The seismic activity analysis in the republic of Crimea

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Abstract. The seismic activity assessment on the territory of the Republic of Crimea and in adjacent areas in 2008-2018 was performed. As the main materials for the study, the literary data on seismic activity on the territory of the Republic of Crimea and in adjacent areas for the period 2008-2018 were used. The collected materials were generalized and systematized by the authors from a unified methodological position, which allowed a reliable enough estimate of the space-time division of earthquakes in the studied region. The seismic events’ activity on the territory of the Crimean-Black Sea region in the period 2008-2018 is analyzed. On average, about 95 earthquakes annually occurred in the region during this period. The results of a comparative analysis of the earthquakes distribution in the region areas are presented. It is shown that most of the seismic events were recorded in the Yalta and Kerch-Anapa regions. Quite a lot of seismic activity was also observed in Alushta. The largest number of earthquakes occurred with the energy class K =6-8 (73.5%), to the seismic events share with K =10-13 accounted for 6.3%. In 2009 and 2014 an increase in seismic events with an energy class K =5 was noted. The presence of any stable trend in the quantity and energy class of earthquakes that occurred during the studied period of time was not detected. The analysis made it possible to evaluate seismic activity in the territory of the Republic of Crimea and in adjacent areas for 2009-2018 and show the temporary changes that occurred in the number of recorded earthquakes, their distribution by the region and energy class.

Introduction

Among a wide range of dangerous natural processes that are widely developed in the territory of the Republic of Crimea, earthquakes (seismic events) stand out in terms of activity and negative impact. The Republic of Crimea (Crimean-Black Sea region), according to [8], is one of the regions of the Mediterranean belt with a relatively low level of seismic activity and a rare frequency of destructive earthquakes, although earthquakes repeatedly occurred on the peninsula during the historical time, the intensity of which reached 8-9 points. In accordance with the general seismic zoning [1], the Crimean Peninsula is assigned to the regions with a shock intensity of 8 points. On weak soils of certain regions in the republic, intensification up to 9 points is possible.

According to [12], the frequency of earthquakes in Crimea with an intensity of 6 points is approximately 50 years, 7 points - 100-200 years, 8 points - 500 years. On the southern coast of Crimea (between Yalta and Sudak), no more than once every 1000 years, 9-point concussions are possible. The earthquake that occurred on September 12, 1927 was the most devastating (up to 7-8
points on a 12-point scale) in the 20th century as a natural disaster in the Crimea. According to [2], as a result of the earthquake, 17 thousand people were left homeless in only one Yalta region (where the population was then 25-30 thousand people), 830 people were injured, 16 people died. The earthquake caused a tsunami with a height of 53 cm in Yevpatoriya, and from 13 to 23 cm in other coastal points. After 1927, the intensity of the shocks did not exceed 4-5 points.

Seismic activity is one of the main parameters characterizing the seismic regime of the territory in the republic, and its knowledge greatly facilitates the understanding of geodynamic processes occurring in the bowels of the region. In the Caucasus (including the Crimean-Black Sea region), the energy nomogram of T.G. Rautian is used to determine the energy class of earthquakes (K_r) by the distance from the seismic sensor to the earthquake source and by the testimony and properties of the seismometer. [4].

In this report, by seismic activity we mean the number of earthquakes in a given range of the energy class that occur in a certain area per unit time (month, year).

**Purpose** of the present study is an assessment of the seismic events’ activity in the Republic of Crimea and in adjacent areas for 2008-2018.

**Main goals** of the research are:
- analysis of the earthquakes’ distribution in the regions of the studied area;
- assessment of changes in the energy class of earthquakes occurred in the region for 2008-2018;
- assessment of the earthquakes’ activity in the territory for 2008-2018.

**Materials and research methods**

As the main materials for the study, literary data on the seismic activity in the Republic of Crimea and in adjacent areas for the period 2009-2018 were used. The collected materials were summarized and systematized by the authors from a unified methodological position, which made it possible to fairly reliably assess the seismic events manifestation activity in the studied region.

It is known that the completeness and accuracy of the recorded seismic events largely depends on the seismic stations network density, the sensitivity of the recording equipment and the methods used to study, which vary significantly over time. When analyzing the materials, the fact was taken into account that in different years the magnitudes of earthquakes in the study area were determined in various ways, which could affect the accuracy of the values of the seismic events that occurred. To ensure comparability and maintain continuity in estimates of the seismic activity for the results obtained in recent years with the previous years’ data, the energy classes of earthquakes were used. In this work, energy-class earthquakes were studied. K_r = 2.5-14.2.

