Gravitational monitoring for the exploitation of UGS – physical precondition, gravity anomalies and obstructive factors

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Summary

Gravitational monitoring physical precondition is considerately important for possibility to improve the process of underground gas storage exploitation. Also gravity monitoring method can help in understanding of natural gas flows in crosswell space as a response on injection-extraction process.

Introduction

The volume of commercial feed of natural gas to consumers has a seasonal nature with the decrease in the summer and significant increase in winter. Taking into account that natural gas production is almost constant in time, scheme of natural gas supply from the wellhead to consumer includes underground gas storage (UGS) facilities, used to inject excess volumes in summer and to cover increased gas use in winter. So operation of underground gas storage consists in seasonal extractions and injections of natural gas. For each UGS technical features including maximum amount of gas in UGS and reservoir pressure are calculated and approved during its projecting. Considering heterogeneity of gas-saturated reservoirs there is a problem of operational control of processes that take place in UGS. First of all it regards the structure of active UGS zone, paths of gas filtration and stagnant zones detection. Hydrodynamic pressure studies in UGS are commonly performed which are based on pressure observation used to solve filtering problem in porous environment. Also methods of distant geophysical control play important role. Among distant geophysical methods of geological environment monitoring 4D seismics is a primary tool. The results of 4D seismic application are described in a large number of publications (Lumley, 2010). However, seismic monitoring is not always effective either because of geological or economic conditions. Between other geophysical methods used for monitoring we can distinguish gravimetric method that is associated with a control of density variation. Another group includes electrical methods, which are widely used recently in exploration process for oil and gas. Today, there are examples of successful application of gravity monitoring for study of volcanic activity, control of groundwater propagation direction, storage and extraction of artificial aquifers, as well as the development of hydrocarbon deposits (Davis, K., Li, Y., Batzle, M., Raynolds, B., 2010). However, the issue of the usage gravity method for monitoring of underground gas storage is still under investigated. Therefore, this abstract deals with physical precondition for gravity application, expected gravity anomalies amplitudes, as well as hindering factors.

Physical preconditions to use gravity for monitoring

Depending on geological conditions of UGS one of three modes of reservoir system exploitation is observed: water drive, gas-mode or mixed. The UGS mode is important as it determines character in mass changes of reservoir, since it influences the change of gravity on the surface. In water drive mode the cyclical movement of formation water is observed and this movement supports reservoir pressure and displaces gas. Water drive mode is characterized by changes in volume of gas-saturated reservoir, since the period of gas saturation supersedes with a period of reservoir water saturation. In case of gas mode, gas-saturated volume is practically unchanged, and there is only a change in reservoir pressure, which depends on the amount of gas in gas storage (Figure 1).

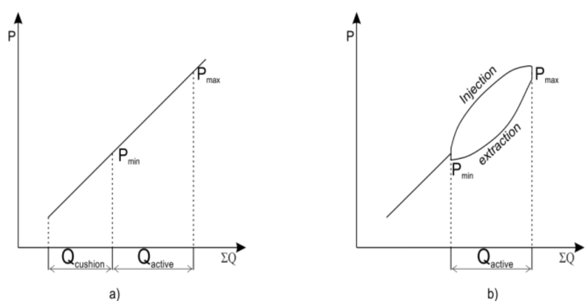

Figure 1: Dependence between UGS reservoir pressure (P) and volume of injected (extracted) gas (ΣQ) in case of the gas (a) and water drive (b) modes

One of the main evaluation parameters of UGS reservoir is its pressure. The parameter that characterizes the mass of gas is its density. There is a directly proportional relationship between these parameters that is subject to the law of Clapeyron-Mendeleev

$$pV=zmRT, \tag{1}$$

where p – pressure in Pa; V – gas volume in m^3; z – gas compaction constant; m – mass of gas in kg; R – universal gas constant in J·kg·K; T – gas temperature in K.

This equation can be rewritten using the relation for the bulk density ρ = m / V.

$$p=z\rho RT. \tag{2}$$

From (2) it is clear that gas density is a function of pressure and temperature $\rho = \frac{P}{zRT}$ (Figure 2).

Since temperature within reservoir does not change significantly, the change in gas density mainly depends from filtration direction and pressure distribution in reservoir.

