SUBSIDENCE PREDICTION CAUSED BY THE OIL AND GAS DEVELOPMENT

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Abstract: Oil and gas development from underground reservoirs disturbs original rock mass balance. The tending of the rock mass to achieve a new, even only temporary balance is manifested in the movements of the ground surface. Movements can affect ground infrastructure like offshore platforms, pipelines and buildings. For increasing the efficiency of the preventive actions a'priori precisely prediction of the subsidence is necessary. By the prediction of surface subsidence changes of pore pressure in time due to exploitation and geometry of the reservoir have to be taken into account. The prediction method based on the influence function of Knothe will be presented in the paper. Some applications according to the oil and natural gas developments will be discussed

1. Introduction

Surface subsidence of areas where oil, gas and water are exploited are a serious problem in various parts of the World. In the coastal regions, vertical movements of the surface may result in flooding or generate extra costs for securing the banks. Such problems were encountered, e.g. in the area of Maracaibo Lake in Venezuela (ca. 3.5 m – maximum subsidence), Mexican Gulf, in California (ca. 10 m – maximum subsidence) and in Japan. The subsidence troughs may be huge in size and the damage to the objects standing on them is comparable to those in the mining areas. Considerable deformations of surface usually can be found in the places where thick fluid reservoirs occur and the host rocks have compaction qualities.

Surface deformations in the areas of oil and gas exploitation can be efficiently predicted on the basis of methods employing the influence functions. These methods make use of relatively uncomplicated mathematical models and are simple in use. Regarding their high efficiency, these methods are not frequently met in the World's literature, therefore the Authors decided to discuss the prediction model based on an influence function applicable to fluid mineral reservoirs.

2. Rudiments of the proposed method

2.1. Discretization of reservoir

All the considerations made in this paper will refer to an elementary part of a reservoir. The whole reservoir will be divided into elementary cubicoids having a square base of side L and height M_0, corresponding to the original thickness of the fluid reservoir [7](fig.1).

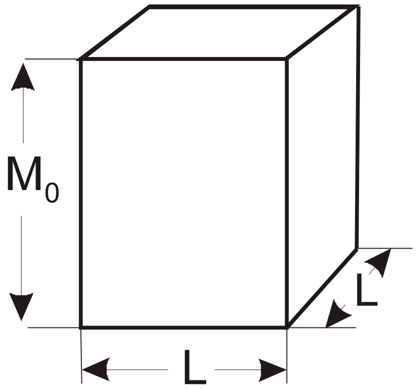

Fig.1. Element of reservoir

This approach enables a description of a varying thickness of a reservoir and simplification of numerical operations. Once the whole gas reservoir field has been divided into elements, the following situation is obtained, fig. 2.

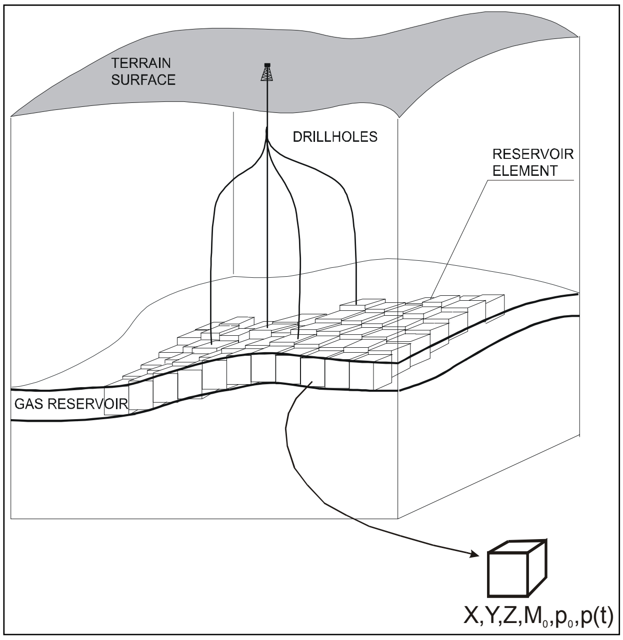

Fig. 2. Gas field divided into elements

2.2. The main cause-and-effect relation

Geometrical-integral influence exploitation model bases on the following cause-and-effect relation (1). Accordingly, the result, i.e. surface subsidence can be determined as a loop of two functions: influence function or transformation function $\varphi(r,z,t)$, and a function describing the cause of rock movement, i.e. compaction $\Delta K(t)$.

$$\Delta S(r,z,t) = \Delta K(t) * \varphi(r,z,t) \tag{1}$$

where: $\Delta K(t)$ - increase of compaction volume of reservoir element in time *t*.

