



Reservoir Stress Modeling for an Oilfield, Cauvery Basin

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Summary

3-D finite element reservoir model has been generated covering a horizontal area of 1 sq. km of an oilfield from Nagapattinam sub-basin, Cauvery basin. The anticlinal reservoir model including three drilled wells has been created with a 20 m thick pay sand layer bounded by 20 m thick overlying shale layer. The underlying shale is varying its thickness from 20 m below extreme ends of sand layer to 120 m below its crest. We have assigned same rock properties for sand and shale layers. The model is constrained at the bottom. Due to application of application of horizontal pressure gradient around the sand/shale layers of 3-D model, principal stress magnitudes change. There is a change in stress direction around wells. Finite element derived stress pattern clearly respond to compressive stress gradient as well as to the model geometry.

Introduction

In as much as many cases the formation pressure cannot be determined during drilling, mud pressures higher than those required are used during drilling. This results in mudfiltrate invasion into the reservoir rocks and formation damage, which obscures true reservoir potential (Belonin et al., 2003). The knowledge of pressure distribution for any oilfield enables one to design proper exploration and exploitation programs. 3-D stress modeling over anticlinal pay sand for clastic reservoir has been carried out from an oilfield in Nagapattinam subbasin, Cauvery basin. 3-D finite element stress modeling aims to illustrate the effect of the applied horizontal compressive stress gradient over the chosen reservoir structure. The local stress field is also influenced by rock properties (namely; the Young's modulus, Poisson's ratio, density) for sand, shale and model geometry. Model predicted results are presenting principal stress magnitude as well as principal stress vectors in this reservoir. Horizontal stress magnitudes generally have been estimated from the fracture closure pressure during fracture treatment.

The least compressive stress magnitudes are estimated for specific depths, and it is rare to encounter enough measurements to provide a detailed profile for a single well (Bell, 2003). In most instances, stress data relevant to one well will be all that are required, but as exploration proceeds, more and more information would be required. It is a practice to use fracture (well test) data in 3-D stress modeling (Djurhuus and Aadnoy, 2003). The need to increase productivity and to reduce drilling formation damage favors the use of 3-D stress modeling over oilfield structure. Finite element technique is used to obtain local stress pattern as well as deformation in this reservoir. Usually

the magnitude of vertical stress is calculated from density log data. The importance of this work is that the modeling results will provide the horizontal stress magnitude in the pay sand, which is very much required for production enhancement as well as reservoir stimulation. The knowledge of stress magnitudes inside reservoir in an oilfield improves wellbore stability analyses (Aadnoy and Hansen, 2005).

Study area

The Cauvery basin located at the eastern continental margin of India exhibits alternating NE-SW trending narrow en-echelon basement ridges and wide troughs. Cauvery basin has been subdivided into following sub-basins: Ariyalur-Pondicherry, Tanjore-Tranquebar, Nagapattinam, Ramnad-Palk bay and Gulf of Mannar. Nagapattinam sub-basin of Cauvery basin hosts many important hydrocarbon bearing structures, viz, Thiruvavur, Nannilam, Kuttanalur, Adikyanamangalm, Kamalapuram, Tulsapatnam, Kovikalappal, Thirukkalar, Pallivaramangalam, Kizhvalur etc (Figure 1). One important oilfield from Nagapattinam sub-basin has been chosen for 3-D finite element modeling. Nagapattinam sub-basin is bounded by Pattukkottai-Manargudi ridge to its west, Karaikal high at its north. The Nagapattinam sub-basin extends eastward into the Bay of Bengal. Maximum thickness of sediments is expected to be 4500 m, out of which the Tertiary sequence is nearly 2250 m thick.

3-D FEM, Cauvery Basin

The Andimadam Formation of the Lower Cretaceous age is the main source rock in Nagapattinam sub-basin. Neravi Formation of Upper Eocene to the Lower



Fig.1. The tectonic frame work of Cauvery basin and distribution of fields in Nagapattinam sub-basin (after Vasudevan et al., 1998).

