5116 Rock RP	–	1774.227	1774.221	1774.054	1774.093	–	–6.1	–167.0	–127.9
187 Wall RP	1799.137	1799.012	1798.997	1798.847	1798.890	–140.2	–15.5	–149.5	–106.3
113 Ground RP	1808.029	1807.895	1807.877	1807.727	1807.747	–152.2	–18.2	–149.5	–129.7
M/P (Jajur) Stamp	1843.042	1842.909	1842.876	1842.717	1842.761	–166.0	–33.4	–159.3	–
M/P Lusaghbyur	1833.443	1833.313	1833.260	–	–	–182.6	–53.0	–	–
1569 Ground RP	1816.586	1816.457	1816.403	–	–	–183.3	–54.0	–	–
4424 Stamp	–	–	1778.867	–	–	–	–	–	–
2002Ground RP	1750.652	1750.535	1750.437	1750.274	1750.319	–214.7	–97.2	–163.6	–118.5
153 Wall RP	–	1341.517	1341.512	1341.450	1341.430	–	–5.1	–61.9	–81.7
161 Wall RP	–	1366.466	1366.462	1366.395	1366.376	–	–4.5	–66.7	–85.3

The differences in the absolute heights of the benchmarks, calculated from the previously completed leveling work in the Spitak geodynamic polygon [7].

According to Tab. 2, the map of modern vertical movements of the Earth's crust in the Spitak earthquake area before the 1988 earthquake was created based on the data from the 8th column. The map for the period of 1989–1990 is shown in Fig. 2, while the map for the period from 1989–1990 to 2002–2006 is based on the data from the 9th column and is presented in Fig. 3. The maps were created using the following method.

Table 2

Some of the data on the differences in elevation marks and stamps carried out in the Spitak Region from 1979 to 2016, along with vertical displacements measured within one year

Numbers and names of bench marks and stamps	Difference in elevation marks according to Tab. 1				The sum of modern vertical movements of the Earth's crust in one year during the period of alignment, *mm*			
	5–3	5–4	6–5	7–5	3/9	4/1.5	5/15	6/9
417 RP (main point)	–90.1	0.0	–147.4	–113.9	–10	0	–9.8	–12.6
050 Stamp	–	–	–151.1	–106.5	–	–	–10.1	–11.8
7505 Rock RP	–	–6.7	–150.3	–105.2	–	–4.5	–10.0	–11.7
9406 Rock RP	–	–20.4	–	–	–	–13.6	–	–
112 Ground RP	–127.5	–16.9	–152.3	–110.1	–14.2	–11.3	–10.2	–12.3
5116 Rock RP	–	–6.1	–167.0	–127.9	–	–4.1	–11.1	–14.2
187 Wall RP	–140.2	–15.5	–149.5	–106.3	–15.6	–10.3	–10.0	–11.8
113 Ground RP	–152.2	–18.2	–149.5	–129.7	–16.9	–12.1	–10.0	–14.4
M/P (Jajur) Stamp	–166.0	–33.4	–159.3	–	–18.4	–22.3	–10.6	–
M/P (Lusaghbyur) Stamp	–182.6	–53.0	–	–	–20.3	–35.3	–	–
1569 Ground RP	–183.3	–54.0	–	–	–20.4	–36.0	–	–
4424 Stamp	–	–	–	–	–	–	–	–
2002 Ground RP	–214.7	–97.2	–163.6	–118.5	–23.8	–64.8	–10.9	–13.2
153 Wall RP	–	–5.1	–61.9	–81.7	–	–3.4	–4.1	–9.1
161 Wall RP	–	–4.5	–66.7	–85.3	–	–3.0	–4.4	–9.5

Isogonal directions of elevation differences, obtained from point data for each phase, were constructed using a digital surface database represented as a square matrix grid (equal divisions of lines corresponding to the same height).

