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Can Induced Seismicity Decrease Under a Long Strong Anthropogenic Excitation?

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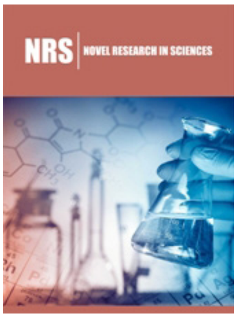

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Abstract

Strong induced seismicity can result from various strong man-made impact on the Earth's crust. In the absence of anti-seismic measures in construction and on soft soils, even moderate earthquakes can produce significant damage. The widely used "semaphore" technique aimed at reducing the risk of induced seismicity fails to incorporate possible generation of induced earthquakes at unusually great distances from places of human impact. Thus, the danger of induced seismicity may be underestimated. On the other hand, there are examples that induced seismicity may decrease under prolonged strong technogenic action. Based on the analysis of the seismic regime in two areas of strong induced seismicity (the Groningen gas field and the shale oil production area in Oklahoma), it was shown that the hazard of induced seismicity decreased under strong long-term technogenic action. A similar conclusion was obtained for Oklahoma from the analysis of the noise in GPS observations. Note that this monitoring method is free of the delay effect, which is almost inevitable in monitoring based on seismicity data. The decrease in induced seismicity can be due to relaxation of the initial tectonic stresses under a strong and long-term anthropogenic impact.

Key words: Anti-seismic; Induced seismicity; Anthropogenic impact; Groningen gas

Introduction

The problem of induced seismicity is not new. Examples of the occurrence of seismicity in previously aseismic areas after the filling of reservoirs, with intensive oil and gas production, water and gas injection into wells, are quite numerous [1-3]. Induced seismicity does not occur in all cases of intense technogenic impact, and the origin of induced seismicity can be partly due to better reporting of small earthquakes [4]. However, in numerous cases, the occurrence of the induced seismicity is quite reliably identified. Such, for example, are the areas of shale hydrocarbon production in North America [5,6], the region of the giant Groningen gas field in the Netherlands [7], the Koina and Varna reservoirs in India [1], the Enguri HPP region in Georgia [8], and others. The number of perceptible earthquakes increased hundredfold in some of these areas. In some cases, induced earthquakes have caused significant damage. Such damage occurring even from relatively small earthquakes can be explained by the lack of anti-seismic measures, sometimes supplemented, as in the case of the Groningen gas field, by soft soils, on which seismic effects are especially strong. After one of such moderate but hazardous earthquake occurring near the Groningen gas field (2018, M=3.4), the Government of the Netherlands decided to sharply reduce gas production and completely stop the gas production by 2030 [https://en.wikipedia.org/wiki/Groningen_gas_field]. In order to reduce the risk of induced seismicity, restrictions are usually introduced on the intensity of technogenic activities. In the case of hydrocarbon production, it is natural to associate the threat of induced seismicity with an increase in the number and maximum magnitude of earthquakes that occur in the vicinity of a given well. It is this approach that is used in the "semaphore" method [5,6,9], which is being widely used to minimize damage from induced seismicity. According to a typical version of this methodology, if an earthquake with a magnitude of M≥2.0 occurs within 5km of the well, then a "yellow light turns on", and a plan is implemented to more carefully monitor the situation and reduce the anthropogenic load. If, later on, an earthquake with a magnitude M≥4.0 occurs in the same area, then the "red light turns on", i.e., the well operation stops and can only be resumed with special permission.

However, the "semaphore" technique is not quite effective. Some presumably induced earthquakes occur farther from the wells (or from reservoirs), and with a greater time delay than is assumed by the "semaphore" technique; and such earthquakes can include quite strong ones [10-12]. It follows from the foregoing that the threat of induced seismicity may turn out to be noticeably higher than assumed in the "semaphore" method. On the other hand, according to long-term monitoring of induced seismicity in the area of the Enguri HPP, [8] noted that after a period of growth, induced seismicity decreased and approached the initial level. Below, we discuss the tendency for a decrease in induced seismicity with continued strong technogenic action and methods for detecting this effect. Let us consider the trend of reducing the risk of induced seismicity in the process of continuing strong technogenic impact taking the induced seismicity in the area of the Groningen gas field as an example, and according to data for the area of intensive production of shale hydrocarbons, Oklahoma, USA. In the second case, we will also discuss the seismic hazard monitoring method based on the analysis of GPS observation noise.

