Hydro-geodynamic and geodynamic processes in the platform territories of hydrocarbon production

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Abstract. This paper presents hydro-geodynamics and geodynamics of the Southern Cis-Urals region. It focuses on geodynamics and seismicity induced by hydrocarbon production by summarizing the published case studies. Natural and man-made changes in bowels of the Earth are usually accompanied by tectonic movements and deformations of earth's surface, which is one of the important factors determining environmental changes and requiring mandatory consideration in engineering-geological surveys and exploitation of deposits. The influence of anthropogenic factors on the geodynamic state of platform areas is considered by the example of Orenburg oil and gas condensate field. The analysis and comparison seismic events with geologic and tectonic structure, natural and technologically impaired hydrodynamics.

1. Introduction

Intensive oil and gas production in large oil and gas bearing regions (Republic of Tatarstan, Bashkortostan, Orenburg Region, etc.) violated the natural environment [1–4], significantly restructured hydro-gas-dynamic and geodynamic processes in the earth's crust in the depth to ten or more thousand square kilometers. Conditions for emergence of a number of environmental problems have arisen and they have significant impact on the development of nature and the quality of life of population in the region.

In large oil and gas bearing regions, dangerous techno-natural processes are developing in the earth's crust upper layer. The seismic activity increases in it, the hydro-geodynamic regime is disturbed, and subsidence of the earth's surface is observed [5–6]. The results of study of hydro-gas-dynamic, geodynamic and geophysical processes and the dynamics of water systems in the developed hydrocarbon fields are based on identification the reasons for the increase in seismic activity during hydrocarbon production. The decrease in pressure in the aquatic system that combines the reservoir waters and the surrounding aquifers of the hydrocarbon deposits during the extraction of hydrocarbons and its increase during the injection of water and other mixtures, violate the natural geodynamic state of the host rocks, destabilize the dynamic water and the solid part of the earth's crust equilibrium [7].

The role of the water factor in natural and man-made seismic events is different. In natural earthquakes, caused mainly by geodynamic processes in the bowels of the Earth, occurring much deeper than the possible penetration of the hydrosphere, ground waters of the upper crust often act only as their precursors. During the preparation of natural earthquakes, primary insignificant displacements of the crustal structures occur, under the influence of which the water level in wells and boreholes rises or falls usually by a small amount. Their level may also decrease or...
increase after earthquakes [1]. Thus in the case of natural earthquakes, changes in the dynamics of groundwater are not the cause, but the consequence of geodynamic processes in the earth's crust.

According to our research data [8], 20-30 seismic events a year with a magnitude of ML = 1-2 or more are recorded on the hydrocarbon fields in the Southern Cis-Urals ten times more frequent than outside the fields.

2. Materials and methods
By the example of Southern Cis-Ural, located in the southeast of the East European Platform, we have established that hydrocarbon extraction has a major effect on the upper crust through the water system [8].

For 45 years of operation of the Orenburg oil and gas condensate field (OOGCF), located on the area over 2000 km², more than 1.2 trillion m³ of raw hydrocarbons and about 30 million m³ of associated formation water have been extracted. As a result, the pressure in the productive stratum decreased from 20.6 MPa to 8.0 MPa and lower. The rapid drop of reservoir pressure creates conditions for flooding the productive strata and complicates the technology of gas production. The inflow of the formation waters to the gas reservoir comes both laterally and vertically from the bottom and from the top. Since the beginning of the OOGCF operation, more than 39 million m³ of water-methanol mixture (WMM) and industrial effluents have been pumped through injection wells to the gas deposits. Estimated stabilizing effects of the WMM and industrial effluent injection are hardly really affect geodynamic processes in the upper crust layers due to their relatively small volume in comparison with the total hydrocarbon volumes and associated water extracted from the depths.

Currently according to our research and data obtained from LLS “Gazprom Dobycha Orenburg”, a hydrodynamic funnel (negative hydrodynamic zone) with a capacity of 11–12 MPa in the OOGCF water pressure system has been formed and its influence zone extends for 20–30 km or more to the north and south from the gas content circuit. The boundary of the hydro-geodynamic effect of gas production on the water-pressure system with the existing control system can be determined only presumably (Fig. 1). According to the investigations of Pinneker, Ye.V. et al. [9-11], the degree of mobility of groundwater is mainly caused by the reservoir properties of rocks and geological and structural features (the presence of faults, the nature of aquifers, etc.).

The volume of the hydrodynamic funnel is determined by the volume of extracted hydrocarbons and associated water minus the water pumped into the depths and infiltrated into the reservoir from the surrounding aquifers, taking into account the porosity and fracture of rocks. Estimation of the amount of water introduced into the gas condensate reservoir can be made using the formula V N Schelkacheva [12]:

\[ V = \beta \cdot V_b \cdot \Delta P, \]

where \( V \) is the volume of formation water introduced into the reservoir, thousand m³, \( \beta \) is the coefficient of elasticity of the reservoir, \( 2 \cdot 10^{-4} \text{MPa}^{-1} \) is taken for OOGCF, \( V_b \) is the volume of water in the hydrodynamic funnel, thousand m³, \( \Delta P \) is the decrease in reservoir pressure in water pressure system. The average decrease in reservoir pressure \( \Delta P \) for 30 years from the start of hydrocarbon production till 01/01/2004 was 3.4 MPa.

