

## Water Saturation Modelling using SCAL data in a multi-layered Offshore Carbonate Reservoir

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### Keywords

Capillary Pressure, Free water level, Rock Quality Index, J-Function, Normalized saturation, SCAL, SHF

### Summary

Initial water saturation ( $S_w$ ) determination and distribution is the most challenging and critical component in reservoir modelling and simulation. In many fields the early wells are thinly spread and the subsequent development wells may encounter a depleted oil column due to movement of water.

The water saturation distribution above the FWL in an oil reservoir is controlled by the balance of capillary and gravity forces. When capillary pressure (SCAL) is available and height above free water level (FWL) is known, initial water saturation can be remodelled. This paper presents a case study of giant carbonate reservoir (M2) of Mumbai High North field simulation model in which the Capillary pressure and saturation distribution is incorporated to accurately describe the reservoir fluid distribution.

A simple J-function approach is applied to a giant carbonate reservoir (M2) of Mumbai High North field where very complex models have been previously attempted. The study combines well information including logs and capillary pressure from cores to determine height above free water level and create a water saturation curve that can be compared to log-derived water saturation. The study also validates that the capillary pressure model generated for one well can be applied to other wells in the field. A satisfactory history match was obtained with improved reservoir dynamics. Although limited SCAL data was available, but the derived saturations were found to be better co-relatable with the well productivities.

In summary, decent match is obtained between the saturation profile generated by this workflow to the saturation in well-logs, and the estimated fluid volumes are in agreement with approved reserves estimation.

### Introduction

The saturation height function is used to predict the saturation for a height above free water level in the reservoir. A combination of well log and core analysis is used to determine the original reservoir saturations. The water saturation information can be directly obtained from preserved cores. However, it is

difficult to preserve cores in their original state due to some changes before brought to laboratories. Therefore, Reservoir engineers often require capillary pressure, an important characteristic of rock for locating hydrocarbon and water in the subsurface. Capillary pressure analysis can help in optimizing drilling programs and thus assisting reservoir engineers in estimating the extent of hydrocarbon accumulations. It is generally measured in laboratory through core sample analysis and can be compared to other field measurements.

Original reservoir water saturation can be reconstructed once the capillary pressure is available and free water level (FWL) is known. The water saturation distribution above the FWL in an oil reservoir is controlled by the balance of capillary and gravity forces. The pressure gradient between the non-wetting (oil) and wetting (water) phases,  $P_c$ , is determined by the difference in fluid densities at the given height from FWL. Hence, the reservoir  $P_c$  is related to thickness (height) of the reservoir.

This paper presents a case study of M2, MHN simulation model in which the Capillary pressure and saturation distribution is incorporated to accurately describe the reservoir fluid distribution.

M2 reservoir is essentially a bio-micritic limestone of middle Miocene age of Bandra formation with vugs and channels exhibiting wide variation in rock properties. The reservoir is sandwiched between a small gas cap and relatively tight aquifer at the edge. It can be divided grossly into two main units, viz. M2-A (upper unit) and M2-B (lower unit) separated by shale. M2-A is relatively a thin unit and M2-B is the main hydrocarbon producing reservoir. Lithologically, this unit is characterized by bio micritic limestone and is found to be represented by three depositional packs, M2-B\_a, M2-B\_b & M2-B\_c separated by thin shale bands.

Present study combines well information including logs and capillary pressure from cores to determine height above free water level and create a water saturation curve that can be compared to log-derived water saturation. The study also validates that the capillary pressure model generated for one well can be applied to other wells in the field.

## Water Saturation Modelling using SCAL data

### Methodology adopted for estimation of saturation height function (SHF) using capillary pressure data (SCAL)

Initial water saturation distribution in a porous media is affected by capillary forces, which are basically a function of Porosity and Permeability. The Swi distribution can be obtained from SCAL data to derive a meaningful correlation with the rock quality index (RQI). Several techniques are available to generate the SCAL based saturation-Height Models.