Declining Trend of Seismic Hazard During Long-Term Strong Anthropogenic Load; Groningen Gas Field

Consider the case of the Groningen giant gas field. The data on the volumes of gas extraction, the earthquake rate, the earthquake recurrence plot, and the trend of increasing b-value over time are shown in Figures 1a-1d. The seismicity regime was estimated from data on reliably recorded earthquakes with a magnitude M>1.3. As can be seen from the figure, a strong increase in induced seismicity began approximately 30 years after the start of intensive gas extraction. In 2010-2015 the increase in the number of earthquakes peaked. Due to the spread of weak water-saturated soils in the area, even rather small events had caused noticeable damage, which imposed restrictions on output. In 2018, there was another earthquake that caused damage, and it was decided to further limit gas production and to completely close the gas production no later than 2030. The values of earthquake numbers in month for the groups of 40 subsequent events with step 20 events are presented in Figure 1b. The decrease in production volumes was accompanied by the desired rapid decrease in the rate of earthquakes (Figures 1a & 1b), As can be seen in Figure 1c, the slope of the earthquake recurrence graph in the interval M>2.7 begins to increase, which indicates a decrease in proportion of stronger events, that is unusual for the case of tectonic seismicity. Besides, the entire time interval of development of strong induced seismicity was accompanied by the trend of increasing b-values (Figure 1d), which corresponds to a trend of a decrease in the proportion of stronger events, and, accordingly, a decrease in seismic hazard over time. To calculate the current b-values the maximum likelihood method applied to successive sets of 60 earthquakes was used. At the turn of 2015, a decrease in seismic hazard due to an increase in b-values was supplemented by a sharp decrease in the rate of events. A noticeable decrease in seismic hazard estimates for the Groningen field area is noted in [13]. But the nature of this decrease is not clear; the decrease in the rate of earthquakes might result from the limitation of production volumes.

Declining trend of seismic hazard during long-term strong anthropogenic load; case of the shale hydrocarbon production, Oklahoma, USA

As another example, also well supported by statistical data, consider the region of intensive shale hydrocarbon production, Oklahoma, USA. The seismic regime of this area was analyzed in [6,9,12], where the connection between seismicity and the injection regime was shown and certain differences in the parameters of induced and natural seismicity were detected. The seismic data used below are taken from https://earthquake.usgs.gov/earthquakes/search/; the well positions and injection regime are taken from the Oklahoma Corporation Commission website, http://www.occeweb.com/og/ogdatafiles2.htm. The crude oil production values are taken from https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=mcrfpok1&f=m. The crude oil production (V/month) and earthquakes rates (N/day) in Oklahoma, and the earthquake magnitudes are presented at Figure 2a. It can be seen that the prominent seismicity had begun with a large delay after the beginning of the oil production, and that the earthquake rate sharply decreased after 2017 despite the continuation of oil active production. Figure 2b shows earthquake-size frequency distribution. A quite typical (for tectonic earthquakes) slope of earthquake-size frequency distribution is observed in the magnitude range up to about M=3.4 and, possibly, for relatively rare events with magnitude M>4.5. In the middle magnitude range (as was previously shown in [12]), the b-value becomes anomalously large, indicating a decrease in the probability of occurring of stronger events. In [12], it was also shown that the slope of the earthquake-size recurrence plot for 3.3<M<4.5 events increase with an increase in local injection values, reaching anomalous values that are uncommon for naturally occurring tectonic earthquakes. In this paper it was also noted that four strongest earthquakes (asterisks, Figure 2a) had occurred in areas of moderate size technogenic load. Thus, for the area of intensive production of shale hydrocarbons in Oklahoma, a clearly expressed trend of a decrease in earthquake number and an increase in the slope of the recurrence graph; accordingly, a decrease in seismic hazard, despite of the prolongation of the strong technogenic load has been identified.

