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SIMULATION OF GEODYNAMIC PROCESSES

Abstract. To select an optimal and environmentally friendly technology for oil and gas development, it is necessary to estimate in advance the likely disfigurement processes of the surface terrain. To this end, it is recommended to develop predictive geodynamic models prior to start of field development, taking into consideration the geological characteristics and tectonic activity of the area under investigation, as well as the specific features of the reservoir.

Research methods. In this paper, two models of subsidence of the ground surface in a hydrocarbon field are considered: a parametric spatial model developed at Delft University of Technology and a model based on the Knoté influence function developed at the Canadian Center for Geodetic Engineering. The first method is more suitable for describing a smooth and gradual subsidence in deep gas reservoirs and allows you to assess the spatial-temporal pattern of movement of the ground surface. In the second method, geodynamic processes are modeled based on the functional relationship between reservoir compaction and subsidence of the day surface, taking into account the location of the oil reservoir, physical and mechanical properties of rocks, changes in reservoir pressure and the results of surface disfigurement monitoring and is recommended for oil fields.

Research results. A comparative analysis of these methods is carried out on the example of the Tengiz oil and gas field in Western Kazakhstan. An evaluation of the developed model accuracy is carried out by comparing the calculated values of soil subsidence with the data of radar interferometry, and estimates obtained by other researchers. Recommendations are given on the application of the considered methods in the generation of predictive models of oil and gas fields, the necessity of calculating the transfer coefficient of the reservoir compaction to the position of the day surface, taking into account the depth of the reservoir and the physical and mechanical properties of the rock massif, is indicated.

Key words: hydrocarbon deposits, ground surface, subsidence, seam roof, seam pressure, geodynamic polygon, geodetic monitoring, radar interferometry, modeling.

Introduction. The western regions of Kazakhstan are rich in hydrocarbon deposits. Here many oil and gas companies have been intensively developing fields for a long period. As a result, disfigurement of surface terrain occurs, in some places reaching significant values.

In order to assess the disfigurement characteristics of the ground surface and to prevent possible economic and environmental consequences, the Government of the Republic of Kazakhstan adopted Resolution on the creation of 30 geodynamic polygons in the areas of development of mineral deposits.

Comprehensive observations of land surface movements in many deposits are now available. However, the issue of mathematical analysis and interpretation of data to enable the generation of an objective geodynamic model and to provide stable predictive estimates of future disfigurements of surface terrain is still at the stage of development.

In this work, performed at KazNRTU named after Satbayev two methods of geodynamic modelling were applied and analyzed. One of which is based on parametric spatial model, and the other on the use of the Knoté influence function. The Tengiz field is considered as the object of research.

Research object. Tengiz field is one of the deepest and largest oil fields in the world. It was discovered in 1979, 350 km southeast of Atyrau city (Fig. 1).

Commercial production began in 1991 with putting into operation of oil and gas complex. In 1990 deal was concluded with the American company «Chevron» to develop Tengiz oil field. In 1993, government of Kazakhstan established «Tengizchevroil» JV LLP jointly with «Chevron». Currently, four companies are already partners: JSC NC «Kazmunaigas» (20%), «Chevron Overseas» (50%), «Exxon Mobil» (25%) and «LukArco» (5%).

Fig. 1. Tengiz field in Kazakhstan

Tengiz field is huge isolated carbonate platform located in the southern part of the Caspian Basin [1,2]. The sedimentary stratum consists of rocks from the Upper Devonian to Quaternary deposits. A specific feature of the field is abnormal reservoir pressure, the presence of a significant amount of hydrogen sulfide and a complex geological structure. The reservoir has a length of 160 km2 and is located at a depth of more than 4000 m, and its thickness is more than 1500 m.

The carbonate massif is a single hydrodynamic system consisting of three stratigraphic objects. Object 1 is composed of rocks of the Bashkir, Serpukhov and Oka stages, object 2 is composed of rocks of the Lower Visean-Tournaisian stages, and object 3 is Devonian sediments[3] Geological reserves in Tengiz are estimated at 26 billion barrels, of which 19 billion barrels fall on Object 1, the remaining 7 billion on Objects 2 and 3 of this field [4]. More than 1 billion barrels have been produced so far.

