ESTIMATION OF WATER SATURATION IN CARBONATE RESERVOIRS WITHOUT RESISTIVITY LOG DATA. PART II: FORMULATION OF A NEW MODEL

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ABSTRACT

This paper is the second part of the two-part report on study for establishing alternative models that are valid for Indonesian carbonate reservoirs. In this second part formulation of the new models is presented. For the study, 407 plug samples taken from various limestone reservoirs in Indonesia were used. Following Lucia's procedure the samples were classified, grouped, averaged, and their capillary pressure data was formulated to form water saturation models that are essentially functions of porosity and height above free water level. Validity test on the models are performed on two wells in West Java with very encouraging results. With using the Archie model as reference, justified using well test data, the new models prove themselves reliable while the original Lucia models provide far too optimistic estimates. The model validity check shows tha the models are valid for at least Class 1 and Class 2 rocks in accordance with Lucia classification. Study on Class 3 rock is needed in the future.

Key words: carbonate rocks, classification, water saturation model, capillary pressure

I. INTRODUCTION

As discussed in the first part of this paper (Widarsono et al., 2008), water saturation is not an easy parameter to determine in the case of severe formation rock's heterogeneity and absence of reliable resistivity log data. In facing such situation Lucia (1983) proposed a new approach that utilizes capilary pressure data of rocks that were groupped into three classes based on their pore configuration types. Widarsono et al. (2008) also show how Lucia's models were formulated and made into easily applicable mathematical expressions.

This second part of the paper essentially offer a new model that has been obtained following Lucia's path of derivation but using data from Indonesia's carbonate reservoirs as input. Similar form of output is also to be presented and it is hoped that this will provide an alternative to log analysis for carbonate reservoirs in Indonesia. A trial of the proposed new model using data from Indonesia's carbonate reservoirs is also to be presented.

II. CORE DATA

As many as 407 limestone plugs taken from fields mostly in Java and Sumatra (e.g. Cemara Barat, Tambun, Jatibarang, Jenggolo, and Gunung Kemala structures) were used in the study. Table 1 lists the regional origins of the core samples. Data for each sample consists of porosity, permeability, grain density, fluid saturation, visual description, and type/ classification. Capillary pressure data for the study was provided by special core analysis laboratory (SCAL) data from seven wells among the fields. Table 2 presents an example of capillary data taken Sukamandi field's plug samples.

Apart for the basic and capillary pressure data, other core-derived data was also prepared for the purpose of validity test on the new formula. The data is log suites, resistivity (a, m, and n), drill-stem test (DST), and water analysis result taken from a well in Subang field. Table 3 summarizes the primary data availability for the model validity chack. Other auxilary data was also prepared consisting of petrographic and scanning electron microscope (SEM) data. This visual data was used for confirming aspects such as litology model and pore configuration type.

III. CLASSIFICATION OF ROCK SAMPLES

In classifying the rock samples, analyses were performed in order to interpret the rocks' characteristics with regards to their facies, class, petrophysical properties, diagenesis, and depositional environment. The rock samples were in general interpreted as to belong to wackestone, packstome, and grainstone classes. The limestone classification was made following the method discussed in Widarsono et al. (2008).

Briefly, the rock samples involved in this study are generally characterized by some typical features. Wackestones are usualy of fine to coarse-grained

Table 1
Regional origins of the core samples

Sedimentary Basin	Formation	Percentage
North Sumatera		15%
South Sumatera	Baturaja	35%
West Java	Parigi, Cibulakan	35%
East Java		10%
Papua	Kais	5%

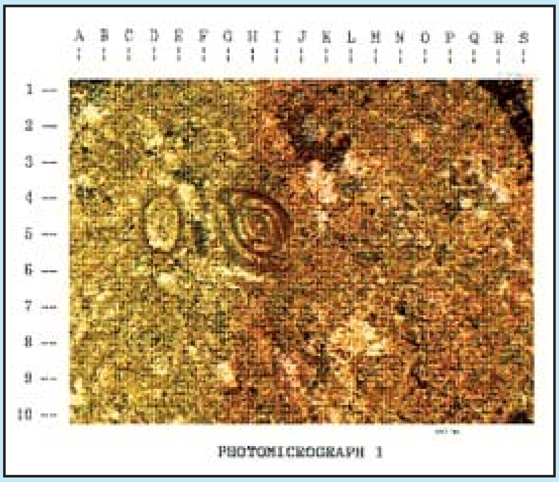

Figure 1
A thin section showing an example of wackestone among the rock samples under study