Two cores from different wells were available in M2 of MH North. Due to poor recovery and shaly nature of one of the recovered core, core analysis was carried out for only one well i.e X. Two conventional cores were cut for the M2 layer i.e. CC1 in the interval 942-965m, mainly cover part of the M2-A layer and the shale between M2-A & B layers and CC2, in the interval 965-983m mainly covering M2-B layer the objective zone. For quality check purpose and to honour the mathematical calculation for Sw the log vs core porosity plot was prepared which resulted in good agreement between log and core porosities (Figure-1).

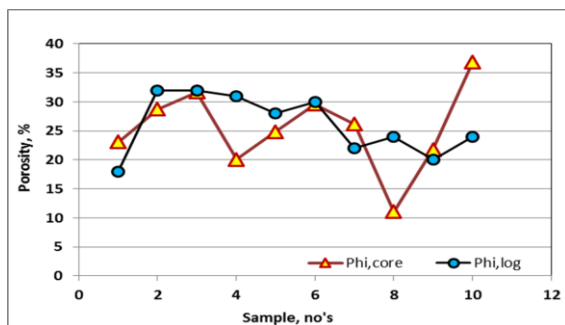


Figure-1: PC curves with derived Swc values for each sample.

Capillary pressure vs Saturation plug data from conventional core was acquired from the MHN field. A total of 18m (CC2) of core was recovered for M2-B, but only ten set samples comprised this capillary pressure data set. Out of the 10, another 2 core data sets were rejected based on the Pc vs Sw curve at reservoir conditions and remaining 8 data sets were incorporated in between M2-B\_a, M2-B\_b & M2-B\_c.

### Defining Capillary pressure

Capillary pressure (Pc) is the pressure difference across the interface between two immiscible fluids arising from the capillary forces. These capillary forces are interfacial tension and surface tension. The capillary pressure is the difference between the pressure in the wetting and the non-wetting phase in a porous media.

$$P_c = P_{nw} - P_w$$

Capillary pressure can also be calculated if the rock-fluid contact angle ( $\theta$ ), radius of contact and fluid interfacial tension ( $\sigma$ ) are known.

$$P_c = (2 \sigma \cos \theta) / r$$

Capillary pressure can also be expressed as a hydrostatic head. It is equal to the product of the density difference of two liquids, height of liquid rise and the gravitational constant (g).

$$P_c = \rho * g * h \quad (1)$$

It is very essential to collect various lab generated data sets of Pc vs Sw, So for that purpose in this study Capillary pressure vs saturation is used which was lab generated from the core of the well X.

### Height above Free water Level

Reservoir rock initially contains water in oil reservoirs and is defined as water-wet rock. When oil migrates into the reservoir rock, it displaces water in the rock. A displacement force is required to overcome the capillary forces in the water saturated water-wet rock. This force is supplied by gravity operating upon the differential buoyancy of the two fluids that result from their different densities. There is a level at which oil cannot replace water further because the driving force is insufficient to overcome the capillary force. This does not occur at the free water level, but at some height above the free water level defined by the displacement pressure. Thus the oil/water contact (OWC) is above the free water level (FWL) in reservoirs.

### Permeability

Since the correlation between porosity & permeability i.e. generated from core data is not very satisfactory, an exponential correlation has been derived & used to calculate permeability K for respective porosity  $\phi$ . The calculated K values are used in the simulation model.

$$K = 0.2e^{15\phi} \quad (2)$$

### Rock Quality Index

It is defined as the square root of permeability up on porosity.

$$RQI = 0.0314 \sqrt{K/\phi} \quad (3)$$

For each data set RQI (Rock quality Index) can be calculated by using equation (3). For RQI calculation, it will read the actual depth wise porosity and for permeability the equation (2) was used.