**The obtained results and discussion**

Seismic monitoring of Crimea started in 1927 [13–15]; the seismic situation in the Crimean-Black Sea region in 2018 was controlled by a network of six stationary seismic stations and three observation points [5, 6]. Dozens of weak tremors occur in Crimea annually in almost all the regions of the republic and in the surrounding areas. So, according to [3], for the period from 1970 to 2012, 2140 earthquakes occurred on the territory of the region (on average, 50 shocks annually) with magnitude М=1.5-5.5. Foci of a significant number of earthquakes were located in the Black Sea at depths of 10 to 40 km.

From the earthquakes occurred at the end of the 20th century, it is possible to distinguish a series of seismic events recorded between the cities of Alushta and Sudak, two of which were felt by a population with an intensity of 2-5 points from June 29 to August 8, 1990. The greatest macro-seismic effect in both cases manifested itself in the area of the village of Privetnoye, located at a distance of 13-14 km from the epicenters [11].

From 2008 to 2018 in the territory of the Republic of Crimea and in adjacent areas, 947 earthquakes occurred (an average of 95 per year) with an energy class K_r=4-13 [5, 6, 8 -11, 15]. Their distribution by years is presented in Table 1. The analysis of the data presented shows an uneven distribution of the number of earthquakes occurred during the study period with two activity peaks (2009 and 2014). Since 1970, such bursts of seismic activity (more than 100 earthquakes per year)
were observed only in 1984 and 1990 [3]. By the months of the year, the number of earthquakes in the Crimean-Black Sea region varies little, although the largest number (mostly weak) is in December.

Consider the dynamics of changes in the number of earthquakes and their energy classes in the Crimean-Black Sea region for the period 2008-2018. (Table 1; Figure 1). In 2008, 61 seismic events were recorded in the Crimean-Black Sea region. Earthquakes were recorded in each of the nine regions of the territory. Most of the epicenters (26.2%) were concentrated in the Alushta region of the territory, but these were mainly weak earthquakes.

Table 1. The earthquakes’ distribution by the energy class (Kr) for 2008-2018.

| Years | Earthquake Energy Class | Total earthquakes |
|-------|-------------------------|-------------------|
|       | 4  5  6  7  8  9  10  11  12  13 |                   |
| 2008  | -  2 11 16 15 11  5  -  -  1 | 61                |
| 2009  | - 17 60 43 26  8  5  2  -  -  | 161               |
| 2010  | -  6 18 32 22 10  3  -  -  -  | 91                |
| 2011  | - 11 24 23 20  7  5  2  -  -  | 92                |
| 2012  | -  3  6 14 16 10  3  -  1  -  | 53                |
| 2013  | -  8 14 18 13  5  6  -  -  -  | 64                |
| 2014  |  2  24 27 33 18 11  3  1  -  -  | 119               |
| 2015  | -  2  4 21 16 11  2  2  -  -  | 58                |
| 2016  |  3  4  9 12 22  4  2  1  1  1  | 59                |
| 2017  | -  5 18 35 15 10  5  1  -  -  | 89                |
| 2018  |  2 12 21 30 24  3  3  5  -  -  | 100               |
| Total |  7 94 212 277 207 90 42 14  2  2 | 947               |

The highest (161 earthquake) activation of the seismic process in the region over the past 50 years was recorded in 2009. The number of the recorded earthquakes more than three times exceeded their average annual number (48 earthquakes) over the previous twenty-year observation period and almost doubled over the current decade. The earthquakes’ centers were mainly located at a depth of 10-40 km. The highest density of seismic event epicenters was recorded in the central part of the region - in the Yalta region (73.3% of all earthquakes occurred in the region). On March 3, a swarm of 22 earthquakes (with energy classes $K_r=4.6-8.4$) was observed east of Yalta $K_r=4.6-8.4$), recorded at a depth of 15-18 km. [3].

No seismic events were observed in the Crimea. The energy class of seismic events that occurred in 2009 ranged from 5 to 11. Most (80.1%) of recorded earthquakes had an energy class $K_r=6-8$. The earthquakes with $K_r=10-11$ accounted for only 4.3% of all the seismic events that occurred in the region.