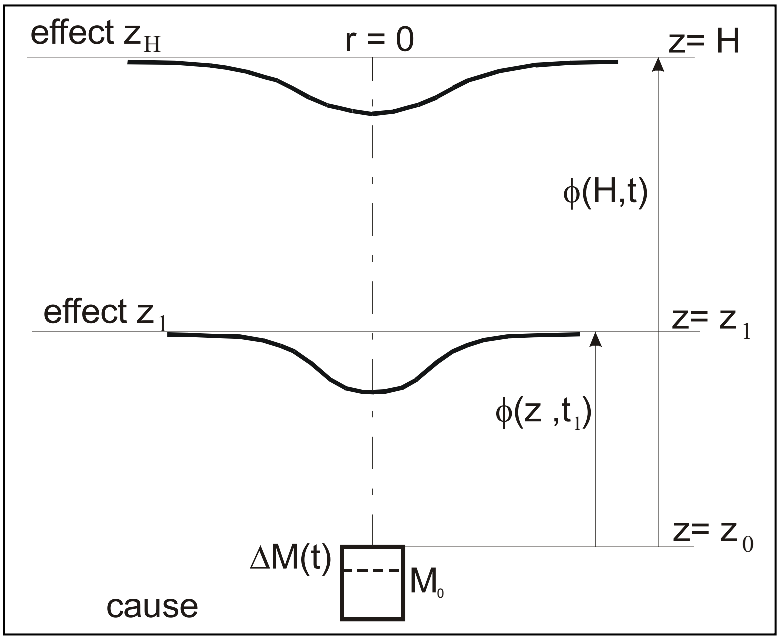

Fig.3. Causal nexus for exploitation of one reservoir element

It should be noted that both functions in eq. (1) are functions of time.

3. Calculation model

Being a cause of rock mass movements, in the case of oil and gas exploitation, compaction depends on changes of pore pressure in the gas or oil field. This relation may be described linearly to some extent:

$$\Delta M(t) = c_m \cdot [p_0 - p(t)] \cdot M_0 \tag{2}$$

where: *ΔM(t)* – change of thickness of fluid reservoir,

c_m – compaction coefficient,

p_0 – original/primary? pore pressure,

p(t) – pore pressure in a moment t,

M_0 – original/primary? thickness of the analysed element of reservoir.

The compaction coefficient c_m depends on the properties of reservoir rocks, depth of reservoirion and original/primary? pressure p_0 [e.g., 15, 16]. The compaction volume for thus defined element of reservoir (fig.1) is:

$$\Delta K(t) = \Delta M(t) \cdot L^2 \tag{3}$$

where: *ΔK(t)* – bulk/volume compaction in a time *t*

The influence functions have been known to be used for predicting surface deformations since Bals published his work in 1931 [1]. In other works employing influence functions written by Litwiniszyn [12] and Knothe [9], the influence functions were justified in the form of a validated Gauss function. The form of the function for predicting the surface may assume the following form:

$$\varphi(r,H) = \frac{1}{R_K^2} \exp\left(-\pi \cdot \frac{r^2}{R_K^2} \right) \tag{4}$$

where: H – depth of exploitation,

r – horizontal distance of calculated point from the reservoir element,

R_K – radius of scattering of exploitation influences after Knothe for a surface:

$$R_{K(z=H)} = H \cdot ctg\beta \tag{5}$$

β - angle of the main influence range, after Knothe.

Predicting the subsidence within a rock mass, the R_K value should be calculated from the following relation:

$$R_K(z) = R_{K(H)} (\frac{z}{H})^n = H^{1-n} \cdot z^{n\cdot} \cdot ctg\beta \tag{6}$$

where: n – coefficient of boundary surface [11, 2, 3, 4, 10, 13].