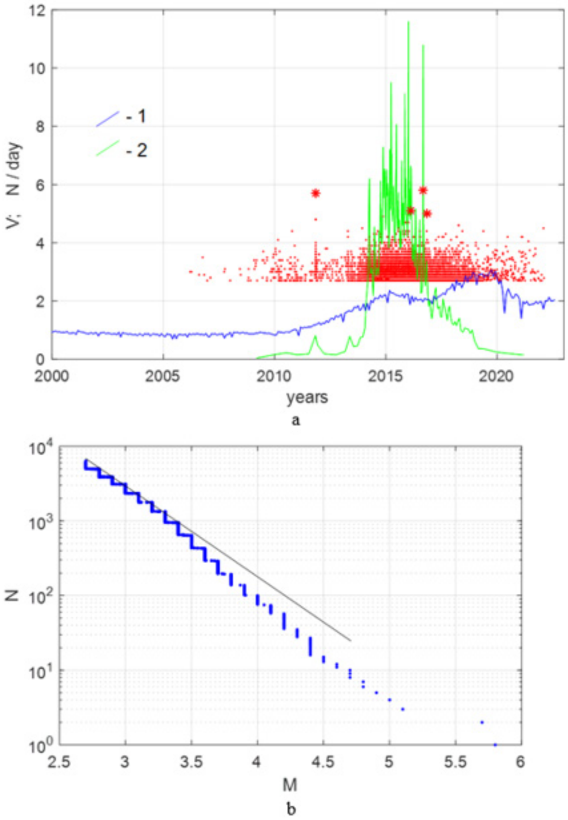

Figure 2: Induced seismicity in the area of active production of shale hydrocarbons (Oklahoma, USA); the rates of oil production (1) and earthquakes (2), and earthquake magnitudes, red points and stars (a); earthquake-size recurrence plot, the line shows the slope for smaller (M≤3.3) earthquakes (b).

Method for Monitoring the Hazard of Induced Seismicity Based on an Analysis of the Noise Field in GPS Measurements

The "semaphore" method discussed above has a further disadvantage in that its performance usually involves a delay or a large margin of safety. This is due to the fact that the method is based on seismicity data, hence the decision depends on the recording of relatively rare larger earthquakes. In order not to miss the increase in hazard of stronger earthquake, the critical magnitude in "semaphore" method is usually greatly underestimated. This shortcoming would apparently be missing in the seismic hazard assessment method based on the analysis of the current noise in the system under study [14,15]. The change in the noise spectrum characterizes changes in the stability of a given system, including geological ones. The growth of system instability corresponds to an increase in the proportion of longer-period oscillations. Previously, the Tohoku mega-earthquake was successfully predicted by this method [14]. The relative contribution of the long- and short-period components of the spectrum is usually characterized by the slope of the spectrum in log-log coordinates (amplitudes of the spectrum and period); an increase in the slope of the spectrum β corresponds to an increase in the contribution of the long-period component and a decrease in the stability of the system. To test the feasibility of implementing such an approach for the analysis of induced seismicity, data on the magnitude of injections during the production of shale oil and the noise of GPS observations in Oklahoma were used. Ground displacement data based on GPS observations were taken from the Nevada Geodetic Laboratory website: http://geodesy.unr.edu/NGLStationPages/RapidStationList. The number of GPS stations suitable for analysis has been available in the area since 2017, so we will do this analysis for 2017-2021.

The slope values of the spectrum of GPS displacements are subject to strong seasonal variation; the slope β is at the maximum in the warm season and the minimum in winter. This feature can be explained by the freezing of the soil in winter and the saturation of the soil with water in the warm season. As is known, the deformability of water-saturated soils is much higher than that of frozen ones. Accordingly, the effective strength (stability) of the geologic environment is higher in the cold season. This interpretation is strongly supported by the persistently opposite directions of the seasonal course in the southern and northern hemispheres. As a result of the study of relationships between the spectral slopes β of the GPS ground tremor, and fluid injection volumes V in Oklahoma a fairly strong spatial correlation R between these parameters was found to be typical. Both positive and negative correlations are observed. In the area of smaller injections, an increase in the slope of the GPS tremor spectrum corresponds to an increase in injection. On the contrary, at large injection volumes, negative correlations of injection V values with the spectral slope values β dominate, which is interpreted as a decrease in the contribution of low frequencies with an increase in injection values and an increase in the stability of the geosystem under study. These two trends were observed for the entire time interval of 2017-2021. As an example, Figure 3 shows the injection V values and the correlation coefficients R of the injection values and spectrum slopes for 2021.