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**J-function**

The Leverett J-function was originally an attempt to convert all capillary pressure data to a universal curve. A universal capillary pressure curve does not exist because the rock properties affecting capillary pressures in reservoir have extreme variation with lithology (rock type). The Leverett's J-function has proven valuable for correlating capillary pressure data within a lithology. J-function is very useful for averaging capillary pressure data from a given rock type for a reservoir.

$$J = \frac{0.218P_c}{\sigma \cos \theta} \sqrt{\frac{k}{\phi}} \quad (4)$$

The factor 0.218 is multiplying to make J-function a dimensionless quantity. The above equation can also be modified in terms of RQI.

**Normalized Saturation (S<sub>wn</sub>)**

The saturation was normalized with respect to irreducible water saturation.

$$S_{wn} = \frac{S_w - S_{wir}}{1 - S_{wir}}$$

Where the S<sub>wn</sub>: Normalized Water saturation  
 S<sub>w</sub>: Water saturation  
 S<sub>wir</sub>: Irreducible water saturation

**Capillary data conversion to reservoir condition**

Capillary pressure is a function of the interfacial tension between two immiscible fluids and the contact angle between the wetting phase and the rock surface. Consequently, to convert data from one fluid system to the other, interfacial tensions (σ) and contact angles (θ) are needed. The various laboratory measurement capillary pressure data sets were converted to reservoir condition using the data provided in Table-1.

$$P_{c,res} = \frac{(\sigma \cos \theta)_{res}}{(\sigma \cos \theta)_{lab}} P_{c,lab}$$

Cond ition	System	Surface tension (σ)	Contact Angle (θ)	Cos θ
Laboratory	Air/Brine	72	0	1
	Mercury/Brine	480	140	0.765

Reservoir	Oil/Brine	29	30	0.866
	Gas/Brine	50	0	1

Table-1: Interfacial Tension and Contact Angle

After converting the P<sub>c</sub> data into reservoir condition, graph between P<sub>c</sub> (res) and S<sub>w</sub> were generated. The tangent to the curve (S<sub>w</sub> axis) generated from P<sub>c</sub> vs S<sub>w</sub> is the S<sub>wir</sub> for the respective data set shown by Figure-2.

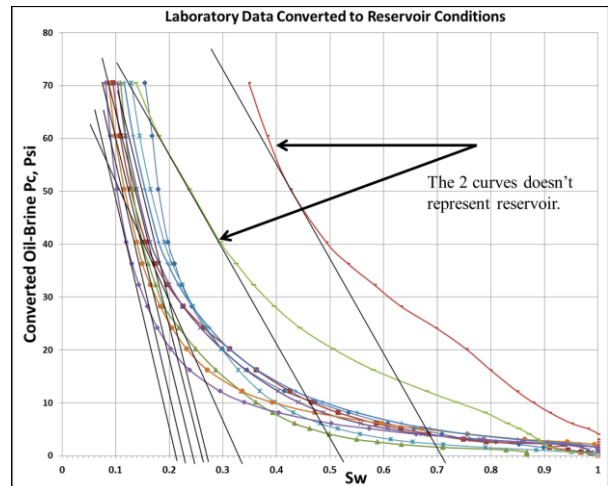


Figure-2: PC curves with derived Swc values for each sample.

The core derived permeabilities are plotted against the core derived porosities (Figure-3) and an exponential relationship is obtained which is further used to obtain normalized J-function plot. The sample phi-K values are found to be represented by equation (2).

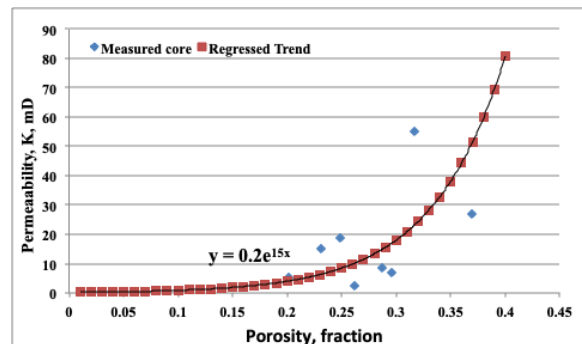


Figure-3: Phi-K plot for each core sample

Plug porosity and derived permeabilities are used to calculate and plot RQI vs. S<sub>wir</sub>. The plot (Figure-4) can be represented by the following exponential relationship.