Table 2
Capillary pressure data for Sukamandi limestone samples

Pressure, PSI				1	2	4	8	15	35
Sample number	Depth meters	Permeability milidarcy	Porocity per cent	Brine saturation per cent pore spave					
Well : SKD - 02									
23		7.54	19.96	83.971	20.602	57.618	47.114	42.842	41.084
20		5.39	16.77	86.724	73.724	60.442	50.846	44.552	42.506
22		2.87	12.92	89.901	77.336	65.611	53.547	47.462	46.306
17		2.59	7.63	90.118	77.804	66.003	53.865	47.643	46.912

Formation	Laboratory measurement				Vsh	Porosity	Sw
	a	m	n	Rw			
Parigi	1	1.95	2.08	0.34	GR-log	N-D	Archie

Table 3
Summary of data to be used in model validity test

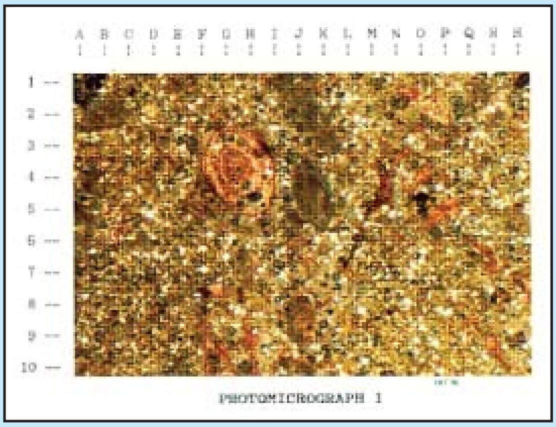

Figure 2
A thin section showing an example of packstone among the rock samples under study

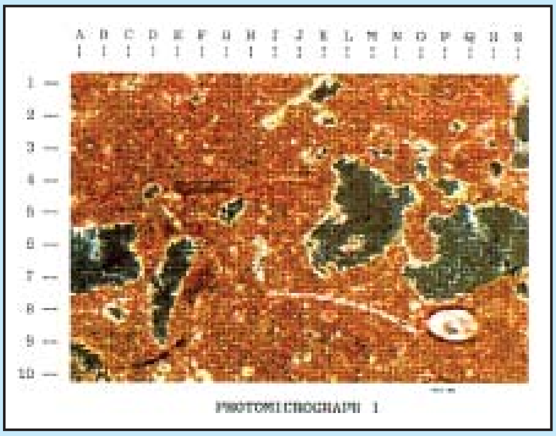

Figure 3
A thin section showing an example of grainstone among the rock samples under study

