The reservoir scale gas distribution and its accurate seismic response

Reza Falahat[1]

[1]Faculty of Petroleum Engineering, Sahand University of Technology, Tabriz, Iran, rezafalahat@sut.ac.ir

ABSTRACT

The main concern in the monitoring of gas injection, exsolution and dissolution is the exact spatial distribution of the gas volumes in the subsurface. In principle, this concern is addressed by the use of 4D seismic data. However, it is recognised that the seismic response still largely provides a qualitative estimate of the moved subsurface fluids; exact quantitative evaluation of fluid distributions and associated saturations remains a challenge still to be solved. It is widely believed that a few percent of gas makes the pore fluid mixture very compressible, so that it cannot be distinguished from a more complete gas saturation. However, because of the fact that a gas distribution viewed at the reservoir scale is distinctly different from that observed at the laboratory scale, conclusions from laboratory measurements may not, in fact, be wholly applicable. Indeed, it is found in this study that the main factor controlling the seismic response is gas thickness, whilst gas saturation *per se* remains approximately constant. Modelling studies show that 4D seismic attributes have a linear trend with gas volume. It is expected that this linear trend is applicable for most of reservoirs that is going under gas injection projects. Reservoir heterogeneity is observed to affect these results by less than 2%.This project reveals the ability of 4D seismic to quantitatively monitor the gas injection, and highlights the fact that laboratory measures are not directly applicable at the reservoir scale.

Keywords: 4D seismic, gas injection, IOR/EOR

INTRODUCTION

Gas is normally injected to the reservoir for disposal, storage or IOR purposes. The fate of injected gas is a key point to continue the project. The reservoir transmissibility is not fully known before gas injection. Thus, 4D seismic has been normally employed for monitoring aims.

Natural gas is an enormously light fluid that has a very small bulk modulus. Figure (1) shows typical effects of gas saturation on the saturated rock velocity. These examples were obtained by laboratory measurements and confirmed by Gassmann's equation (1951), and highlights an extreme non-linearity in the system. There is a dramatic drop in the saturated velocity as the first few percent of gas is introduced. The saturated velocity is approximately constant for higher gas saturations, and due to the density effect it lightly increases. It is concluded that gas saturation of a few percent has a dramatic effect on the P-wave velocity and this is similar to that of complete gas saturation (the red line in Figure (1-a)). Utilizing these laboratory based observations, Lumely et al., 2008 argued about quantitative application of 4D seismic to detect gas saturation variation.

In the 4D seismic literature, different seismic responses are proposed for the gas saturation variation (Figure (1)). The laboratory shows an extreme non-linear seismic response to gas saturation variation (Figure (1-a). The linear seismic response was chosen by Huang *et al.* 2001, but a linear response with positive gradient (opposite direction to Huang *et al.*, 2001) was employed by Dumont *et al.* 2001 (Figure 1-b). Finally, some intermediate seismic response (between linear and extreme-nonlinear) to the gas saturation variation were proposed by Sengupta and Mavko 2003 (Figure (1-c)). The diversity of these examples highlights the fact that, gas is not handled properly in the seismic domain. It is our belief that it is the reservoir scale gas distribution which is misunderstood. The literature has been supported mainly by laboratory-based measurements. Gas migration and distribution is different at the laboratory scale versus the reservoir scale.

GAS SATURATION: THE PHYSICAL MEANING IN THE RESERVOIR SCALE

Gas saturation distribution is well defined in the literature relevant to the capillary pressure. Capillary pressure is defined both in terms of density difference and in terms of interfacial tension as below (Tiab and Donaldson, 2004):