The distribution of the hydrodynamic funnel beyond the OOGCF occurs due to a decrease in its capacity within the boundaries of the field without a significant change in its total volume. Valuation calculations by the formula (1) showed that by 2004 the volume of water in the water-pressure system in the area of anthropogenic impact \( V_b = 120,000 \text{ million m}^3 \), and the volume of water introduced into the reservoir is \( V = 81.6 \text{ million m}^3 \). On January 1, 2014, with an average decrease in reservoir pressure by 4.2 MPa from the start of field development, the volume of water that had infiltrated into the reservoir increased to 105 million m³. The volume of gas extracted from the pore fissure space reservoir under pressure of 16 MPa and a temperature of 32 °C is estimated to be about 4.9 billion m³. Thus, the amount of formation water introduced into the reservoir on January 1, 2014 is only 2.1% of the volume of extracted gas from reservoir.
Due to the vertical and lateral heterogeneity of the filtration-capacitive properties of rocks, the field is characterized by instability of the pressure reduction rate, changes in the levels of formation water and the formation of watering zones, both in terms of area and section, and of time. The development of the hydrodynamic funnel and the watering of the deposit are interrelated.

**Figure 1.** Pressure distribution in reservoir waters of OOGCF, watering zone containing ever-flooded wells, and seismic activity of the OOGCF region on the 01.01.2017 (based on VOLGOURALNIPIgaz LLC and authors' data)

1-3 - seismic events (energy class: 1- 3.5-5.0; 2- 5.1-7.5; 3- 7.6-11), 4 - isobars of formation pressure, MPa, 5 - structure-forming faults, 6 - direction of flow of formation water in water pressure system, 7 - well watering zones.

In the presence in the oil and gas-bearing region of several closely located oil and gas fields under development, the zones of technologically low reservoir pressure are combined into a general district disturbance of the natural hydrodynamically balanced system of underground waters, and stresses are formed in the solid part of the Earth's crust.
With a pressure decrease in the aquatic system of hydrocarbon fields, there is less opposition to lithostatic subsidence of upstream rocks and swelling of a low-permeability base of a field under the action of a retained high pressure of deeper laying aquifers.

It indicates the dominant role of the water system in the formation of the stress-strain state, geodynamic and seismic activity of the earth's crust in the hydrocarbon production fields. The highest seismic activity is observed in the areas with the greatest drop of reservoir pressure and in the areas of faults along which it extends beyond the fields territory.

3. Results and discussion

The study of regularities of the influence of the dynamics of the water system of the hydrocarbon fields’ area on seismic and geodynamic activity was carried out in 2010-2017 on the basis of the data from the network of seismic stations built by us in the Southern Cis-Urals. Within 5 km from the faults, the density of events is 0.00263 units / km² per year. In the strip at a distance of 5 to 10 km from the fault it decreases by 23% to 0.00203 units/km² per year. On the distance 10 km from the fault, the number of events decreases 2–3 times in comparison with their number in zones less than 5 km from them and is about the average seismic event density in the entire oil and gas bearing territory of Southern Cis-Ural region controlled by the network of seismic stations, and it is equal to 0.0008 units / km² per year.

In the fault zone, which is 1% of the territory of the Southern Cis-Urals under seismic monitoring, about 30% of all events take place. Outside the developed hydrocarbon fields at a distance of more than 15 km, the seismic energy released is less than 10⁴ J / km² per year and has no significant impact on the total seismic activity in the region.

Per thousand square kilometers in a planetary tectonic fracture zone, about 9 events are recorded a year with an average seismic energy of 7.03 · 10⁶ J / km² per year, and in some areas up to 10⁹ J / km² per year. In the entire territory controlled by the seismic network per thousand square kilometers, 2-3 events with seismic energy of up to 1.14 · 10⁶ J / km² a year are recorded. This is 7 times less than its average release in the fault zone. Consequently, it is possible to hypothesize that higher seismic activity is formed in the fault zones.

The estimation of the distance distribution law relevance of the recorded seismic events to the fault [8] let us claim that the connection of seismic events with fault zones is statistically proved and that most of the events occur in fault zones. This allows us to specify the geological structure, in particular the position of fault structures and nodes of the stress-strain state of the geological environment, as well as to identify areas with disturbed hydrodynamic processes.

Seismic activity distribution analysis of the Southern Cis-Urals region bowels shows gravitation of seismic events to the developed hydrocarbon fields.