Complex geodynamic monitoring is carried out systematically at the field, including: high-precision geometric leveling, seismic survey, as well as space radar survey.

According to the analysis of the results of radar monitoring of displacements of the ground surface, carried out in the period from 2004 to 2009[5], the soil subsidence accelerating in time takes place in the area of active development of the field. The maximum subsidence rate in the center of the trough is 30 mm per year. It was also found the appearance of another bowl of subsidence, located to the northeast of the first.

In general, according to the data carried out by different researchers, the trend of an increase in the rate of soil subsidence is confirmed. Thus, for the main bowl, the maximum subsidence rate in the field was in the periods 1991-2000. - 12 mm / year, 2004-2010. - 30 mm / year, in 2016-2017 mm / year - 60 mm / year [6].

Similar facts take place at other deposits in Kazakhstan and testify in favor of the need for a preliminary assessment of the geodynamic consequences of the development of deposits, based on an objective predictive geodynamic model, at the stage of production planning [9-10].

Methods for modelling the subsidence of the ground surface in oil and gas fields. Various approaches and algorithms are used to generate predictive geodynamic models for hydrocarbon fields. In particular, the use of a stochastic model based on the influence function [7], the generate of a coupled hydrodynamic-geomechanical model of an oil field, as well as the use of cellular automata for modeling geodynamic activity. All of these methods have their own advantages and specific features that must be analyzed on the example of a specific field in order to determine the most effective approach. In this regard, the KazNRTU named after Satbayev considered and analyzed two methods for modeling the subsidence of the ground surface:

- parametric spatio-temporal model of trend, taking into account subsidence rate in the center of bowl [7];
- model based on the Knoté influence function, considering connection between subsidence of the ground surface and reservoir compaction [8];

Parametric spatio-temporal model of trend

Spatial -temporal subsidence trend model was presented in the work [9], to describe land subsidence due to gas production. In this method, height *Hi* of benchmark *i*, at the time *t* can be written as:

$$H_{i,t} = H_{i,t_0} + z_{i,t-t_0} + \eta_{i,t}\ , \tag{1}$$

where:

H_{i,t_0} – initial benchmark height before subsidence at the time t_0;

$z_{i,t-t_0}$ – vertical disfigurement due to gas production approximated by spatio-temporal trend model;

$\eta_{i,t}$ - noise caused by stochastic benchmark instability

According to this trend model, subsidence can be represented as:

$$z_{i,t-t_0} = v(t - t_0)\exp\left(-\frac{1}{2}r_i^2\right) + \zeta_{t-t_0},\quad (t_0 < t < t_{end}), \tag{2}$$

Where:

- t_0, t_{end} - subsidence start time and action end of subsidence model;
- r_i – standardized radius from center of subsidence bowl to point i:
- ζ_{t-t_0} - noise ratio, which takes into account stochastic discrepancies between spatio-temporal trend model and actual subsidence due to gas production.

Standardized radius is determined from following expression:

$$r_i^2 = \frac{(x_i - x_c)^2 + (y_i - y_c)^2}{r^2}, \tag{3}$$

where:

- x_c *и* y_c - center coordinates of subsidence bowl;
- r - radius from center of subsidence bowl to inflection point.

Subsidence of land surface as function of reservoir compaction.

In the development process of oil and gas fields, reservoir rocks are compacted due to volumetric compression of pores and repackaging of individual granules and grains. In this regard, during creating stable model of subsidence of the ground surface, it is necessary first of all to take into account the value of reservoir compaction. In general, compaction magnitude depends on the drop in reservoir pressure, thickness of productive layer, physical and mechanical properties of enclosing rocks and reservoir rocks[10].

Oil and gas reservoirs are generally long horizontally and relatively thin vertically. Therefore, it is assumed that reservoir is deformed in uniaxial mode in the vertical direction. In this case, compaction capacity of rock is characterized by one-dimensional compaction coefficient *Cm*.