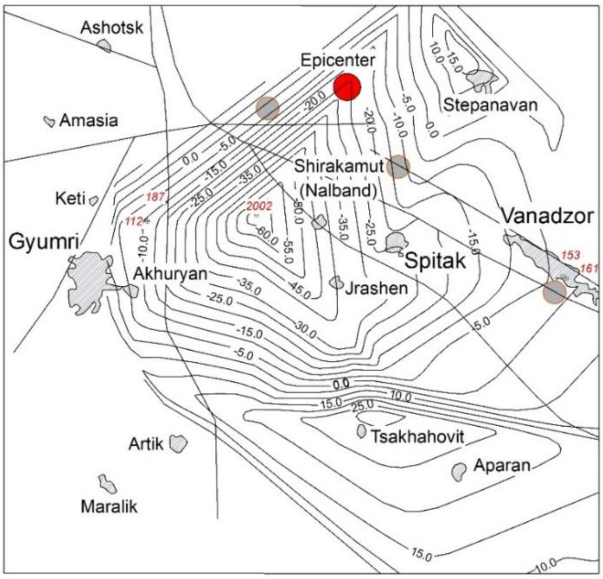

Fig. 2. Map of vertical movements of the Earth's crust in the Spitak earthquake region before and during the 1989–1990 period.

Graphic data files, obtained using the software package “GIS Map-2011 (Panorama-11)”, were modified and converted into AutoCAD DXF files.

Let’s now analyze the data presented in the two maps. Looking at the map of vertical movements of the Earth’s crust in the Spitak earthquake region (Fig. 2), it is clear that in the area extending from the epicenter and three hypocenters, including Vanadzor and the Northern part of Tsaghkahovit, as well as from Akhuryan to benchmark 2002, the Earth’s crust subsided at a rate of up to 64.8 *mm*/year. In contrast, the Earth’s crust rose by up to 15 *mm*/year in the Southern, Western, and Northwestern parts of Stepanavan, and by 25 *mm*/year from the North of Tsaghkahovit Village.

Based on these observations, we conclude that during the earthquake, the Earth’s crust rose from the hypocenter towards the Northeast (Stepanavan) and to the South (Tsaghkahovit). In contrast, in the areas extending from benchmark 2002 to the West of the Shirakamut (Nalband) community, the Earth’s crust subsided.

The matrix grid was constructed using the Average Weight Interpolation method with the software package “GIS Map-2011 (Panorama-11)”, based on the values from the provided tables.

Electronic data on the isogonal directions of the vertical movement velocities of the Earth’s crust were generated for the schemes shown in Fig. 2 (for a subsidence of 5 *mm*) and Fig. 3 (for a subsidence of 1 *mm*).

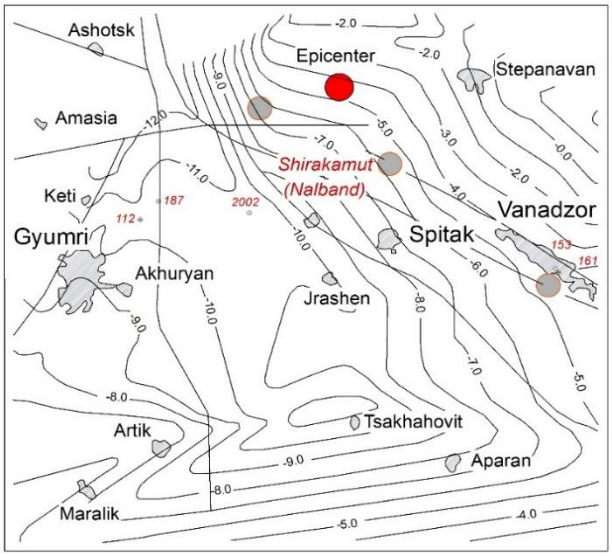

Fig. 3. Map of vertical movements of the Earth’s crust in the Spitak earthquake region from 1989–1990 to 2002–2006.

From the map of vertical movements of the Earth’s crust in the Spitak earthquake area shown in Fig. 3, it is evident that between 1989–1990 and 2002–2006, the Earth’s crust subsided at a rate of up to 12 *mm*/year across the region. This includes areas from the villages of Stepanavan, Vanadzor, and Tsaghkahovit to benchmark 2002, where the subsidence rate varied from 2 to 10 *mm*/year, and from the villages of Tsaghkahovit, Artik, Gyumri, and Keti, where the subsidence rate ranged from 8 to 12 *mm*/year.