In 2010, after high seismic activity in the previous year, the region experienced a decline in seismic activity - there were 91 earthquakes in the range of energy classes $K_r=5-10$. The main concentration of earthquake sources was noted in Alushta (31.9%), Sevastopol (20.9%) and Kerch-Anapa (19.8%) areas. The hypocenters of most earthquakes in the Alushta region were located at a depth of 15-16 km, and in Sevastopol - at a depth of 29-39 km. No seismic events were observed in the North-West region. In January, November and December, the largest number of earthquakes was noted, and in June, August and September - the minimum. Tangible (M=3.6) the earthquake occurred on July 24, 48 km southwest of the city of Sevastopol [14]. The majority (79.1%) of the recorded earthquakes in the region had an energy class $K_r=6-8$. The earthquakes with $K_r=10$ were accounted for only 3.3% of all seismic events that occurred in the region.

Seismic activity in 2011 did not differ from the previous year, there were 92 earthquakes with an energy class $K_r=5-11$. The maximum density of the earthquake epicenters was observed in Yalta and Alushta regions (63% of the total), a significant part of seismic events was recorded in the Kerch-Anapa region (15.2%). On September 9, a swarm of 10 earthquakes that had a shallow depth (12–22
km), was observed for 7 hours south-east of Yalta. Significant earthquake (M=4.1) occurred on March 17 in the Black Sea basin at a depth of 31 km [15]. The majority (72.8%) of the recorded earthquakes in the region had an energy class Kr=6-8. The earthquakes with Kr=10-11 constituted 7.6% of all the seismic events that occurred in the region accounted for.

Figure 1. The distribution of earthquakes occurred during 2008-2018, in the territory of the Crimean-Black Sea region

The minimum seismic activity for the studied period of time was observed in 2012, only 53 earthquakes with an energy class were recorded K_r=5-12. The largest number of earthquake epicenters (47.2% of the total) at depths up to 26 km was noted in the Kerch-Anapa region, and the strongest earthquake of the year (K_r=12.1) was recorded here, what happened on December 10 at a depth of 24 km [14]. The majority (75.5%) of the recorded earthquakes in the region had an energy class K_r=7-9. The earthquakes with K_r=10-12 constituted only 7.5% of all the seismic events occurred in the region.

In 2013, seismic activity in the region increased slightly (64 earthquakes), compared with the previous year, but still did not reach the average annual values. The central part of the region (Yalta and Alushta districts) was characterized by the highest density of earthquake epicenters (43.7% of the total), a significant number of outbreaks was noted in the Kerch-Anapa region (28.1%). The depth of most (92.2%) earthquakes did not exceed 20-25 km. A tangible earthquake occurred on October 15 in the Yalta region. With the highest intensity (4 points), it manifested itself in Yalta, the villages of Gurzuf and Partenit [11]. The energy class of seismic events that occurred in 2013 ranged from 5 to 10. Most (70.3%) of the recorded earthquakes had an energy class K_r=6-8. The earthquakes with K_r=10 constituted 9.3% of all seismic events that occurred in the region accounted for.

A significant increase in seismic activity in the region was recorded in 2014. The total number of seismic events (119) increased significantly, compared to the previous year. The central part of the region (Yalta and Alushta regions) was still characterized by the maximum density of the earthquake epicenters (54.6% of the total), a significant number of them were concentrated in the Kerch-Anapa (18.5%) and Sevastopol (13.4%) areas. The strongest earthquake of the year (M=3.9) happened on March 2 in the Yalta region. This earthquake was noted by 122 seismic stations of the world [14, 15].
The energy class of seismic events that occurred in 2014 ranged from 4 to 11. Most (70.6%) of the recorded earthquakes had an energy class $K_e = 5\text{-}7$. The earthquakes with $K_e = 10\text{-}11$ constituted 3.4% of all the seismic events in the region occurred.

In 2015, seismic activity was observed in the Crimean-Black Sea region (58 earthquakes) relative to the previous year and their average annual number. A significant mass of the earthquake epicenters (15.5% of the total) belonged to the Black Sea. The maximum epicenters’ density (27.6%) was recorded in the central part of the region (Yalta and Alushta regions), as well as in the Kerch-Anapa (24.1%) and Sevastopol (17.2%) regions. Epicenters of the two most powerful earthquakes of the year ($M=3.1$) were located in the Kerch-Anapa and Azov-Kuban regions. The depth of the earthquake sources in all areas was within 4-35 km. The earthquakes were most frequently observed in May and July [5]. The energy class of the seismic events that occurred in 2015 ranged from 5 to 11. Most (82.8%) of the recorded earthquakes had an energy class $K_e = 7\text{-}9$. The earthquakes with $K_e = 10\text{-}11$ constituted 6.9% of all the seismic events that occurred in the region.

