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Ground Movement above Compacting Petroleum Reservoirs – Physics, Parametric Study of Typical Offshore Reservoirs, and Integration with Seismic Imaging.

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Ground movement due to hydrocarbon production, commonly referred to as subsidence, has been studied extensively in petroleum engineering. In addition to the obvious environmental and operational consequences, ground or seafloor subsidence is measured more readily than reservoir deformations and thus is an important source of geomechanical data. In addition, recent attention has focused on the use of time-lapse seismic data in conjunction with direct subsidence measurements to image reservoir compaction in addition to fluid movement.

Complex coupled simulation of reservoir flow and geomechanics is necessary for predictions or history matching the reservoir compaction and subsidence (e.g., Settari and Walters, 2001) . Typically the results are specific to a particular field, and the dependence of ground movement on the problem parameters can be counter-intuitive due to complexity of the compaction physics, reservoir geometry and geomechanical properties. In particular, the properties of the under- and overburden and sideburden are often assumed to be linearly elastic and constant.

In this work, we examine systematically the influence of the geomechanical properties of the reservoir surroundings and the physics of compaction on subsidence. This investigation is carried out for two idealized, but realistic scenarios:

- A model representative of the chalk reservoirs in the North Sea (e.g., Ekofisk or Valhall) at a reservoir depth of about 3000 m
- A model based on a deep water multi-zone reservoir in the Gulf of Mexico at water depth of about 2600 m.

Variation of surface deformations with the different combinations of the stiffness of the overburden, underburden and sideburden was established by coupled reservoir flow and geomechanical modeling. One of the major parameters varied was the ratio $R_E = E_o/E_r$ (where E_o is the modulus of the overburden and E_r that of the reservoir). At some conditions, the subsidence follows the expected pattern with R_E, i.e., the surface deformation approaches the reservoir top deformation as R_E decreases. However, in some cases the softening of the overburden results in a decrease of the subsidence, and for extremely low R_E surface heave instead of subsidence can result. This has been observed before (Ferronato et. al., 2001) but only in very idealized conditions.

Another aspect studied is the physics of the compaction. We compared linear and nonlinear elastic (hyperbolic) models with hysteresis (approximating elasto-plastic behavior) with more complex models including water weakening. An efficient, but simple algorithm for the change of porosity due to water weakening was formulated. One conclusion reached is that the water weakening can be more important for reservoir performance than the nonlinearity of the rock response in the elastic region.

Finally, the paper discusses the issues arising in integration of the coupled modeling described above with the interpretation of time lapse (4-D) seismic. Although such integration has been proposed before (see, e.g., the references in Settari and Sen, 2007), its implementation has been always “one-way”, using the variation of stress and mechanical properties to modify seismic velocities. We propose a truly iterative system, where the seismic and geomechanical modeling is iterated on to simultaneously satisfy all available constraints. As a result, the compaction resulting from the seismic interpretation should agree with the compaction generated by the geomechanical model. The iterative process will result in better reservoir characterization. Experience from using this concept in heavy oil operations in Alberta is described.

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