$$S_{wir} = 0.03RQI^{-1.3}$$

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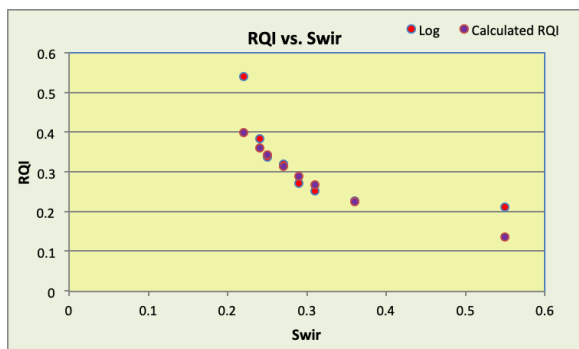


Figure-4: RQI vs Swir Plot, Calculated vs Actual

The Leverett J-function was used to normalize capillary pressure data to take into account variations in porosity and permeability. After getting the value of RQI and Swir for each data set, now it's time to calculate J-function and Swn values for individual data set. In this method, initially the capillary pressure vs. saturation data for all core samples is converted to a single J function by using equation (4). A plot between normalized saturation and J-function by combining all the data set was generated (Figure-5). The following relationship is representing the J-function trend.

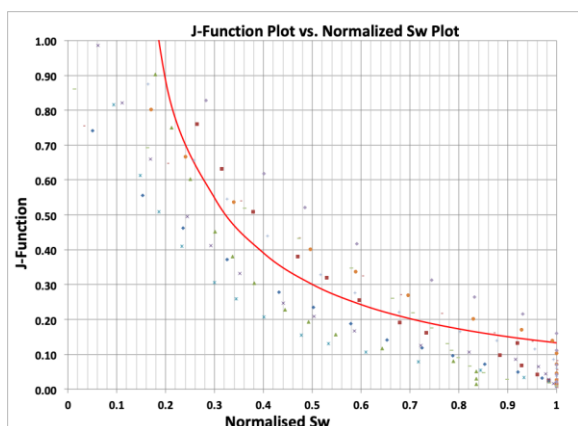


Figure-5: J-function versus normalized water saturation

$$J = 0.133S_{wn}^{-1.176}$$

RQI and Swc relationship is later used to denormalise the saturations for each grid cells using the depth, porosity and phi-k transform.

**Modelling using J-fuction:**

Once the water saturation model was built, it was applied to the wells and compared to water saturation calculated from well logs.

After verifying the authenticity of well X, the model was applied to 10 other wells of MHN field. The water saturation-versus-pressure model was converted to a water saturation-versus-height model by replacing the pressure attribute with height above free water level (in true vertical depth), reservoir

porosity and permeability. The output was a water saturation curve which had no dependency on a resistivity log measurement. The height above free water level is considered at 990m, msl whereas the OWC is at 980m, msl. Comparison of Sw in few wells (Log Processed vs J-function) is shown in Figure-6.

There was good agreement between the two models (log saturation and saturation calculate using capillary & J-function). Moreover, J-function derived saturations were more reliable in terms of production performance of the wells.

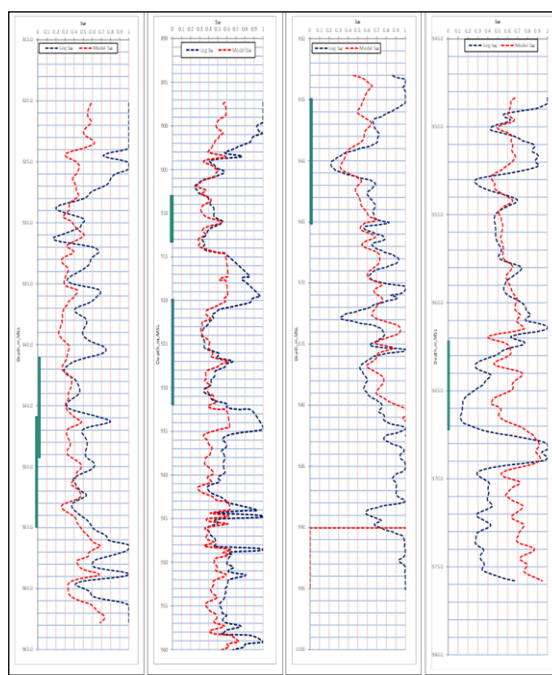


Figure-6: Comparison of Sw in few wells (Log Processed vs J-function)