It has been revealed [13, 14] that in the oil and gas fields contours the density of events averages 0.0024 units / km² per year. In the area limited to 10 km from the field, it decreases by 44% to 0.0013 units / km² per year. On the distance 10 km from deposits, the number of events decreases 3-4 times compared to their number in the deposits contour and has a density of 0.0008 units / km² per year. Consequently, in the fields contour and 10 km around them, occupying 1.6% of the total territory controlled by seismic monitoring of the Southern Cis-Urals, more than 35% of all recorded events take place. A number of hydrocarbon fields in the Southern Cis-Urals are near fracture and there are fault zones on their territory crossing the depression funnels. There are three large faults on the territory of OOGCF, and seismic events are recorded in the area of their intersection with technogenic disturbances.

In the area of OOGCF, most of the released energy and seismic events occur in the area of the hydrodynamic funnel. Within its limits, the density of the registered events is 5–6 times greater, and the released seismic energy is 10 times more than on the average in the Southern Cis-Urals.

Territories remote from the zones of technogenic disturbances (central and eastern parts of the Cis-Ural foredeep, southeast of the Caspian syncline, etc.) with undisturbed groundwater dynamics have much lower frequency of seismic events and they are probably caused by natural tectonic processes.
4. Conclusion
1. In the Southern Cis-Urals the reduction in reservoir pressure reaches 12 MPa or more when oil and gas fields are intensively used. As a result, the direction and velocities of groundwater flow, as well as filtration-volume properties of the geological environment, its geodynamic equilibrium, and man-made and technogenic-natural earthquakes intensify.
2. A multiple increase of the earth's crust seismic activity in the areas of developed hydrocarbon deposits has been estimated. Its maximum activity is spatially confined to hydrodynamic funnels, concentrating in the zones of highest formation pressure drop and tectonic disturbances.
3. Identification of geological structure features of a sedimentary cover and the top part of a crystal basis and their water systems allows to model and predict consequences of developing technogenic-natural geodynamic processes at hydrocarbons production.
4. Monitoring of natural and anthropogenic seismicity makes it possible to clarify the geological structure of the upper part of the Earth's crust, including the position of fault structures and to identify areas of anthropogenic pressure disturbances in the groundwater system.

References
[1] Kissin I G 1982 Zemletrjasenija i podzemnye vody [Earthquakes and groundwater] M: Nauka p 176
[2] Adushkin V V, Rodionov V N, Turuntaev S B and Yudin A E 2000 Seismichnost mestorogdeniy uglevodorodov [Seismicity in the oil field] Neftegazovoe obozrenie 12 2 pp 2–17
[3] Hubbert M K and Rubey W W 1959 Role of fluid pressure in mechanics of overtrust faulting Geological Society of America Bulletin 70 pp 115–166
[4] Pennington W D, Davis S D, Carl-son S M, Dupree J and Ewing T E 1986 Evolution of seismic barriers and asperities caused by the depressuring of fault planes in oil and gas of South Texas Bulletin of the Seismological Society of America 76 pp 939–948
[5] Gibowicz S J and Lasocki S 2001 Seismicity induced by mining: Ten years later Adv Geophys 44 pp 39–180
[6] Baker M R, Doser D I and Luo M 1991 Geologic and oil field controls on earthquakes in the War-Wink Field, Delaware Basin Bulletin - West Texas Geol. Soc. 31 1 pp 5–12
[7] Suckale J 2009 Induced seismicity in hydrocarbon fields Adv Geophys 51 pp 55–106
[8] Tsviak A V, Nesterenko M Y and Nesterenko A M 2018 Modern Technogenic Geodynamics of Platform Territories by Example of Southern Cis-Urals Proceedings of the International Symposium “Engineering and Earth Sciences: Applied and Fundamental Research
[9] Pinneker E V 1977 Problemy regional’noy gidrogeologii (Zakonomernosti pasprostranenia i formirovaniya podzemnyh vod) [Problems of regional hydrogeology (Regularities of distribution and formation of groundwater)] M: Nauka p 196
[10] Van Eij, R.M.H.E., Mulders, F.M.M., Nepveu M, Kenter C J and Scheffers B C 2006 Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands Eng. Geol. 84 3–4 pp 99–111
[11] Schelkachev V N and Lapuk B B 2001 Podzemnaja gidravlika [Underground hydraulics] Izhevsk: NIC Regularnaya i haoticheskaja dinamika p 736
[12] Vlatskiy V V, Nesterenko M Y and Tsviak A V 2016 Informatsionnaja i telekommunitcionnaja sistema monitoringa geodinamicheskikh i seismicheskikh protsessov na neftegazodobyvajushih territorijah [Information and telecommunication system for monitoring of geodynamic and seismic processes of oil and gas producing territories Ecologia i razvitie obsh’estva 3 18 pp 15-23
[13] Nesterenko M Y, Nesterenko Yu M and Sokolov A G 2015 Geodynamicheskie processy v razrabatyvaemyh mestorogdeniah uglevodorodov (na primere Yughnogo Preduralia) [Geodynamic processes in hydrocarbon fields under development (on the example of the Southern Cis-Urals)] Yekaterinburg: UrO RAN p 186