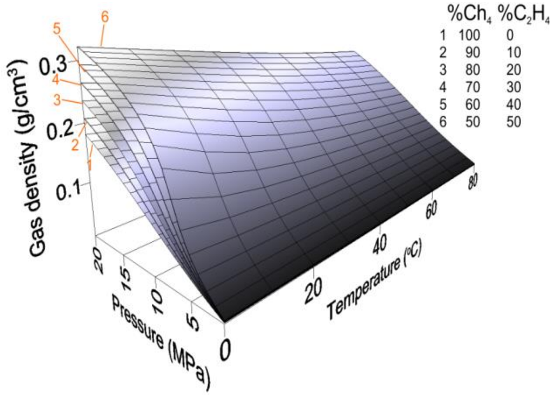

Figure 2: Dependence between gas density of different composition and reservoir PT conditions

Injection or extraction of gas leads to changes in reservoir pressure, which by-turn leads to a change in gas density. Changes of gas density in the reservoir causes changes of gas-saturated rock density, which in the case of pure gas mode can be calculated by the known equation (Figure 3):

$$\rho_r=\rho_m(1-\Phi)+\rho_g\cdot\Phi, \qquad (3)$$

where: ρ_r – gas-saturated rock density in g/cm^3; ρ_m –matrix density in g/cm^3; ρ_g – gas density in g/cm^3; Φ – porosity.

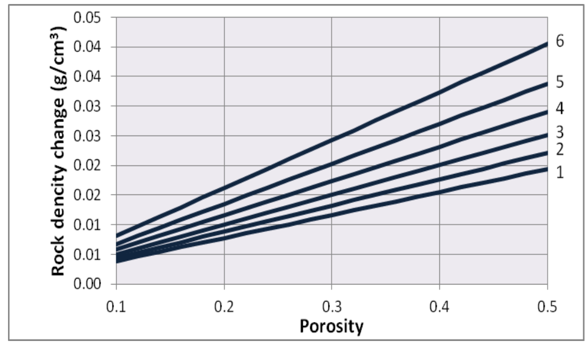

Figure 3: Dependence between density and porosity of gas-saturated rocks in case of different gas composition (reservoir temperature is 20 °C, the change of reservoir pressure is 5 MPa)

Also amplitudes of gravity effects will depend on the volume of the active UGS zone, including area, and effective thickness and also depth to gas-saturated reservoir. To assess the influence of various parameters of the gas-saturated reservoir on gravity we made calculations for the model of material horizontal cylinder (4) with radius R, depth Z and thickness H.

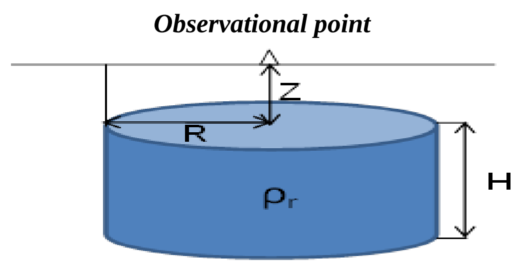

Figure 4: Simplified model of gas-saturated reservoir

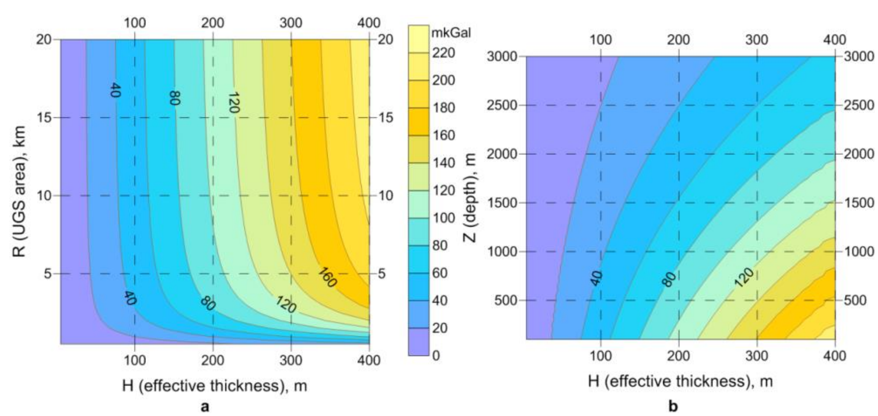

Figure 5: Dependence of gravity anomaly amplitudes from geometrical parameters of gas-saturated reservoir. Component composition of gas is %CH_4=90, %C_2H_6=10; reservoir pressure change is 5 MPa, reservoir temperature is 20^{o}C, porosity is 0.3. Reservoir depth is 800m (a) (Δg=f(Z=800m,R,H)); radius of UGS active zone is 3 km (b) (Δg=f(Z,R=3 km,H))

$$\Delta g = 2\pi G \rho_r H \left(1 - \frac{z}{\sqrt{(R^2+z^2)}}\right), \qquad (4)$$

where Δg – gravity anomaly amplitude in m/s^2; G – gravitational constant ($6.673 \cdot 10^{-11}$ $m^3/kg \cdot s^2$); ρ_r - gas-saturated rock density in kg/m^3