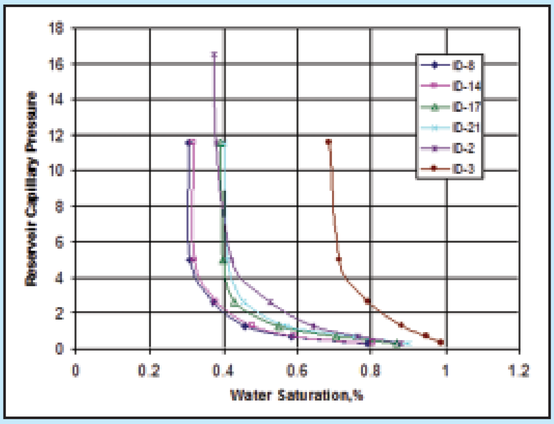

Figure 4
Capillary pressure curves for wackestone samples

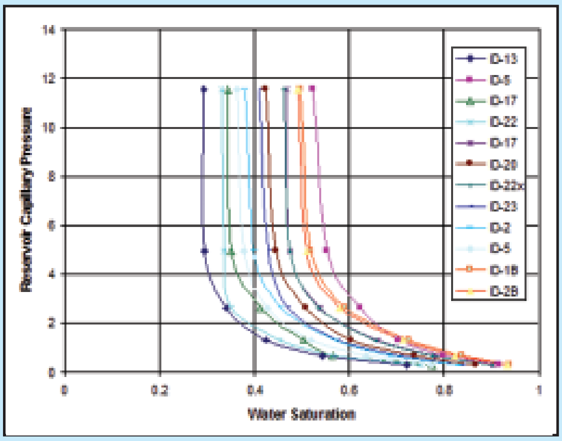

Figure 5
Capillary pressure curves for packstone samples

skeletal wackestones dominated by coral fragmens, planktons, echinoderms, bryozoa, milliolids, and ostracods (Figure 1). This poorly to moderately sorted limestone is made of 40% to 65% carbonate mud. As in accordance with the Lucia classification, this rock is classified among Class 3 rocks.

Packstones of the studied samples are characterized by their medium to coarse skeletal materials consisting of larger fossils of coral, bryozoa, and echinoderms with irregular appearance of red algae and bivalves (Figure 2). Smaller fossils are also present represented by benthonic foraminifera such as Amohistegina sp, Lepidocyclina sp, and Miogypsina sp. This kind of rocks are classified into Class 2 in the Lucia classification.

The rock samples that were classified as grainstone are characterized by their poor grain sortation and presence of large amount of skeletal material such as larger coral fragmens and foraminiferas (Figure 3). Other skeletal material that are usually present are bryozoa, bivalves, gastropods, and other calcareous benthonic foraminiferas. These rocks are categorized among Class 1 rocks in accordance with Lucia classification. Some boundstones among the studied samples are also classified into this class.

IV. FORMULATION OF THE NEW MODELS

Selection of capillary pressure data

First step in the formulation is to select capillary pressure data in accordance with the rock samples that have been classified into Class 1, Class 2, and Class 3. As discussed previously these three classes are represented grainstones (and boundstones), packstones, and wackestones, respectively. Figures 4 through 7 present the capillary pressure data for the four rock types. All capillary curves have been converted into reservoir condition following the method presented in Widarsono et al. (2008).

The capillary pressure curves shown in Figures 4 through 7 have apparently diffences in the pore configuration. This is, at least, shown by the difference in irreducible water saturation (S_{wirr}) values. The wackestones, having the expectedly lowest permeability, are represented by a range of S_{wirr} values of 30% - 70%, packstones by 25% - 55%, graistones by 23% - 37%, and bounstones by 25% - 35%.

As the second step, correlations were made between water saturation and capillary pressure averaging (power law) and normalization among the capillary pressure curves using the J-function (JF) approach to yield

- Class 1: $JF = 0.71 S_w^{-3.8774}$ with $R^2 = 0.8372$
- Class 2: $JF = 0.3606 S_w^{-5.3589}$ with $R^2 = 0.8081$
- Class 3: $JF = 0.653 S_w^{-4.9542}$ with $R^2 = 0.968$