For elastic isotropic rock, one-dimensional compaction coefficient can be expressed in terms of elastic modulus E and Poisson's ratio *v*:

$$Cm = (1+v)(1-2v)/[E(1-v)] \tag{4}$$

Reservoir compaction taking into account changes in seam pressure Δ*p* and reservoir thickness h can be determined by the following formula:

$$C = C_m \Delta p h \tag{5}$$

For transition from reservoir compression to subsidence of day surface, various expressions can be used including method using the Knoté influence function:

$$k_z = \frac{e^{\left(\frac{\pi r^2}{R^2}\right)}}{R^2} \tag{6}$$

where: r - is horizontal distance between reservoir element and subsidence surface point, R- is radius of critical area (minimum area that gives maximum possible subsidence).

In the work [11], expression is presented for calculating subsidence of the ground surface using the the Knoté influence function, adapted for liquid mineral deposits.

$$S = -a\int_A C k_z dA \tag{7}$$

where: *a* - is distribution factor showing relationship between maximum reservoir compaction and corresponding subsidence of day surface,
A - is productive area,
dA - is elementary particle of productive layer.

The value of the parameter a is in the range from 0 to 1. The maximum value shows that the compaction of the reservoir is almost completely repeated by the day surface, which is unlikely, and the minimum value indicates that the disfigurement of the reservoir attenuates before reaching the ground surface, which is quite possible with a significant thickness cover layer and solid mass resistant to disfigurement. Many researchers have tried to empirically determine a more accurate relationship between the magnitude of reservoir compaction and soil subsidence. As a result, it was revealed that for large reservoirs located close to the surface of the ground, the subsidence spread coefficient will be maximum, approximately a = 1[12].

However, in reality, it is not only the geometry and location of the reservoir that play a role, but also the elastic properties of the reservoir rock and overburden. Russian scientists A.S. Maznitsky and L.M. Serednitsky studied the effect of the physical and mechanical properties of the reservoir on soil subsidence, based on the expressions:

$$\Delta h = c_1 c_m h \alpha \Delta p, \tag{8}$$

$$\eta = c_2 \Delta h[2(1 - v_c)]\left(1 - \frac{\beta}{\sqrt{1+\beta^2}}\right). \tag{9}$$

where Δh is one-dimensional compaction of the reservoir; c_1, c_2 are coefficients depending on the elastic properties of the overburden and the reservoir, the depth of the reservoir and its dimensions;

α is the Biot's coefficient; v_c is the Poisson's ratio of the overburden, ß = H / R is the ratio of the reservoir depth to its radius. As a result of studying various types of reservoirs, it was found that for a sandy reservoir with a thickness of 1600 m, the ratio between soil compaction and subsidence is in the range of 0.531 to 0.590. In the case of the carbonate reservoir, the compaction and subsidence values were found to be less. It was found that the maximum compaction corresponds to the minimum values of Young's modulus and Poisson's ratio of the reservoir rocks, and also that the subsidence of the ground surface decreases with an increase in the rock hardness of the overburden, as well as with a decrease in the reservoir area.

The results of modeling the subsidence of the ground surface. At the first stage, a parametric method was applied, taking into account the speed at the center of the trough. Figure 2 shows results of analysis of radar monitoring data [13] for 2016-2017, according to which maximum subsidence rate is 58 mm. Along the profile 1-2, subsidence bowl was built according to observed values and model values calculated at the considered profile points according to formula (1).

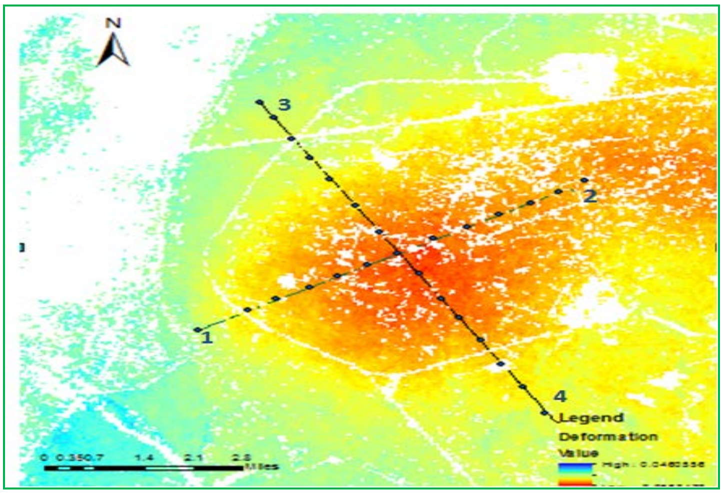

Fig.2. Subsidence bowl in Tengiz oil and gas field [7]