Comparing Fig. 2 with Fig. 3, it is clear that following the 1988 earthquake, the Earth's crust in the Spitak Region subsided at a rate of 60 *mm*/year during 1989–1990. This subsidence decreased to 12 *mm*/year by the period of 2002–2006 (near the 2002 benchmark), meaning the rate of subsidence dropped by approximately five times. Additionally, the data from Tab. 2 and the graph (profile) in Fig. 4 show that the subsidence continued until 2016 at a rate of 9–12 *mm*/year. It is believed that the Earth's crust subsidence in the region is continuing at the same rate today.

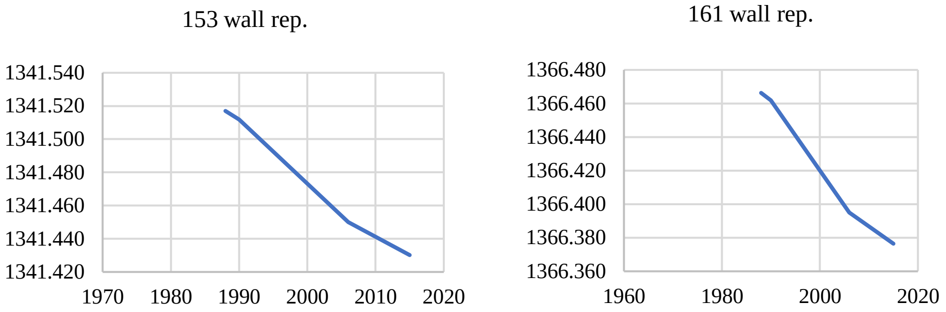

Fig. 4. Graph of vertical displacement for wall benchmarks 153 and 161 from 1989 to 2015.

Table 3

Information on the epicenters of earthquakes with a magnitude of $M \geq 2.5$ that occurred in the Amasya, Ashotsk, and Bavra Regions from January 1, 2020, to March 31, 2022

Time in the Hearth (UTC)					Geographical Latitude	Geographical Longitude	Magnitude	Depth of the Hypocenter, *km*
Year	Month	Day	*h*	*min*				
2020	1	18	1	28	41.00	44.05	3.7	10
2020	1	18	4	20	41.00	44.00	2.5	10
2020	1	19	10	15	41.02	44.03	2.6	10
2020	8	30	8	7	41.00	43.95	2.9	10
2020	9	22	22	1	41.00	43.92	2.7	10
2020	10	5	19	10	41.15	43.98	2.8	10
2021	2	7	21	23	41.13	44.03	2.6	10
2021	7	1	9	45	41.15	43.92	2.5	10
2021	7	8	6	26	41.13	44.00	2.5	10
2021	7	11	10	42	41.15	43.93	3.0	10
2021	8	6	23	36	41.15	43.92	2.8	10
2021	8	7	4	28	41.15	43.97	3.6	10
2021	8	9	3	24	41.15	43.92	2.8	10
2021	8	9	4	3	41.15	43.97	2.6	10
2021	8	10	21	17	41.15	43.98	2.6	10
2021	10	24	17	4	41.12	43.97	3.9	10
2021	10	25	12	57	41.13	43.92	2.7	10
2021	10	25	17	0	41.10	43.92	2.5	10
2021	11	5	2	28	41.13	43.97	2.6	10
2021	12	15	21	0	41.15	43.97	2.8	10
2022	2	13	18	25	41.17	43.95	5.4	10
2022	2	14	14	13	41.13	43.95	3.2	10
2022	2	14	17	3	41.15	43.93	3.0	10
2022	3	10	17	26	41.15	43.95	2.6	10
2022	3	23	17	10	41.12	43.92	3.6	10