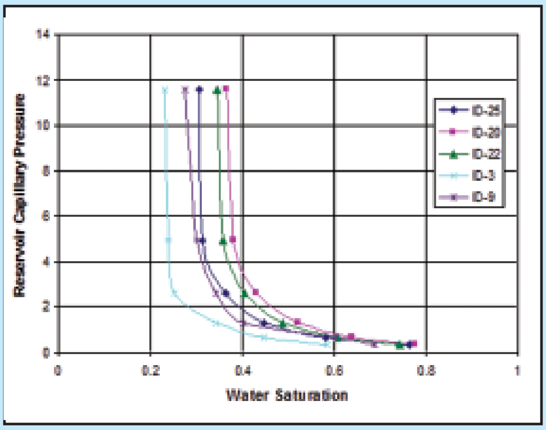

Figure 6
Capillary pressure curves for grainstone samples

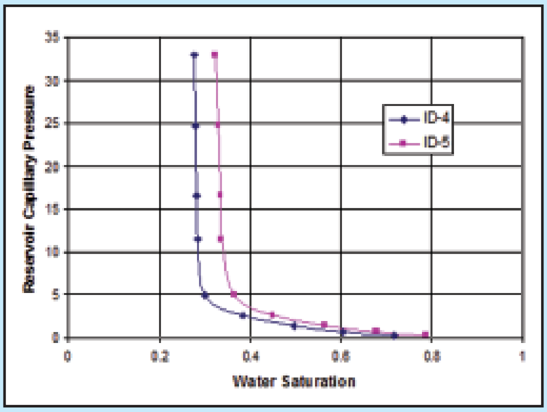

Figure 7
Capillary pressure curves for boundstone samples

Porosity vs. Permeability correlation

Following the classification of the rock samples into three classes, porosity – permeability relationships were determined through plotting porosity and permeability data belonging to each class. Figure 8 shows the plots and correlations for the three classes. As exhibited by the plots, no sharp correlations are visible even though there are clear correlations between porosity and permeability. However, scatters are also obvious implying that there could be overlapped domains among the rock types. Some wackestones could be part of Class 2 while some packstones could also be part of Class 3 rocks. Nevertheless, porosity (ϕ) – permeability (k) relationships for the three classes have been found as follows

Class 1: $k = 0.07021 \phi^{2.2923}$ (1)

Class 2: $k = 0.000925 \phi^{3.1744}$ (2)

Class 3: $k = 0.0000509 \phi^{3.527}$ (3)

Formulation of new water saturation models

By combining Equation (5) in Widarsono et al (2008) of

$$J(F) = \frac{h}{144} (\rho_1 - \rho_2) \sqrt{\frac{k}{\phi}}$$

where ρ_1 and ρ_2 are densities of heavier and lighter fluids, with Equations (1) through (3) water saturation (S_w) models - see Atmoko (2007) for complete derivation – water saturation equations of

$$S_w = 1.25472h^{-0.25759}\phi^{-0.03815} \tag{4}$$

for Class 1 rocks,

$$S_w = 1.55178h^{-0.1866}\phi^{-0.02442} \tag{5}$$

for Class 2 rocks, and

$$S_w = 2.4350h^{-0.20185}\phi^{-0.03592} \tag{6}$$

for Class 3 rocks are derived, with *h* is height above free water level at which capillary pressure is zero.

From Equations 4 through 6 it is clear that the new water saturation models are functions of, beside porosity, height above free water level. This implies that the models are suitable for cases in which reservoirs of concern are at their initial condition. The models simply estimate water saturation vertical distribution, depending on the porosity (i.e. permeability), up to positions above which water saturation values are simply the irreducible water saturation. At any other conditions that have involved flows as the results of production operations these models are simply not valid.

Model Validity Test

For validity test on the newly proposed water saturation models, log data from two wells in Subang field was used. A complete set of standard log data (gamma ray, spontaneous potential, resistivity, neutron, density, acoustic, and caliper) was available for the analysis.

In term of rock quality, Subang structure can be divided into two parts; the upper 30-meter of poor to fair quality rocks and the better and thicker lower parts with average thickness of 120 meters. Porosity estimation using the most suitable method has yielded average porosity values of 14% and 22% for the upper and lower parts, respectively.

Information from petrographic (thin section) and scanning electon microscope (SEM) has shown that the upper interval is generally made of bioclastic packstones with intercrystalline porosity, dolomite crystalls, and secondary porosities caused by

