Semi-Analytic Modelling of Subsidence1

Peter A. Fokker2 and Bogdan Orlic2

This paper presents a forward model for subsidence prediction caused by extraction of hydrocarbons. The model uses combinations of analytic solutions to the visco-elastic equations, which approximate the boundary conditions. There are only a few unknown parameters to be estimated, and, consequently, calculations are very fast. The semi-analytic model is applicable to a uniform and layer-cake stratigraphy, with visco-elastic parameters changing per layer, and an arbitrary depletion pattern. By its capabilities to handle a multi-layered visco-elastic subsurface, the semi-analytic model fills the gap between the analytic single-layered elastic models available to date and the more elaborate numerical, e.g. finite element, models.

KEY WORDS: subsidence, reservoir compaction, geomechanics, semi-analytic model, visco-elasticity.

INTRODUCTION

Production of hydrocarbons reduces the reservoir pressure. This pressure change affects the in-situ stress field through poro-elastic coupling. The reservoir may compact, resulting in land subsidence or seabed subsidence. Classical examples are the Wilmington oil field in California (Mayuga and Allen, 1969), the Ekofisk oil field in chalk in the Norwegian sector of the North Sea (Nagel, 1998) and the Groningen gas field in the northern part of the Netherlands (Doornhof, 1992; Houtenbos, 2000).

Rate of compaction at reservoir level and surface subsidence are mutually dependent. Forward modelling can be used if the amount of reservoir compaction is known, or if it can be predicted to an acceptable confidence level, and when existing or future subsidence has to be estimated.

Various authors have studied the subsidence caused by hydrocarbon extraction and proposed methods for subsidence prediction. Geertsma (1973) was the first to apply an analytic, linear forward model, based on the nucleus of strain concept, for a single-layer elastic subsurface. Others have expanded his formulae,

---

1Received 26 August 2004; accepted 8 December 2005; Published online: 2 November 2006.
2Netherlands Institute of Applied Geoscience TNO – National Geological Survey, P.O. Box 80015, 3508 TA Utrecht, The Netherlands; e-mail: peter.fokker@tno.nl; bogdan.orlic@tno.nl.
or presented alternatives. Van Opstal (1974) included the effects of a rigid base-
ment. Fares and Li (1988) presented a general image method for a plane-layered
elastic medium, which involves infinite series of images. Both analytic solutions
are, however, limited to media with two interfaces and therefore to a two-layer
model of the subsurface.

A different approach is the use of numerical codes, such as finite elements
(Morita and others, 1989; Johnson and others, 1989; Fredrich and others, 1998;
Chin and Thomas, 1999). These enable simulation of the full relationship between
flow in the porous medium and geomechanics, taking into account complex struc-
tural geometry and heterogeneity of the subsurface (Settari and Walters, 2001). In
contrast to the analytical models, the numerical models of the subsurface usually
demand more time to be constructed and to be computed. There remains, however,
a gap between the fast single-layer and two-layer analytical models available to
date and the more elaborate finite-element models.

The present paper discusses a multi-layer linear visco-elastic model, of which
the elastic part was briefly presented earlier in Fokker (2001). The model presented
here is more sophisticated than the available single-layer and two-layer analytical
models and requires less computational effort than finite-element calculations.
The smaller computational requirements make the method suitable for inversion,
i.e. using subsidence data to increase knowledge about compaction at the reservoir
level.

A NEW MODEL FOR SUBSIDENCE PREDICTION

The new modelling approach combines elements of analytic and numerical
approaches (Fokker, 2001). The method combines a number of analytic functions
that satisfy the elasticity equations in such a way that the boundary conditions
are approximated. Such an approach makes the method more widely applicable
than analytical approaches, while the calculation times are much smaller than for
numerical (e.g. finite-element) simulators. It is typically 3 orders of magnitude
faster than finite-element calculations and much more flexible in the sense that
changes in the elasticity profile are easy to implement.

The method for subsidence prediction has been inspired by a similar concept
used by Fitts (1989) for calculation of the pressure field for Darcy flow in a
porous medium. Fitts started with the pressure solution of a flowing well in the
unlimited three-dimensional space and utilized fields of point sources and
sinks distributed around interfaces to fulfill the boundary conditions in a number
of selected points. His approach was followed by Fokker and others (2005) to
develop a fast model for the productivity prediction of horizontal wells in fractured
reservoirs.

The semi-analytic method is similar to boundary-element methods (Crouch
and Starfield, 1983). There are, however, a few differences. In the semi-analytic