As can be seen from Fig. 3, model curve is flatter than actual one. At the edges of subsidence bowl, there are large values discrepancies in the subsidence of the ground surface than in bowl center, where values are more correlated with each other.

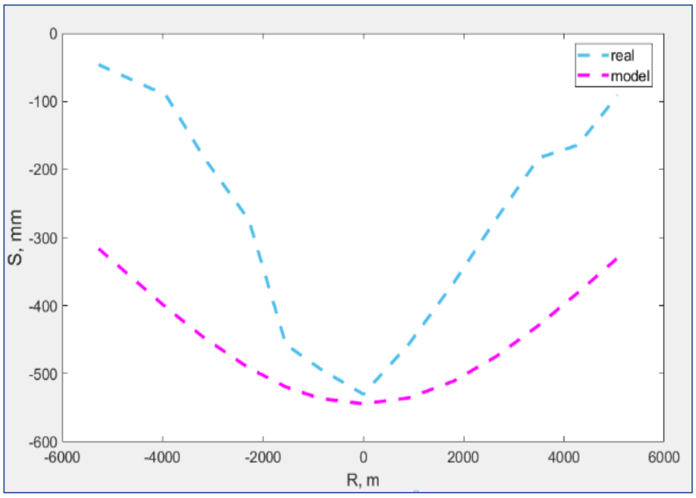

Fig. 3. Subsidence bowls obtained from observations and model

However, spatial representation of subsidence bowl (Fig. 4) speaks in favor of application of this expression with certain coefficient, which makes it possible to accelerate subsidence process in time and approach observed values of disfigurement of surface terrain. Another limiting factor of this method is the need to know the value of the rate of subsidence in the center of the trough. That is, in order to use this approach at the stage of field development planning, it is necessary to calculate a priori the likely rate of subsidence of the ground surface as a result of hydrocarbon production.

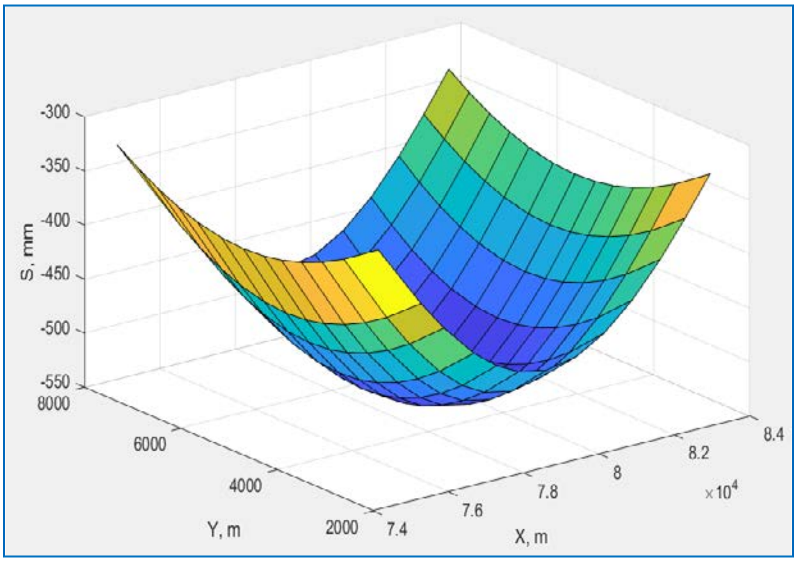

Fig. 4. Subsidence bowl obtained from the calculated data

At the second stage, the subsidence of the ground surface was simulated taking into account the compaction of the reservoir. In this approach, when calculating the model values of the subsidence of the ground surface along the profile 1-2, the values of the elastic modulus were taken, as for a carbonate reservoir, in the range of E = 50,000 - 90,000 MPa and the Poisson's ratio in the range of v = 0.20 - 0.30. Depending on the reservoir compaction, *C* took values *a* = 0.55, 0.65, and 0.75[15]. Standard deviation from observed values of subsidence of the ground surface were respectively: 75 mm, 48 mm, 62 mm. As can be seen from Figure 5 and standard deviations, the closest imitation is obtained with value *a*=0.65.