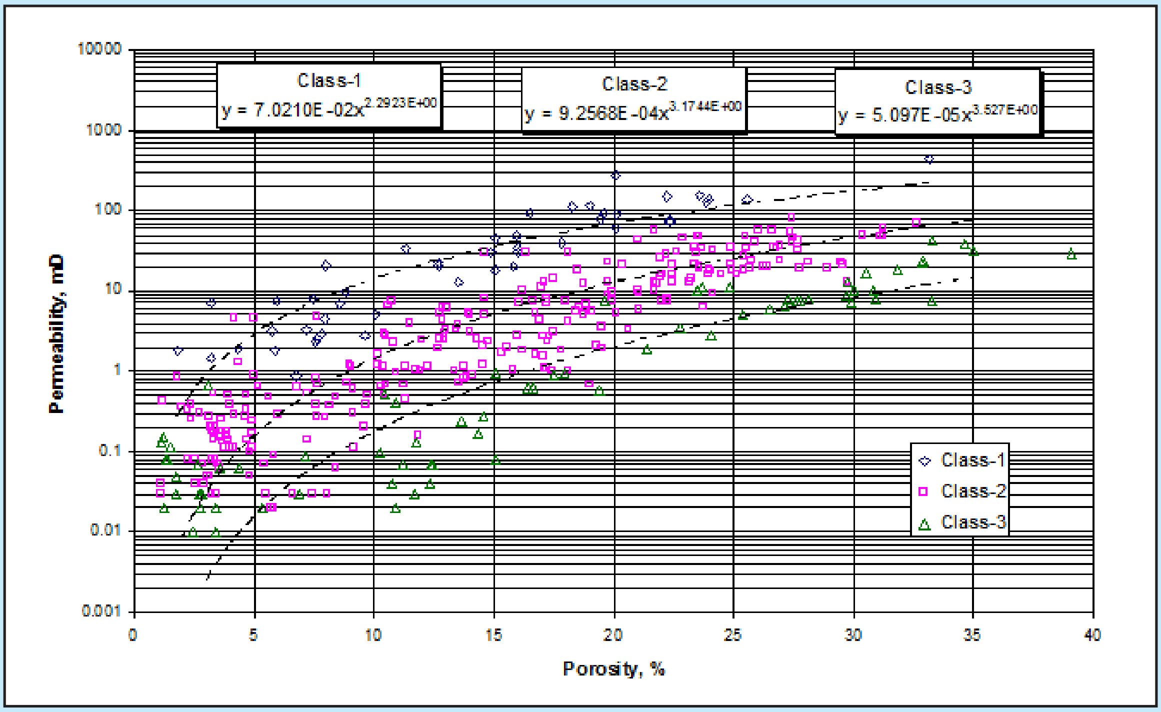

Figure 8
Porosity – permeability correlations for the three classes

disolution and fracturing. In general, this interval can be classified as having Class 2 rocks. For the lower interval no laboratory data was available but from the log analysis it appears that the interval is made of rocks belonging to Class 1.

In the log analysis for the two wells (SBG-X1 and SBG-X2) used in the model validity test, porosity was estimated using neutron-density log cross-plot. Considering that the lithology in general is carbonate water saturation was estimated using Archie water saturation model with input data as listed in Table 3. Results of porosity and water saturation estimation are presented in Table 4.

Water saturation (Archie) estimates appear to be in reasonably good conformity with well test and capillary pressure data. For instance, water saturation estimate for SBG-X1 well's Lower zone (Class 1 rocks) is 33.15%. This zone was tested and yielded gas and water at 7 MMSCFD and 89 BWPD (water cut, WC = %), respectively. When this data is confronted to potential irreducible water saturation (S_{wirr}) range of 23% - 37% (Figures 6 and 7 combined) the water saturation estimate seems to be a bit too optimistic. However, when it is considered that Class 1 rocks are characterized by 'touching vugs' (Figure 9), which could result in very high porosity and permeability, then the more likely S_{wirr} values should take the lower side of the range. S_{wirr} values of 25% - 30% are likely to conform well with the well test data.

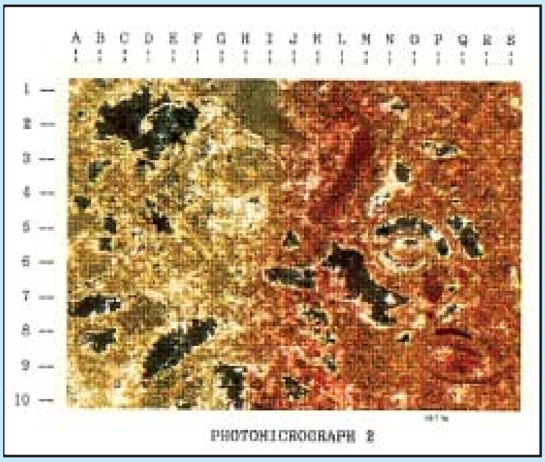

Figure 9
A thin section showing vugs that are connected to form 'touching vugs' porosity and permeability system