$$P_c = \frac{2\sigma Cos\,\theta}{r_c} = gh(\rho_w - \rho_o) \qquad (1)$$

Where, P_c = capillary pressure, σ = surface tension, θ = contact angle, r_c = radius of the tube, h = height of interface, ρ_w = the density of water ρ_o = the density of oil For a distribution of tubes, the capillary pressure causes a distribution of wetting fluid into the tubes. The capillary increase starts from around free water level (FWL), the point of zero capillary pressure. Above the hydrocarbon-water contact, water saturation decreases with increased height, until it reaches at irreducible water saturation. The distance between the hydrocarbon-water contact and the irreducible water saturation is named transition zone. Water saturation is constant (S_{w-ir}) above the transition zone and capillary pressure becomes independent of the height. The transition zone is the only part of reservoir with saturation variation, so it is important to know its magnitude, and which parameters control it. The height of transition zone is proportional to capillary pressure (Equation 1), which is related to the size of the pores and their distribution (r_c), interfacial tension (σ), the wettability and inversely proportional to the fluid density difference ($\Delta\rho$). The literature review, and of course the modelling show that for gas injection to relatively high quality reservoir (permeability above 10 MD), there will be a negligible transition zone. It is due to Equation 1, in which the height is reversely proportional to density difference between gas and liquid, as well as to pore radius. As a result, for gas injection into an aquifer, injected gas migrates toward the upper parts of reservoir due to the gravity effect. The gas saturation is the maximum gas saturation ($1\text{-}S_{wir}$) within the gas cap. The lower part of the reservoir contains 100% water saturated (Figure 2-a). Inside a specific thickness in the upper part of reservoir (gas thickness), the magnitude of gas saturation is constant. It is the gas thickness which varies horizontally. There are higher gas thicknesses around the injection well and a small thickness away from the well location. The gas thickness increases by further gas injection (Figure 2-a – left to right), but the gas saturation is approximately constant in that layer. Thus, in fact the main player in the seismic domain is gas thickness. For appropriate detection of this behavior, a very fine scale simulation model is necessary to catch a sharp transition zone. This has been verified using variety of reservoir simulation models with different range of heterogeneities. The modelling confirms the previous conclusion about gas distribution in the reservoir (Figure 2-a). Heterogeneity introduces a few percent deviation (less than 2%) on the gas saturation distribution. This study is also benefited from a case study in North Sea, in which gas was injected into a clastic sandstone reservoir for the period of 4 years. It agrees with the conclusion about gas saturation distribution.