For calculating this coefficient, n = 0.5 can be assumed.

Basing on elasticity theory, in 1970s Geertsma proposed an influence function in the following form [5, 6]:

$$\varphi(d) = -\frac{1-\upsilon}{\pi} \cdot \frac{H}{d^3} \tag{7}$$

where: υ - Poisson coefficient,

d – distance of the calculated point from the reservoir element.

Other examples of influence functions to be potentially used for predicting deformations in the exploitation conditions can be found in literature, e.g. Kochmański, Perz. The application of the function in the form presented in (4) seems to enable a more precise validation of the model. Owing to the fact the process of rock mass deformation over the oil or gas exploitation area develops in time, it is crucial to introduce a function of time *f(t)*. It describes the delaying impact of the rock mass:

$$\varphi(r,z,t) = \varphi(r,z) \cdot f(t) \tag{8}$$

According to Knothe, the function has the form:

$$f(t) = 1 - \exp(-c \cdot t) \tag{9}$$

where: c – time coefficient, which gives a full description of the delaying influence of a porous reservoir rock on the lowering pore pressure and the delayed influence of the onlying rocks.

Predicting the surface subsidence, they can be calculated by superpositioning the elementary subsidence's. Elementary subsidence caused by exploitation of a fluid from one or any element of reservoir will be written in compliance with (1) as:

$$\Delta S_{j,i}(t) = \Delta K_i(t) \cdot \varphi(r_{j,i}, z_{j,i}, t) \tag{10}$$

where: j – number of calculation point,

i – number of reservoir element,

$r_{j,i} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}$,

$z_{j,i} = z_j - z_i$.

Using the linear superpositioning, a subsidence of any point in a time *t* can be calculated from:

$$S_j(t) = \sum_{i=1}^{i=N} \Delta S_{j,i}(t) \tag{11}$$

where: N – number of reservoir elements ($1 \le i \le N$).

The subsidence distribution over a large fluid reservoir with the on-going exploitation can be calculated on the basis of known reservoir pressure distributions. Having divided of the whole reservoir into constituent elements it was possible to precisely describe the reservoir pressure distribution, its changeability in time and space, and hence to precisely model the surface subsidence in time. If the element of a reservoir were treated as an object initiating rock mass movements, it can be described values of such attributes as, e.g. location (x, y, z), thickness M_0, primary pore pressure p_0, pressure caused by exploitation in the successive moments of time $p_1(t_1)$, $p_2(t_2)$, etc. Contemporary numerical techniques enable operation of attributes for each reservoir element not only at the stage of calculation and prediction of subsidence's. Having had a description of attributes, spatial analyses can be made. Their objective can be, e.g. determining efficiency of a given exploitation method or prevention against too big deformations of the sea bed on shelves or on the surface.

4. Practical application

4.1. Prediction of surface subsidence

The Authors verified the presented model on some real-life examples. These were oil reservoirs under the North Sea and gas reservoirs in one of European countries.

The modeling in the case of the gas field was made in stages. The results of calculations were compared with the levelling measurement and presented in figure 5. Parameters of the calculation model, i.e. R_K, c, c_m, were determined on the basis of data measured as subsidence points on surface by a moment *t* and as compaction properties of the reservoir. The prediction of subsidence for the successive period (t_{i+1}) was calculated with the use of these parameters and expected decreases of pore pressure value in time t_{i+1}. Therefore, it was possible to obtain an exceptionally high accuracy of predicted subsidence's, which was not attainable with other methods [7, 8]. In view of the cause-and-effect relation mentioned in section 2, the parameters of the model can be also identified. This was indicated by, among others, results of analyses carried out for a gas field, where the inverse analysis of measured surface subsidences enabled determining the compaction coefficient value c_m [14]. The obtained values were convergent with the results of laboratory tests by Teeuw [15].