Table 4
Results of log analysis for SBG-X1 and SBG-X2 wells

Well	Zone	Class	Porosity, %	Sw (Archie), %	Well Test
SBG-X1	Upper	2	13.89	48.16	N/A
	Lower	1	22.06	33.15	Qg=7MMSCFD, Qw=89 BPWD
SBG-X2	Upper	2	14.15	46.72	N/A
	Lower	1	22.67	31.3	Qg=3.5 MMSCFD

Table 5
Comparison between results of conventional log analysis (Archie), Lucia models, and the new models

Well	Zone	Class	Por, %	Sw (Archie), %	Sw (new), %	Sw (Lucia), %	Well Test
SBG-X1	Upper	2	13.89	48.16	50.36	38.34	N/A
	Lower	1	22.06	33.15	35.67	10.53	Qg=7MMSCFD, Qw=89 BPWD
SBG-X2	Upper	2	14.15	46.72	46.19	31.10	N/A
	Lower	1	22.67	31.3	31.56	8.84	Qg=3.5 MMSCFD

For the Lower zone of SBG-X2 well, the water saturation (Archie) estimate is 31.3% with corresponding well test data of Qg = 3.5 MMSCFD with no water production. The absence of produced water means that the water saturation in that zone is equal to irreducible water saturation or $S_{wirr} = S_w =$ 31.3%. Comparing this estimate to the corresponding analysis of SBG-X1's Lower zone above, one can speculate that even though both Lower zones are of Class 1 rocks the SBG-X1's Lower zone is likely to have higher permeability than the SBG-X2's Lower zone. This is supported by the fact that the tested gas production rate of SBG-X2's Lower zone is only half of the SBG-X1's tested gas production rate.

For the two wells' Upper zones (Class 2 rocks) the water saturation (Archie) estimates are around 46% - 48%. No firm justification for the S_w estimates, but since the S_w estimates for the Lower zones have been well justified using the well test and S_{wirr} data then it can safely be assumed that the estimates for the Upper zones are also justified.

After the application of Archie models for the two wells is well justified estimation using the new models, as well as the Lucia models, were performed. Water saturation estimation using the original Lucia models (see Widarsono et al., 2008) appear to yield very optimistic (i.e. low) estimates (see Table 5). For the Lower zones in the two wells the S_w estimates are around 8% - 10%. Comparing to the 23% - 37% irreducible water saturation range for Class 1 rocks, the S_w estimates are far too low. Similarly to the Lower zones, S_w estimates for the Upper zones may also be considered too optimistic.

Application of the newly formulated models (i.e. the 'new' models) has proved encouraging. Tests on Class 1 and Class 2 rocks resulted in S_w estimates that are very close to the estimates produced using Archie model. Considering the validity that has been shown by the Archie model, this means that the new models have proved themselves to be valid also, at least for Class 1 and Class 2 rocks. No validity test has been made on Class 3 rock since, understandably, no data were of primary importance for such low flow-quality rocks. Nevertheless, such test should also be performed in the future whenever the needed data has become available or been made available. With the establishment of the new models, an alternative way for determining water saturation data in carbonate reservoirs has been proposed.

V. CONCLUSIONS

From the study, some primary conclusions have been drawn:

- An alternative method for estimating water saturation in carbonate reservoirs has been validated and proposed to be used.
- Water saturation estimation for carbonate reservoirs can now be performed in cases where there is no reliable resistivity log data and absence of laboratory-derived resistivity data.
- The new models are valid at least for use on Class 1 and Class 2 rocks. Validity test on Class 3 rocks has to be performed in the future.
- Lucia models tend to produce too optimistic (i.e. too low) water saturation estimates for, at least, the reservoir rocks used in this study.
- The new models are valid for Indonesian carbonate reservoirs, even though further application and tests using core samples from other carbonate reservoirs are suggested.

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