A comparison of Log vs J-Function Derived water Saturations at the top of M2 reservoir is as shown in Figure-7.

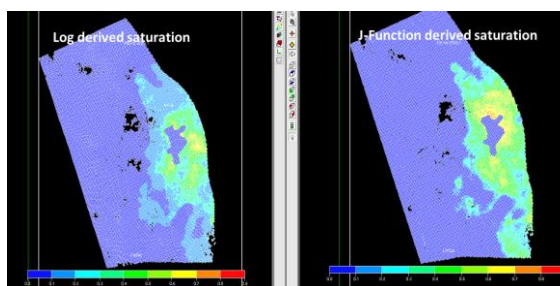


Figure-7: Log vs J-Function Derived water Saturations at the top of M2

**History Matching & Validation:**

A satisfactory field level match could be obtained with J-function calculated saturation distribution. The multi-layered completions of both the injectors and

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producers coupled with no-knowledge about the actual layer-wise intakes make it extremely difficult to match the water cut in all the wells. Moreover, there are no artificial permeability channels imposed in the model to force a match. Neither any attempt been made to produce water behind the casing through imposed completions in layers not recorded in the well history. However, the model is able to capture the water cut behaviour in majority of wells.

The field level water cut calculated from log derived saturation modelling shows high water cut at early stage of production which deviates from the historical data. However, water cut from J-function derived saturation model matches well with history further validating the reliability of saturation height modelling (Figure-8).

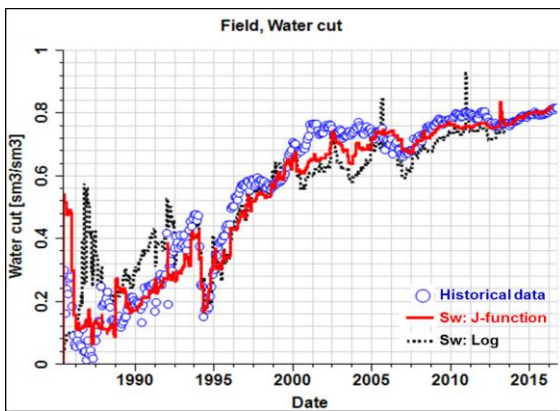


Figure-8: Field level water cut match using Log derived water saturation & J-function calculated water saturations.

Performance of one well ‘Z’ was predicted on the basis of this model as a test case. The model predicts this well to produce about 60 bopd oil with 90% water cut since the well is close to OWC. However, on actual performance this well performed much better with close to 300 bopd oil with initial water cut of 40%. While analysing the reason for poor performance of this well in the model it was found that this well encountered M2-B<sub>a</sub> top at a depth of 8m shallower than the depth envisaged in the model (Figure-9).

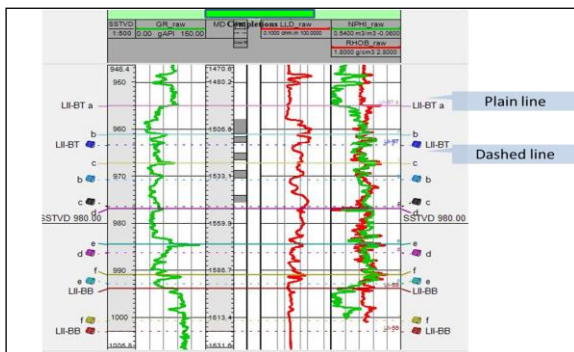


Figure-9: Well coming 8m shallower than the model depth with good saturation. Dashed lines are model mapped horizons and plain ones are well tops based on correlation.