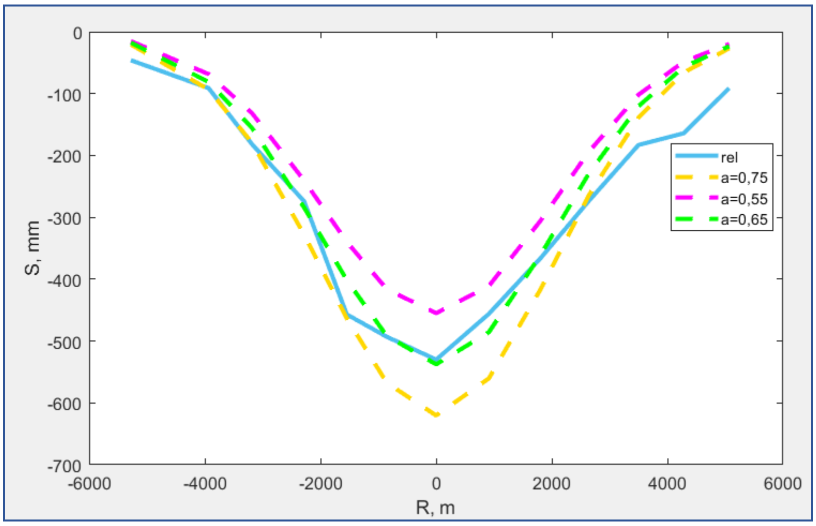

Fig.5. Comparison of real subsidence bowl with the model ones

In this method, during calculating factor a, it may be more objective to use formula that takes into account thickness of overburden and geomechanical properties of constituent rocks. Since, by what percentage of transferred reservoir compaction to day surface depends on these factors. Expression can be obtained empirically, based on data analysis number of fields. If subsidence of the ground surface is determined from observations, and reservoir compaction is also known, then by solving inverse problem it is possible to determine percentage or degree of transmission of reservoir compression to the surface. Further, it is possible to determine type of connection between parameter a and thickness of overburden H, while taking into account physical and mechanical properties of rocks of this layer, in the form of certain factor associated, for example, with Poisson's ratio. Only some difficulty lies in obtaining reliable data on various deposits that have long-term observations of disfigurement of day surface [16].

Conclusions. To create stable predictive model of oil and gas field, it is possible to use both parametric spatio-temporal trend model and method using Knoté influence function. However, in the first case, it is necessary to introduce a coefficient (multiplier) correcting the shape of the subsidence bowl in order to improve the correlation between the model and observed values of soil subsidence. In the second case, it is necessary to more accurately determine the value of the parameter a, which represents the percentage of transfer of reservoir compression to the day surface in the form of subsidence. At the same time, it is possible to use a probabilistic distribution law that takes into account the depth of the reservoir and the physical and mechanical properties of the overburden and reservoir rocks.

Taking into account the fact of an increase in the rate of subsidence of the day surface in long-term development fields, it is necessary to introduce the practice of preliminary assessment of geodynamic activity at the stage of planning the field operation. To achieve the most objective result, a comprehensive assessment of the geomechanical, hydrodynamic and geodynamic models of the hydrocarbon field can be performed.

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ГЕОДИНАМИКАЛЫҚ ПРОЦЕСТЕРДІ МОДЕЛЬДЕУ

Андатпа. Мұнай және газ кен орындарын игерудің тиімді және экологиялық таза технологиясын таңдау үшін жер бетіндегі ықтимал деформациялық процестерді алдын-ала бағалау қажет. Осы мақсатта қарастырылып отырған аумақтың геологиялық сипаттамалары мен тектоникалық белсенділігін, сондай-ақ коллектордың өзіндік ерекшеліктерін ескере отырып, кен орындарын игеру басталғанға дейін болжамды геодинамикалық модельдерді құру ұсынылады.