Oligocene age forms the main reservoir. Besides Neravi Formation, hydrocarbons have also been discovered in the Bhuvangiri, Nannilam and Kamalapuram Formations. Maximum hydrocarbon discoveries have been found in the southern flank of Karaikal ridge from where a number of significant discoveries have been made from prospects like Narimanam, Thiruvapur, Kamalapuram, Adikyamangalam and Nannilam areas (Prabhakaran and Ganesh, 2002, Venkataramaiah et al., 2002). Based on the exploratory results, six major hydrocarbon bearing Formations have been identified in the Cauvery basin which are namely; Fractured basement, Andimadam/Lower Palk bay Formation, Bhuvangiri/Upper Palk bay Formation, Nannilam Formation, Kamalapuram Formation and Neravi Formation. Oil and gas have been found in different Formations ranging in age from Pre-Cambrian basement through Andimadam, Bhuvangiri and Nannilam Formations of Cretaceous age to Kamalapuram Formation of Paleocene–Eocene age and Neravi Formation of Oligocene age.

Methodology

Finite Element Model (FEM) for an anticlinal reservoir of an oil field from Nagapattinam sub-basin are generated and calculated using ANSYS (Intermediate version) finite element software package. Boundary

constraints represent a key element in understanding the modeling results.

Using the software the 3-D region representing the clastic reservoir is divided into solid tetrahedral elements whose corners are called nodes. The displacement function and stress-strain relationship for the element material (Young's modulus, Poisson's ratio) fix both the strain and stress distributions in the element as functions of the element nodal point displacements.

The principal stress S_1 corresponds to the vertical stress whereas the principal stresses S_2 and S_3 refer the horizontal maximum and minimum principal stresses respectively. In terms of principal stresses S_1 , S_2 and

S_3 the equivalent stress magnitude, can be expressed in the following form (Chandrupatla and Belegundu, 1997):

$$S_{eqv} = 2^{-1/2}[(S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_3 - S_1)^2]^{1/2}$$

Principal stress magnitudes and equivalent stress magnitudes are plotted for stress contour plots of the 3-D finite element model.

Model setup

The reservoir model has been constructed from such an oilfield of Nagapattinam sub-basin, which is hydrocarbon bearing. There are three pay sands in this oil field. Only one dipping pay sand has been considered for 3-D modeling whose crest is lying at a depth of 2190 m. The 3-D model covers 2000 m in x direction and 500 m in z direction (Figure 2). The model covers the vertical depth interval from 2170 to 2330 m along y direction. We have not considered the exact dip of the anticlinal structure. It is assumed that the strike direction of the anticlinal oilfield is aligned with the horizontal z direction of 3-D model.

The top shale layer is 20m thick and is underlain by 20m thick sand layer. The middle sand layer is sealed with shale layer at the bottom. Bottom area of shale layer is considered as flat. The crest of overlying shale layer is considered at a depth of 2170 m whereas the flat bottom of shale layer is at a depth of 2330 m. The thickness of the bottom layer is varying from 20 m at its sides to 120 m at the crestal part. Three wells are located at top, right flank and left flank respectively. The finite element grid consists of 15,471 solid tetrahedral elements composed of a network of 3708 nodes. Model has been constrained vertically as well as horizontally at the bottom (Figure 2). We have applied



mean horizontal compressive pressures of 18 MPa, 20 MPa and 22 MPa at four vertical sides of top shale, middle sand and bottom shale layers respectively. The rock material properties have been assumed based on the measured rock mechanical properties of sediments lying in Nagapattinam sub-basin (Chatterjee and Mukhopadhyay, 2002, Table 1).

Table 1. Elastic Rock properties employed in the 3-D FEM for reservoir in Nagapattinam Sub-basin.