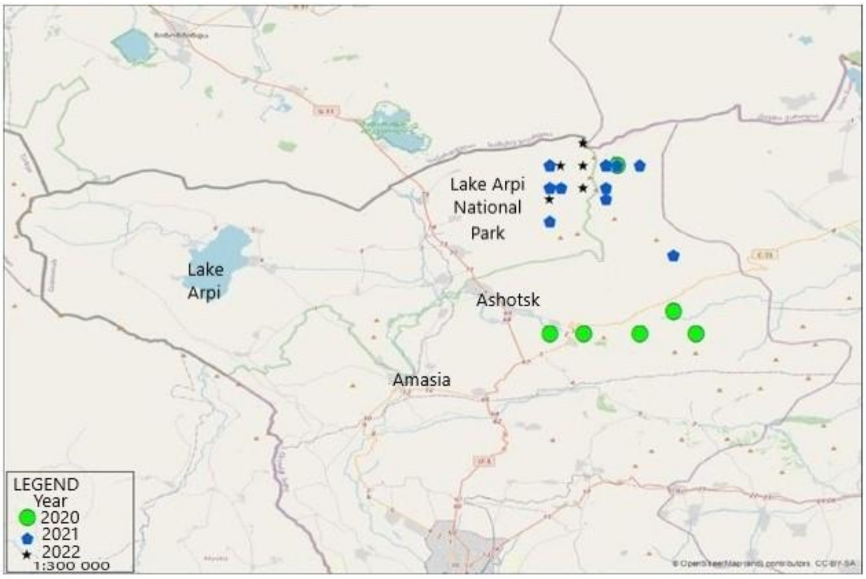

Fig. 5. Map of epicenters of earthquakes with M ≥ 2.5 that occurred in the Amasya, Ashotsk, and Bavra Regions from January 1, 2020 to March 31, 2022.

Conclusion. Let us present an example of geodetic earthquake forecasting from global practice. For the first time, the mechanics of earthquake occurrence and preparation were analyzed, and based on this, A. Pevnev's quantitative theory [10] was developed. This theory allows for the theoretical derivation of all the main experimental patterns of earthquakes.

Analysis of measurements made after earthquakes proves that the movement of geodetic points is not chaotic, but obeys a certain pattern, that is, the maximum displacement is recorded at points adjacent to the fault, and the further the points are located, the more regularly and quickly the displacement of the Earth's crust decreases. Therefore, along with geodetic monitoring, it is necessary to conduct serious scientific research and analysis of the results, which will contribute to the widespread introduction of the geodetic method of earthquake forecasting and the development of seismic geodesy in the republic.

It is known that earthquake forecasting and seismic risk assessment work is a complex and joint study in geodetic, geological, geophysical and seismological specialties. Considering that the earthquakes often occur in the region, we contacted the RA Ministry of Emergency Situations, as an authorized body of the RA government, with a request to provide information on magnitudes above 2.5 in the region during the specified period (Tab. 3). In response, we received the information presented in Fig. 2 and Fig. 5.

In addition, we proposed that, as the authorized body, a joint technical project be developed, involving relevant specialists, to conduct research at the IV stage of the Spitak geodynamic testing ground using geodetic, geophysical, and seismological methods. To proceed, appropriate adjustments would need to be made to the previously prepared technical projects, which should also incorporate the leveling work conducted in the adjacent areas of the testing ground. Based on the data obtained from this work, the causes and regularities of the dynamics of the Earth's crust, in relation to the stresses caused by energy accumulation in the Earth's crust, will be determined. Unfortunately, we have not yet received a response regarding these recommendations.

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ՍՊԻՏԱԿԻ ԵՐԿՐԱՇԱՐԺԻ ԳՈՏՈՒ ԵՐԿՐԱԿԵՂԵՎԻ ԺԱՄԱՆԱԿԱԿԻՑ ՈՒՂՂԱՁԻԳ ՇԱՐԺԵՐԻ ՄՈՆԻԹՈՐԻՆԳԻ ԱՐԴՅՈՒՆՔՆԵՐԻ ԿԻՐԱՌՈՒՄԸ ԴՐԱ ՀԵՏԱԳԱ ՈՒՍՈՒՄՆԱՍԻՐՈՒԹՅՈՒՆՆԵՐԻ ՀԱՄԱՐ