In 2016, seismic activity in the region remained almost unchanged (relative to the previous year), 59 earthquakes with 3.0–5.1 magnitudes occurred, which turned out to be lower than their average annual number for the current ten-year period of observations. The greatest number of epicenters was located within the boundaries of the Kerch-Anapa region (27.1%) at depths of 3-35 km. Significant density of epicenters was also observed in Yalta and Sevastopol districts (42.4% of the total). A small number of earthquakes were recorded in the Black Sea (8.4%). The largest number of seismic events was recorded in May and October, and the earthquakes with maximum energy classes occurred in July and October. On May 13, a shock was recorded in the central part of the region, which manifested itself with the greatest intensity of concussions (4-5 points) in the city of Alushta [15]. The energy class of the seismic events that occurred in 2016 was $K_e = 5\text{-}13$. Most (72.9%) of the recorded earthquakes had an energy class $K_e = 6\text{-}8$. The earthquakes with $K_e = 10\text{-}13$ constituted 8.5% of all the seismic events occurred in the region.

2017 was characterized by moderate seismic activity, 89 seismic events were recorded in the region ($M=2.5\text{-}3.6$). The maximum number of earthquakes was recorded in the Kerch-Anapa region (51.7% of the total), mainly at a depth of 10 km. Three of them were palpable, including the most powerful earthquake of the year, which occurred on June 16 with magnitude ($M=3.6$) and registered by 246 stations of the world [5, 6]. Significant density of the earthquake epicenters was in Yalta (13.5%) and Sevastopol (12.3%) areas. The energy class of the seismic events that occurred in 2017 ranged from 5 to 11. Most (76.4%) of the recorded earthquakes had an energy class of $K_e = 6\text{-}8$. The earthquakes with $K_e = 10\text{-}11$ constituted 6.7% of all the seismic events that occurred in the region accounted for.

In 2018, 100 earthquakes occurred in the region. The highest concentration of earthquakes was recorded in the Yalta region (29.0% of the total) at depths of 10–36 km. A significant number of seismic events were noted in the Kerch-Anapa (19.0%), Alushta (15.0%) and Sudak - Feodosiya (14.0%) areas at the depths up to 33 km. Such significant seismic events as the earthquakes with $K_e = 10.5$ happened on September 13 southeast of Yalta (at a depth of 29 km) and with $K_e = 11.0$ happened on October 15 in the central part of the Azov Sea [6]. The energy class of the seismic events that occurred in 2018 amounted to $K_e = 4\text{-}11$. Most (75.0%) of the recorded earthquakes had $K_e = 6\text{-}8$. The earthquakes with $K_e = 10\text{-}11$ constituted 8.0% of all the seismic events that occurred in the region.

**Summary**

The systematization and analysis of various sources containing information on seismic activity in the Republic of Crimea and in adjacent areas made it possible to assess its scale and degree of activity for 2008-2018. The paper shows the ongoing temporary changes in the number of earthquakes that have occurred, their distribution over the territory regions and the energy class. On average, over the studied period, 95 earthquakes occurred annually in the region. The most seismically active were 2009 and 2014; they accounted for 29.6% of all the occurred earthquakes. The seismic year was the quietest in 2012 (5.6% of the total number of earthquakes over the studied period).
A comparative distribution analysis of the number of seismic events in the territory’s regions showed that over the studied period the largest number of them occurred in Yalta (33.3% of the total), Kerch-Anapa (22.7%) and Alushta (15.9%) regions of the Crimean-Black Sea region. The minimum number of earthquakes was recorded in the North-West region (0.9%). It should be noted that in this area seismic activity was noted only in 2008, 2009 and 2016.

The energy class (K_e) that occurred during the studied period of the seismic events ranged from 4 to 13. Most (73.5%) of the recorded earthquakes had an energy class K_e = 6-8. The earthquakes with an energy class of K_e = 10-13 accounted for only 6.3% of all the seismic events that occurred in the region.

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