The correct depth would have generated enough oil saturation on the saturation-height-model for a better prediction which further validated the reliability of our saturation-height model.

In some wells the match between log saturation and Pc saturation was not strong. So a comparison of saturation with actual well production performance was attempted. For example, in well Y the comparison is shown is Figure-10.

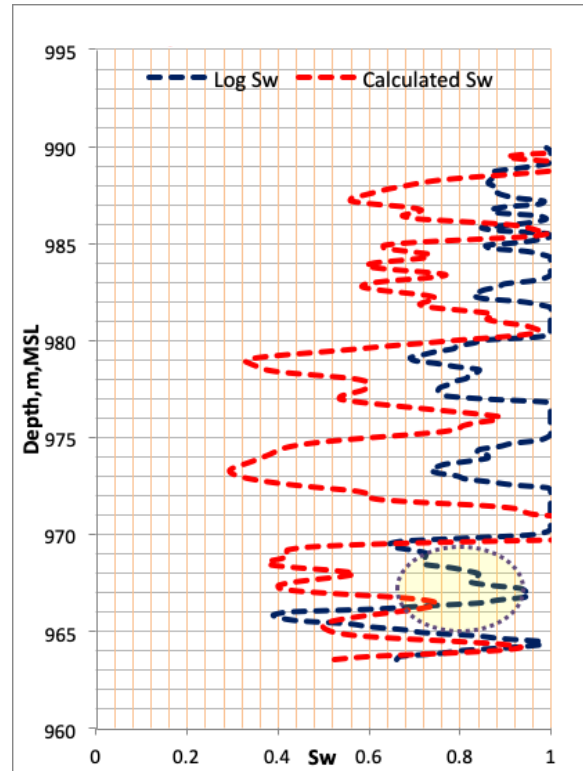


Figure-10: Comparison of Log Sw with Pc derived Sw in well Y

The production performance of the Y (Figure-11) shows that this well produced around 600 m<sup>3</sup>/d liquid with no water cut initially for a period of about five months from interval 959.4-963.6m, 963.6-969.4m. After production of five months the water cut jumped to 50% and then continue at a range of 80%. The significant feature is that this well produced about 0.25 MMm<sup>3</sup> oil from near the OWC. The upscaled grid saturation based on the log saturation show oil saturation in the range of 35-40% in M2-B<sub>b</sub> layer. However the J-function derived model saturations are able to sustain the well oil production rate. So the saturation calculated by Pc is more accurate than the log saturation.

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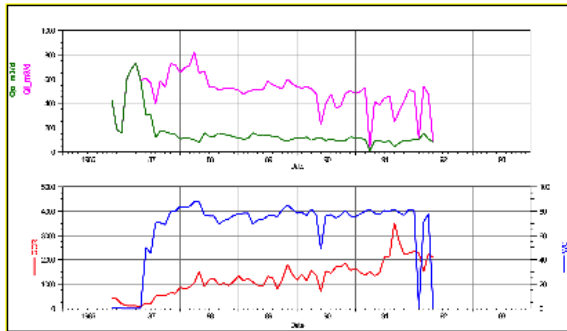


Figure-11: Production performance of well Y

### Conclusions

The capillary pressure model developed from core data of one well effectively predicted the water saturation in other wells within the same field. The capillary pressure analysis of well X provided a more consistent indication of water saturation than using the traditional resistivity based computed saturation.

The analysis demonstrated the ability to use capillary pressure data from one well to calculate height above free water for any other well within the same connected reservoir.

By considering the capillary pressure derived water saturation in the existing model, the estimated fluid volumes are in agreement with approved reserves estimation. The derived saturation height model using J-Function was found to be better co-relatable with the well productivities and a decent history match was obtained at field as well as well level.

This method is a quick fit approach for modeling water saturation in complex reservoir with sufficient SCAL data accurately representing the reservoir for better history match and good predictability.

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