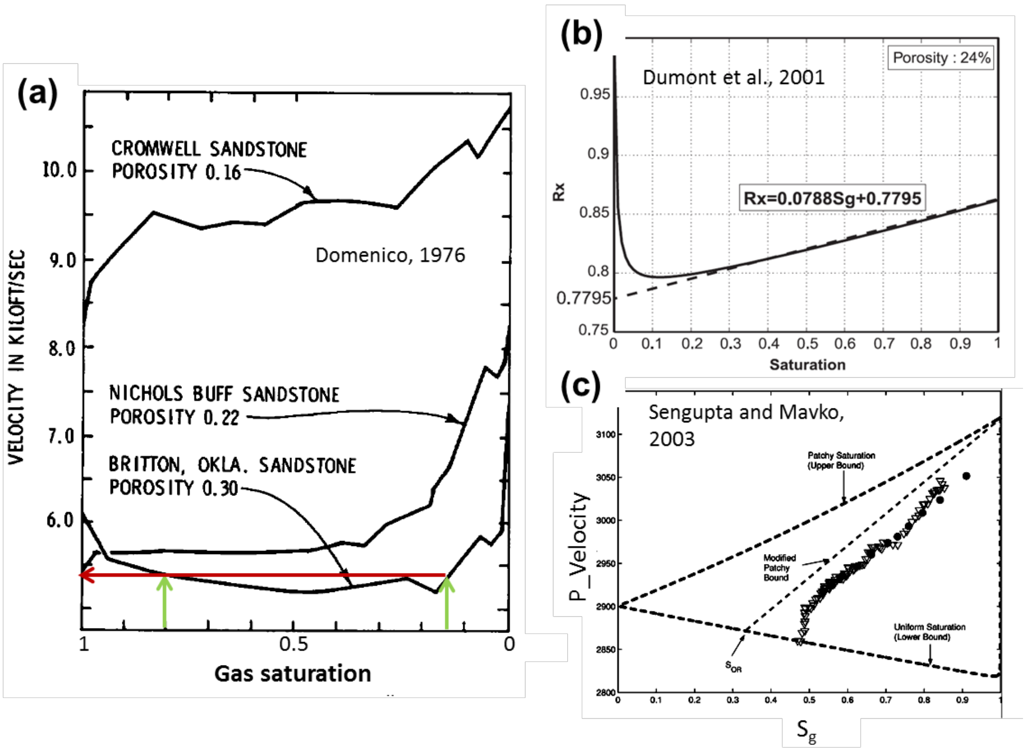

Figure 1 Predicted seismic response for the gas saturation variation employed by a) Domenico 1976, b) Dumont et al. 2001 and c) Sengupta and Mavko 2003.

On the other hand, up-scaled models are normally employed in the industry. To model it, the thickness of reservoir is divided into only several cells (see Figure 2-c). The same gas volume as in the Figure 2-a is injected at each stage (left to right). The cell is too thick to be filled by a small gas volume at the primary stages. The gas saturation increases in upper cell and reaches at the maximum gas saturation on the fourth step. It is followed by the gas saturation increase on lower cell to reach at the $S_{g\text{-}max}$ at the last step.

For the next stage, the entire layer thickness is taken as one cell and the same gas volume as in the Figure 2-a and c is injected. Due to the lack of gravity effect at this scale, gas is homogenously distributed across the entire cell (Figure 2-e – left to right). It is similar to the procedure in the laboratory. A rock sample is taken to be injected by gas (Figure 2-g). The gas saturation now varies from zero to the maximum gas saturation during the injection. I this case, the only controlling variable is gas saturation as the gas thickness is constant (this is not, of course, the reservoir scale reality).