Ամփոփում

Ուսումնասիրվել են 1988 թ. Սպիտակի երկրաշարժի վերաբերյալ ԱՄՆ-ի, ԽՍՀՄ-ի, Ճապոնիայի, Հայաստանի և այլ երկրների մասնագետների հեղինակած աշխատություններից տվյալներ: Ամփոփվել, վերլուծվել և հաշվարկվել է Սպիտակի տարածաշրջանի գեոդինամիկական պոլիգոն օբյեկտում նախկինում կատարված նիվելիրացման աշխատանքների արդյունքում ստացված հենանիշերի բացարձակ բարձրությունների տարբերությունները: Այդ տվյալների հիման վրա ստեղծվել է Սպիտակի երկրաշարժի տարածաշրջանի երկրակեղևի ժամանակակից ուղղաձիգ շարժերի քարտեզը երկրաշարժից առաջ՝ 1988 թ. և հետո՝ 1989–1990 թթ. դրությամբ: Կառուցվել է նաև (1989–1990 թթ. մինչև 2002–2006 թթ. ընկած ժամանակահատվածի) երկրակեղևի ժամանակակից ուղղաձիգ շարժերի քարտեզը, որից պարզ երևում է, որ երկրակեղևի նստեցման 9–12 *մմ*/տարի արագությունը շարունակական բնույթ է կրում մինչև 2016 թ.: Ենթադրվում է, որ տարածաշրջանում նույն արագությամբ շարունակվում է երկրկակեղևի նստեցման գործունեությունը: Այդ վարկածը հաստատվում է ՀՀ արտակարգ իրավիճակների նախարարության ներկայացրած (01.01.2020–01.03.2022 ժամանակահատվածում) Ամասիա, Աշոցք և Բավրա տարածաշրջաններում տեղի ունեցած M ≥ 2,5 մագնիտուդայով երկրաշարժերի էպիկենտրոնների վերաբերյալ տվյալներն ու քարտեզը: Առաջարկվում է գեոդեզիստ, երկրաբան, գեոֆիզիկոս և սեյսմաբան մասնագետների մասնակցությամբ կազմել նախագիծ տվյալ տարածաշրջանում կրկնակի գեոդինամիկական մոնիթորինգ իրականացնելու համար: Ստացված տվյալների հիման վրա կպարզաբանվի երկրակեղևի դինամիկայի երևույթների պատճառները և դրանց օրինաչափությունն ընդերքում տեղի ունեցող լարումների փոփոխման նկատմամբ:

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ПРИМЕНЕНИЕ РЕЗУЛЬТАТОВ МОНИТОРИНГА СОВРЕМЕННЫХ ВЕРТИКАЛЬНЫХ ДВИЖЕНИЙ ЗЕМНОЙ КОРЫ РЕГИОНА СПИТАКСКОГО ЗЕМЛЕТРЯСЕНИЯ ДЛЯ ДАЛЬНЕЙШИХ ИЗУЧЕНИЙ

Резюме

Изучены данные о Спитакском землетрясении из научных работ, предоставленных специалистами США, СССР, Японии, Армении и других стран. Обобщены, проанализированы и рассчитаны различия абсолютных высот реперов, полученные в результате ранее выполненных нивелирующих работ на геодинамическом полигональном объекте Спитакского региона. На основе этих данных была создана карта современных вертикальных движений земной коры в районе Спитакского землетрясения до землетрясения 1988 г. и после землетрясения 1989–1990 гг. Также построена карта современных вертикальных движений земной коры с 1989–1990 по 2002–2006 гг., из которой хорошо видно, что скорость оседания земной коры 9–12 *мм*/год сохраняется до 2016 г. Считается, что в настоящее время в регионе продолжается проседание земной коры с такой же скоростью. Эту гипотезу подтверждают официально предоставленные МЧС РА данные и карта эпицентров землетрясений с магнитудой M≥2,5, произошедших в Амасийском, Ашоцком и Баврском районах за период 01.01.2020–01.03.2022. Рекомендуется при совместном участии специалистов-геодезистов, геологов, геофизиков и сейсмологов разработать проект проведения двойного геодинамического мониторинга в данном регионе. На основе полученных данных будут выяснены причины явлений динамики земной коры и закономерности их изменений в зависимости от напряжений.