Rock Type	Young's modulus (GPa)	Poisson's ratio	Average density (kg/m ³)
Sand	40	0.25	2300
Shale	40	0.25	2300

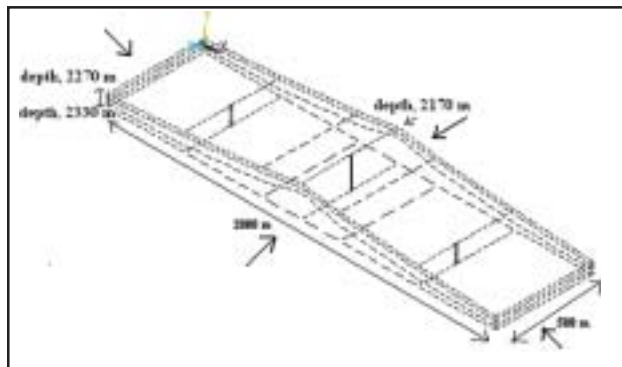


Fig. 2. 3-D reservoir model showing three wells, one at top and other two at dipping sides. Arrows are indicating compressive horizontal pressure gradient which are applied at four sides of the model.

Results from FEM

Modeling results show the distribution of stress pattern over 3-D reservoir model. Due to application of horizontal pressure gradient, pressure contour pattern are symmetric around the wellbore. (Figures 3a, b, and c). The principal stress (S_1) magnitude varies from 5 to 41 MPa. The magnitude of S_1 increases vertically downwards. The principal horizontal stress magnitudes S_2 and S_3 ranges 0.4 to 26 MPa and 0.7 to 19 MPa respectively. Equivalent stress magnitude varies from 0.4 to 43 MPa (Figure 4). The equivalent stress magnitude increases towards the dipping sides from top to bottom of the model. The equivalent stress magnitude in the pay sand ranges from 14 to 20 MPa. The magnitude of horizontal stress S_2 is more than the principal horizontal stress magnitude S_3 . The pay layer exhibits variation of horizontal stress magnitudes under the above said model boundary conditions.

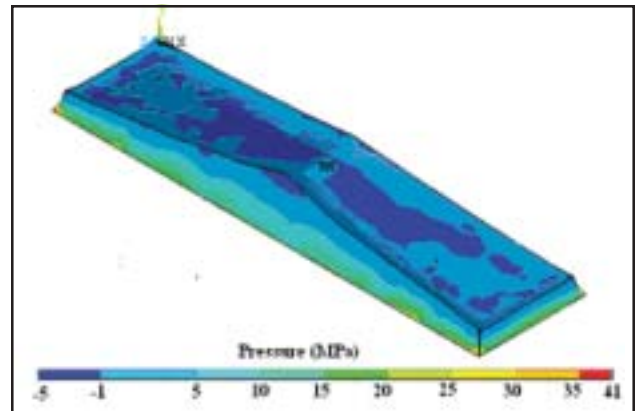


Fig.3a. Displaying principal (S_1) vertical stress magnitude under compressive horizontal pressure gradients applied at four sides of 3-D model. Negative value representing low value at top of the model as well as opposite direction to the other stress pattern inside pay layer and bottom part of the model.

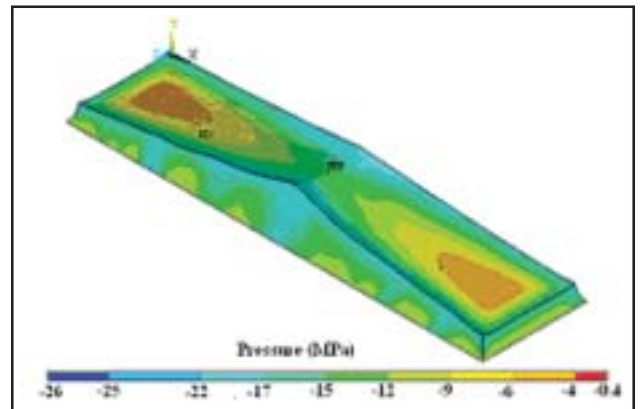


Fig.3b. Displaying principal (S_2) horizontal stress magnitude. Negative value of 12 to 17 MPa representing S_2 stress magnitude inside the pay layer.