Бұл жұмыста көмірсутектер кен орнында жер бетінің шөгуінің екі моделі қарастырылады: Дельфт технологиялық университетінде дамыған параметрлік кеңістіктік модель және Канаданың геодезиялық инженерия орталығында жасалған Кнотэ әсер ету функциясына негізделген модель. Бірінші әдіс терең газ коллекторларындағы тегіс және біртіндеп шөгуді сипаттауға ыңғайлы және жер беті қозғалысының кеңістіктік-уақытша заңдылығын бағалауға мүмкіндік береді. Екінші әдіс бойынша геодинамикалық процестерді модельдеу мұнай қабатының орналасуын, жыныстардың физикалық және механикалық қасиеттерін, резервуар қысымының өзгеруін және беткі деформацияны бақылау нәтижелерін ескере отырып, коллектордың тығыздалуы мен күн бетінің шөгуі арасындағы функционалды байланыс негізінде жүзеге асырылады және мұнай кен орындары үшін ұсынылады

Осы әдістердің салыстырмалы талдауы Батыс Қазақстандағы теңіз мұнай-газ кен орны үлгісінде орындалды. Модельді құру дәлдігі топырақтың шөгуінің есептелген мәндерін радар интерферометриясының деректерімен және басқа зерттеушілер алған бағалаулармен салыстыру арқылы бағаланды. Мұнай-газ кен орындарының болжамды модельдерін құру кезінде қарастырылған әдістерді қолдану бойынша ұсыныстар берілді, резервуардың тереңдігін және массив жыныстарының физикалық-механикалық қасиеттерін ескере отырып, коллектордың тығыздағышын күндізгі бетке беру коэффициентін есептеу қажеттілігі көрсетілген.

Негізгі сөздер: көмірсутегі кен орындары, жер беті, шөгу, қабаттың жоғарғы беті, қабат қысымы, геодинамикалық сынақ алаңы, геодезиялық бақылау, радиолокациялық интерферометрия, модельдеу.

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МОДЕЛИРОВАНИЕ ГЕОДИНАМИЧЕСКИХ ПРОЦЕССОВ

Аннотация. Для выбора оптимальной и экологичной технологии разработки нефтегазовых месторождений, необходимо заблаговременно оценить вероятные деформационные процессы земной поверхности. С этой целью, рекомендуется строить прогнозные геодинамические модели до начала разработки месторождений, с учетом геологических характеристик и тектонической активности рассматриваемой территории, а также специфических особенностей коллектора.

В данной работе рассмотрены две модели оседания земной поверхности на месторождении углеводородов: параметрическая пространственная модель, развитая в Дельфтском технологическом университете и модель, основанная на функции влияния Кнотэ, разработанная в Канадском центре геодезической инженерии. Первый метод, более подходит для описания плавного и постепенного оседания в глубоких газовых коллекторах и позволяет оценить пространственно-временную закономерность движения земной поверхности. Во втором методе, моделирование геодинамических процессов осуществляется на основе функциональной взаимосвязи между уплотнением коллектора и оседанием дневной поверхности, с учетом расположения нефтяного пласта, физико-механических свойств пород, изменения пластового давления и результатов мониторинга деформации поверхности и рекомендован для нефтяных месторождений.

Сравнительный анализ данных методов выполнен на примере Тенгизского нефтегазового месторождения в Западном Казахстане. Выполнена оценка точности построения модели, путем сравнения расчетных значений оседания грунта с данными радарной интерферометрии, и оценками, полученными другими исследователями. Даны рекомендации по применению рассмотренных методов при построении прогнозных моделей нефтегазовых месторождений, указана необходимость расчета коэффициента передачи уплотнения коллектора на положение дневной поверхности с учетом глубины залегания резервуара и физико-механических свойств пород массива.

Ключевые слова: месторождения углеводородов, земная поверхность, оседание, кровля пласта, пластовое давление, геодинамический полигон, геодезический мониторинг, радарная интерферометрия, моделирование.