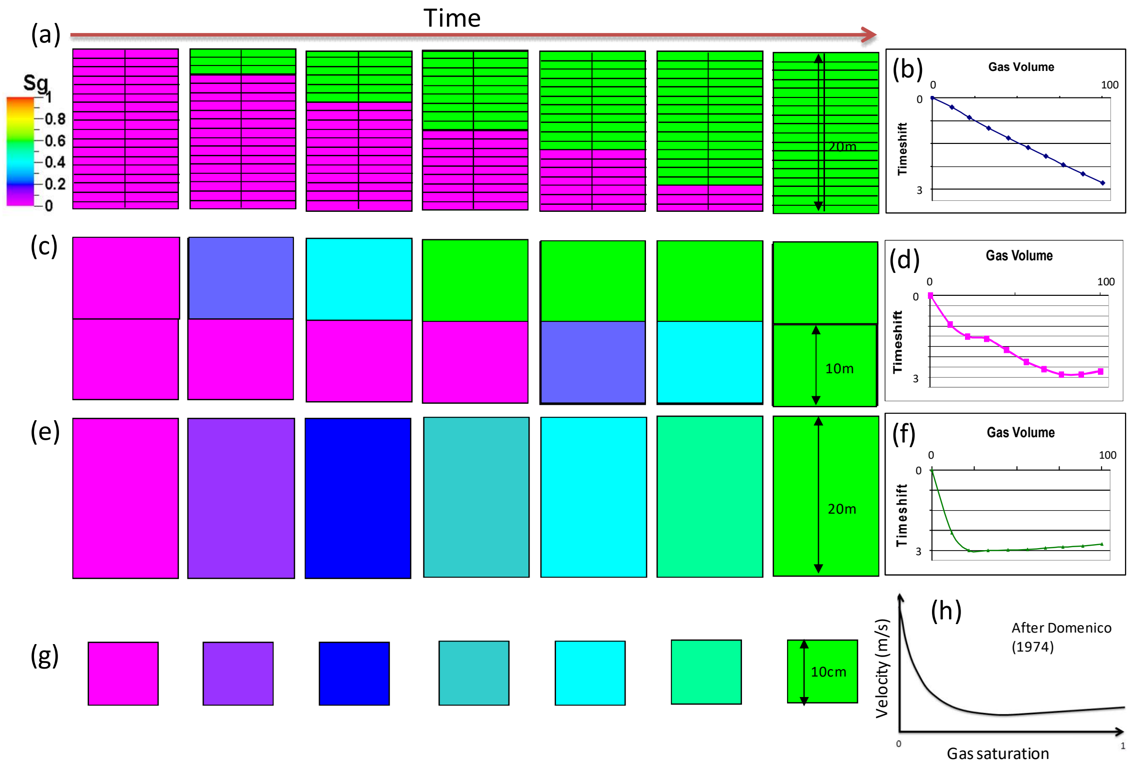

Figure 2 The gas saturation distribution at fine scale (a), coarse scale (c) and very coarse scale (e) reservoir model and at laboratory (g). (b), (d), (f) and (h) are the seismic response for each corresponding scenario.

SEISMIC RESPONSE TO THE INJECTED GAS

To understand the accurate 4D seismic response to the injected gas, similar to Falahat et al., 2011, Equation (2) can be analytically derived:

$$\Delta A = h_g \left\{ \left(\frac{Z_{sh} - Z_g}{Z.V'} \right) - \left(\frac{Z_{sh} - Z_w}{Z.V} \right) \right\} s'(t) = a.h_g \qquad (2)$$

where ΔA, h_g and S (t) are amplitude change, gas thickness and first derivation of wavelet. Z_{sh}, Z_g, Z_w Z, V and V′ are impedance of shale, gas and water saturated sand, average impedance, water saturated and gas saturated velocity, respectively. Since, except gas thickness (h_g) all terms are constant, it can be simplified as a in Equation 2. Thus the 4D seismic attribute is controlled by the injected gas thickness.

To analyse this observation in detail, the numerical modelling is employed. Here, following Amini et al., the full simulation to seismic modelling algorithm is applied. In Figure 2, 4D seismic signal for each of the mentioned scenarios are plotted on the right hand side of scenarios (b, d, f and h, respectively). The fine scale model (the reality), shows a linear relationship between the injected gas and 4D seismic attribute. This observation matches with Equation 2. However, for up-scaled models, there are deviation from the linear response (Figure 2-d). This graph illustrates the effect of saturation variation. Thus, unlike the fine scale cells, where the thickness grows gradually (saturation fixes), the incomplete saturation changes the response into a more non-linear response.

The well-known non-linear response is now obtained for fully up-scaled model (Figure 2-f). This clearly highlights the need for employing fine scale simulation model to produce the accurate gas distribution and seismic response. Another conclusion is that, by employing an up-scaled model in synthetic seismic modelling, the results may show considerable deviation from the observed seismic. On Figure 2-f, there is observed an extreme non-linear trend that matches with the laboratory-based relationship between gas and seismic (Figure 2-h). This is understandable, since, in both cases, gas is injected into the cell to increase the gas saturation. However, this is against the reservoir scale gas distribution.

CONCLUSION(S)

Gas is typically injected to the reservoir for disposal, storage or IOR purposes. Spatial distribution of the gas volumes in the subsurface and the fate of the injected gas is a key point to continue the project. 4D seismic is typically employed for monitoring aims. Analysis of the seismic literature on gas reveals some misunderstandings that cause problems during quantitative monitoring of gas using seismic data. It is widely believed that a few percent of gas makes the pore fluid mixture very compressible, so that it cannot be distinguished from a more complete gas saturation using seismic techniques. To analyse it in more detail, this study reviewed the concepts of reservoir engineering such as the capillary pressure and transition zone, to understand the reservoir scale gas distribution. It is observed that gas saturation is approximately constant inside gas thickness. Variety of simulation with different range of the heterogeneity confirmed this observation. Thus, the main parameter that induces 4D seismic change is gas thickness. It was also observed that reservoir heterogeneity does not affect this conclusion significantly. Analytical and numerical modelling in the seismic domain highlights a linear seismic response to the injected gas thickness or volume for 4D seismic attributes.

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