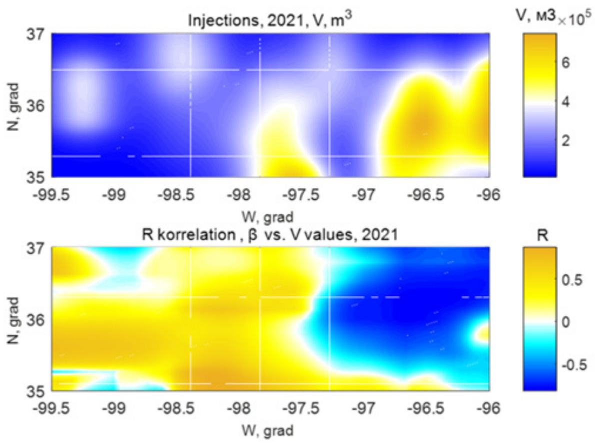

Figure 3: Comparison of the injection V values (upper panel) and the correlation coefficient R of the slope of the spectrum of GPS displacements β and the injection values, V (lower).

Discussion

Based on the analysis of data for the areas of induced seismicity in the Groningen (Netherlands) giant gas field and intensive development of shale hydrocarbon (Oklahoma, USA) production, the tendency of an anomalous increase in the slope of the earthquake recurrence plot with an increase in technogenic loads is shown. This effect, which corresponds to a decrease in the proportion of stronger seismic events, can be interpreted as an indication of the trend of decreasing hazard due to induced seismicity. Besides, for the case of Oklahoma the earthquake rate values also decreased essentially. Physically, this effect can be explained by the relaxation of the initial tectonic stresses under strong and long-term technogenic loads.

Methods for monitoring the hazard of induced seismicity based on the analysis of seismicity statistics are potentially fraught with either delays or significant margins of safety and hazard overestimation. Such defects can be eliminated by the method based on the analysis of the noise component of GPS displacements. This method was implemented on the basis of injection values and GPS monitoring data for the Oklahoma induced seismicity area for the period 2017-2021. A typical high correlation of spatial fields of injection volumes V and values of the slope β of the tremor spectrum of GPS displacements (in log-log coordinates: amplitude, period) was detected. An increase in the slope of the spectrum is usually interpreted as an indication of an increase in the relative contribution of the long-period components and a decrease in the stability of this system. Opposite correlation signs are observed: negative in areas of high technogenic load and positive in areas of low injection values. Thus, the results of analysis of the GPS displacement noise field are in good agreement with the results of the seismicity analysis.

Conclusion

Our analysis of statistically representative data in two areas of strong triggered seismicity (the Groningen giant gas field in the Netherlands and the shale oil production area, Oklahoma, USA) has revealed the trend of the risk of triggered seismicity being reduced with continued high anthropogenic loads. Earlier, such a trend was noted for the Enguri HPP area, Georgia [8]. A similar result - a decrease in the instability of the geophysical medium under continued strong anthropogenic loads - was obtained from the analysis of noise in GPS observations in Oklahoma. The tendency of induced seismicity being reduced under prolonged and strong technogenic excitation can be explained by the removal of tectonic stresses that give rise to strong earthquakes. The existence of a trend towards a decrease in seismic hazard during a long-term strong technogenic excitation, if confirmed by further studies, can have important practical applications. The results of the GPS noise analysis support the effectiveness of this approach for seismic hazard monitoring. Note that this monitoring method can be free of the delay effect, which is practically inevitable when seismic activity is monitored [16].

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