Calculation results showed (Figure 5) that amplitude of gravity anomaly depends on effective thickness of gas-saturated reservoir, depth and to a lesser extent from its planar dimensions – radius R. The maximum anomalous effects reach values up to 200 µGal that can be successfully recorded by modern gravimeters, which allows the measurement of the gravity data with an accuracy of 3 µGal. This gives physical background for application of gravity monitoring for medium and large-capacity underground gas storages. Specific values of expected gravity effects should be calculated taking into account geological structure and reservoir properties of each individual UGS.

Gravity anomalies and obstructive factors

Gravity monitoring survey requires rigorous attitude to the measurement process and use of modern high-precision gravimeters because most of underground gas storages have a small effective thickness of gas saturation (<30 m) and the effects that will be observed during UGS exploitation can range only between 3-10 µGal. Therefore hindrance factors should be considered. The experience of earlier investigations shows that most influential factor which is difficult to reduce is the change of groundwater level. Among the others there are variations of atmospheric conditions during measurements and changes in gravity station`s altitude due to cyclical movements of the earth's surface over gas storage (Herwanger, J., Koutsabeloulis, N., 2011). The issue of the impact of the above factors is the subject of many papers (e.g. Ferguson, J. F., T. Chen, J. L. Brady, C. L. V. Aiken, and J. E. Seibert, 2007).

Practical application

In the period from 2012 to 2013 for the first time in Ukraine there was performed gravity monitoring research at one of the largest UGS - Dashava. Active capacity of Dashava UGS is 2.2 billion m^3 of gas and it has gas mode of reservoir exploitation. The aim of the study was prediction of inner structure of active zone in interwell space. There was four series of measurements performed. Two of them took place in neutral period just after UGS full depletion and others two were done in neutral period after UGS full injection. As a result of the survey there were obtained gravity anomalous effects measured on strictly fixed gravity stations reduced for elevation and groundwater changes (Figure 6) which include useful signal of gravity anomalies caused by changes in UGS and some noise that occurred during the process of measurement.

Conclusions

The study showed the possibility to use gravity data for monitoring of UGS exploitation. The primary premise for gravity monitoring is the quality model of the geological environment, which is built using high-resolution 3D seismics, petrophysics of reservoir rocks and other geological, geophysical and technical information. Calculations illustrate that gravity effects associated with UGS exploitation are significant and can be registered by modern gravimeters. Validity of the assessment made is confirmed by results of gravity monitoring of Dashava UGS. As a next step of this research the prediction of UGS reservoir properties will be done together with analysis of their relation to structural features and industrial characteristics of the active zone of Dashava UGS.

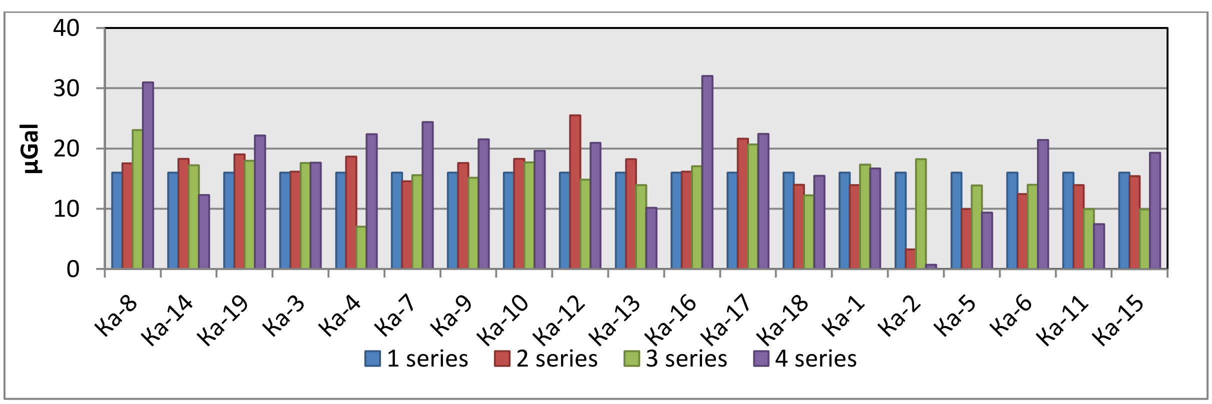

Figure 6: Observed time-lapse changes of gravity (Bouguer anomalies) at Dashava UGS. Measurements made on strictly fixed gravity stations