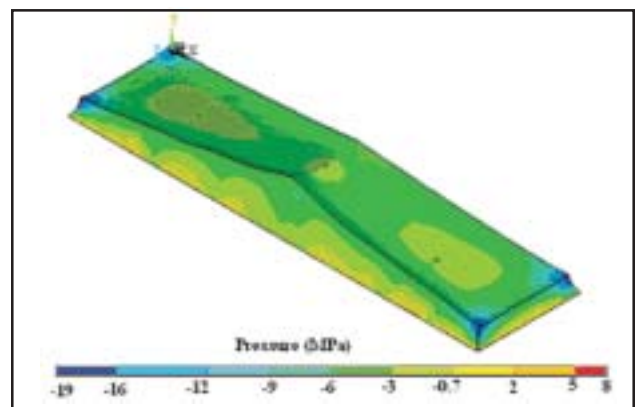


Fig.3c : Displaying principal (S_3) horizontal stress magnitude. Negative value of 3 to 12 MPa representing S_3 stress magnitude inside the pay layer.

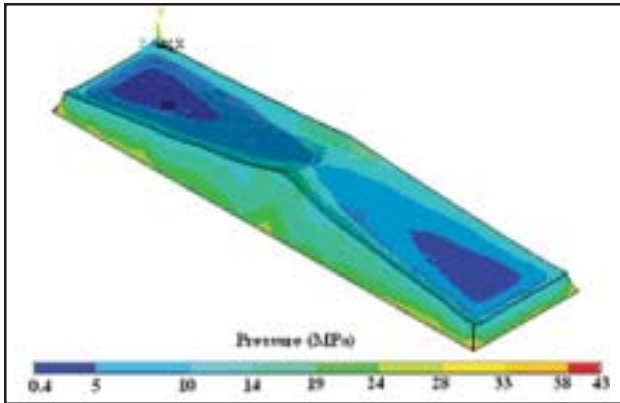


Fig.4. Displaying equivalent stress contour for 3-D reservoir model.

The S_2 magnitude around the well located at top is about 12 to 15 MPa and around the wells located at dipping sides of the anticlinal model is 6 MPa. The S_3 magnitude around the well located at top and other two well located at dipping sides is about 1 MPa or less. It is noticed from the stress contour pattern that the variation in S_2 magnitude is more around the well and throughout the model that compared to the stress contour pattern of S_3 . The equivalent stress contour pattern is indicating the affects of S_1 , S_2 and S_3 stress acting on the constrained model.

The magnitudes of principal stress S_1 , S_2 and S_3 increase from crestal part towards the dipping side which is not constrained. Stress magnitudes also increases vertically downwards. From the modeling result it is also observed that the ratio between minimum stress and vertical stress (0.4) agrees with the stress ratio found previously from the oilfield stress data in this basin (Chatterjee and Mukhopadhyay, 2001).

The orientation of stress vectors is affected by the model geometry i.e inclination of dipping sides, as well as applied pressures. Magnitude of principal stress vector S_1 is more than that of horizontal principal stress S_2 and S_3 . The orientation of S_1 is aligned with the vertical axis. The orientation of S_2 and S_3 are orthogonal to each other. The previous works on 2-D finite element stress modeling across the oil fields in Cauvery basin and regional stress data over the Cauvery basin also show a change in stress magnitude and orientation in Nagapattinam sub-basin (Chatterjee and Mukhopadhyay, 2003 and Gowd et al., 1992).

Conclusions

3-D Finite element model has been generated for anticlinal clastic reservoir from an oilfield in Nagapattinam

sub-basin. We have not considered the overburden pressure at the top shale layer of the reservoir. We have considered only horizontal pressure gradient around the alternate shale/sand layers. Minimum stress magnitude (S_3) varies 3 to 12 MPa in middle pay layer whereas equivalent stress magnitude ranges 14 to 19 MPa in the pay sand layer. Stress magnitude increases with depth. The stress ratio calculated from the modeling results is 0.46 which matches with the stress data found previously for wells in the Nagapattinam sub-basin. Model predicted horizontal principal stress magnitudes as well as orientation with respect to strike direction of the anticlinal structure would provide more information in calculating fracture gradient, finding fracture propagation direction in this reservoir.

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