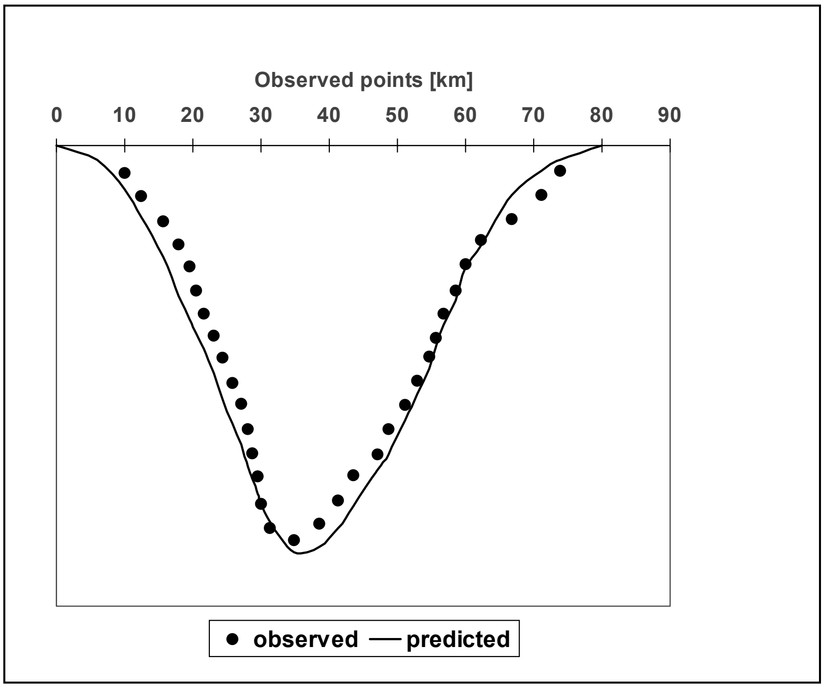

Fig. 4. Prognosed surface subsidences against measured values

4.2. Geodesy surveying measurements of surface subsidence

While presenting the applicability of the model, attention was drawn to the fact that knowledge of the actual course of surface deformation was extremely important. Measurements of deformations are usually made with the use of such geodesy surveying methods as levelling of measuring points. For the last 10 years GPS and remote sensing methods (e.g., InSAR) have been more and more commonly applied. By determining the increase of subsidence between individual moments of time, a whole description of changes in the trough over the exploited reservoir is being made. Designing the parameters or elaborating remote sensing data, the measurement points should be so densely distributed as to make their maximum distance equal to:

$$l = 0{,}1 \cdot R_K \qquad (12)$$

Taking into account (5), this can be written as:

$$l = 0{,}1 \cdot H \cdot ctg(\beta) \qquad (13)$$

It should be noticed that this distance in the average conditions of fluids exploitation is considerable.

The time elapsed between measurements is also important for the specific fluid reservoirs. It should be less than the time of occurrence of the assumed boundary difference of subsidence ΔS_G. With such a criterion, it is possible to determine an average admissible time span between the successive measurements of surface subsidence:

$$\bar{\Delta} t = \frac{\Delta S_G}{c_m \cdot \bar{M}_0 \cdot \bar{\Delta} p_{\Delta t}} \frac{\bar{H}^2}{F} \cdot ctg^2 \beta \tag{14}$$

where: $\bar{M}_0$ - low thickness of reservoir,

$\bar{\Delta} p_{\Delta t}$ - average decrease of reservoir pressure in time Δt,

$\bar{H}$ - average depth of deposition,

F – total surface of the reservoir.

As the decrease of pressure can be written as:

$$\bar{\Delta} p_{\Delta t} = \frac{\partial p}{\partial t} \cdot \Delta t = \dot{p} \cdot \Delta t , \tag{15}$$

where: $\dot{p}$ - gradient of pore pressure, then eq. (14) will finally take the form:

$$\bar{\Delta} t = \sqrt{\frac{\Delta S_G}{c_m \cdot \bar{M}_0 \cdot \dot{p} \cdot F}} \cdot \bar{H}\, ctg\beta \tag{16}$$

It follows from eq. (14) that the time span between individual observations depends on a parameter typical of mineral exploitation rate. In this case it is described by a gradient of pore pressure decrease.

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