Introduction

The hydrocarbon exploration process may induce seismic activity. This leads to production-related geohazards in the area of the reservoir. The result of the induced seismicity is subsidence and horizontal shifts of the rock mass, which can lead to casing breaks, damage to buildings, communications, pipelines, and other infrastructure facilities at the field. All this causes significant production costs to increase. In addition to financial costs, possible environmental damage must be noted. It can be flooding of the field and nearby territories, landslide phenomena; environmental pollution associated with a possible spill of oil products, etc.

One of the methods of remote control of the local geodynamics is seismic monitoring (Kendall et al., 2019; Loginov et al., 2015). It allows us to determine the parameters of seismic events within the field from the seismic records, as well as to identify areas of increased seismicity and investigate the dynamics of their behavior. However, a high level of industrial noise makes it difficult (or in some cases impossible) to detect signals from weak local earthquakes. This is especially true for surface observation systems.

One way to reduce industrial seismic noise is to deepen the seismometers and to use so-called buried arrays. For example, Richards and Aki (1980) shows that placing of seismometer at the depth of 100 meters reduces the noise level by about 10 times. In theory, this increases the signal-to-noise ratio by the same amount. However, there are alternative points of view on this problem. Eisner et al. (2011) shows that the increased depth of the seismometers will negatively affect the amplitude of the signal since it doubles when reflected from the free surface.

This paper presents the results of experimental work on deepening seismometers of the surface local seismological network in the oilfield, proving its effectiveness. It was shown that after deepening the seismometers, the average network sensitivity increased by 0.92 (ML), and the number of recorded weak earthquakes increased by 10 times. This result agrees very well with the theoretical data.

Acquisition system and experimental results

The surface seismological network consisted of six seismic stations. The distance between neighboring stations was 5-10 kilometers. Verification of the results was carried out according to the catalog of seismic events recorded by the downhole microseismic monitoring system at a depth of more than 3000 m, which is of higher sensitivity, at least in the neighboring area. The monitoring well is placed almost in the center of surface acquisition.

Due to the different geological structure of the media, the optimal depth interval for seismometers installation is different for each place. We chose the optimal depth interval with the use of the results of field tests. In our case, the optimal depth was 70-90 meters.

Locally the area of the field is characterized by relatively weak seismicity: none of the local seismic events are included in the regional seismological catalogs. In addition, over the past 10 years, the surface network recorded about 5 to 7 local earthquakes per year. For a more detailed study of the local dynamic processes, it was necessary to increase the sensitivity of the network. Figure 1 shows the records of a local earthquake with magnitude 1 (ML), produced simultaneously by surface and buried networks. For the visualization, the records of each channel are normalized.

One can see from the figure, the signal from the earthquake can be detected from the records of all stations in the shallow network, while on the surface network records, the signal is clearly detected only in the records of one station, which is closest to the hypocenter. All other records of the surface network are subject to seismic noise of high intensity.

Let us compare the level of seismic noise for surface and shallow networks. To do this, we filter the recordings with a band-pass filter with a pass-band from 1 to 20 Hz. The noise reduction with the
increase of seismometer depth for different stations varies from 2.5 to 40 times. This big difference is probably due to the heterogeneous distribution of seismic-noise sources at the surface. In particular, the suppression of noise from local objects in proximity to seismic stations is much more effective than from large industrial facilities located on the territory of the field. In addition, it was noted that the noise level at some points after the deepening of the seismometers varies significantly during working and non-working hours, which again confirms the conclusions about local noise sources. Nevertheless, the average noise reduction for the entire network was 11 times, which is very well consistent with theoretical data (Richards and Aki, 1980).

Figure 2 shows the catalog of microseismic-event magnitudes (Bormann et al., 2002; Yaskevich et al., 2018) recorded by the downhole microseismic monitoring system. The events detected also by the surface network are shown in green. The criteria of detection were the possibility to determine the arrival times for P- and S-waves in the seismic records of three or more stations at the surface (or at the shallow stations).
Figure 2 Seismic events catalog obtained from the downhole microseismic system before and after seismological network seismometers deepening. Red points – events that detect on seismological data. The green line indicates the representativity of the earthquake catalog of the shallow network.

The figure 2 demonstrates that, as a result of the increased depth of the seismometers, the seismic network began to detect without gaps local earthquakes with magnitudes over 0.65 (mt). However, the existing catalog does not provide an opportunity to give an accurate assessment of representativity before deepening the network. This is due to the small number of events with a magnitude greater than 1. We can only say that the surface network did not register two events with a magnitude of 1.2 (mt) during one year before deepening.

To evaluate the increase in network sensitivity induced by the increased depth of seismometers, we will use the level of noise at each seismic station, we calculate the sensitivity of the entire network before and after the placement of seismometers into shallow boreholes. After calculating the difference and averaging the result, we obtain the average value of the increase in the sensitivity of the network with deepening. To calculate the local magnitude depending on the hypocentral distance, we use the expression from (Hutton and Boore, 1987). All calculations were performed based on experimentally obtained values of the seismic noise level. As a result, it turned out that the average value of the increase in network sensitivity for the entire field territory was 0.9 (ML).

Conclusions and discussion

A joint analysis of downhole microseismic and seismological monitoring catalogs shows that the deepening of seismometers made it possible to record all local earthquakes with magnitudes of 0.65 (mt) and higher. This result corresponds to an increase in sensitivity by magnitude ML by 0.9, and an increase in the number of recorded local earthquakes by about 10 times. This is in good agreement with (Richards and Aki, 1980).

The result is may be applied to the fields characterized by induced seismicity and high level of industrial noises because such an increase in the number of recorded weak earthquakes can have a significant impact on the results of the seismicity analysis.
To make the placement of seismometers into shallow boreholes economically feasible, in other projects we use downhole tools composed of modern low-frequency geophones with increased sensitivity. Although their declared frequency range starts from 4.5 Hz, it is possible to increase frequency band up to 0.5 – 1 Hz with the using methods of frequency correction of their records (Havskov and Alguacil, 2004; Maxwell and Lansley, 2011; Dergach et al., 2019). The use of relatively cheap geophones also lessens the costs of cementing of wells required when installing expensive broadband seismometers. Due to the simplicity of their design, geophones are considered as reliable sensors that retain factory metrological characteristics for many years. Because of this, in the case of a large number of observation points, it is cheaper to drill a new well and use a new device than to provide conditions for the maintainability of equipment at all points.

The placement of seismometers in shallow boreholes is not the only effective way to increase the sensitivity of the network. An additional increase in the sensitivity will be provided by the enhancement of the number of stations. We calculated that doubling the number of monitoring points at the testing area increases the sensitivity of the network by about 2 times. In the case of this field, the number of recorded events would increase by 5 times.

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References


