IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 04, Issue 12 (December 2014), ||V2|| PP 37-44

Research on saturation computation model and parameter determination methods for low permeability reservoirs with high mud

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***Abstract**：Gulong oilfield lies in the intersection of provenance of western peripheral Song liao Basin, where the reservoir permeability is low and the mud and calcic is high, resulting in the complicated calculation in water saturation. The common saturation computation model for shaly reservoirs can not get a better application in the field scale development due to more parameters .Based on the classic Archie formula, the formula of water saturation for the shale and calcareous reservoirs is derived to fit for field scale development，and the obtaining value methods of change value which is related to formation depth and porosity are respectively established guided by geochemical field theory and classification statistics at the same time aiming at two difficulties, which are the value of formation water resistivity in the Archie formula is difficult to obtain and the rock-electro parameters are greatly affected by pore structure. The relative error of the result of the established model is 5.38% compared with the actual sealing core data, and the effect is good. It is shown that the model and the parameter value decision methods have guiding significance in scale development for low permeability reservoirs with high mud and calcic content.*
***Keywords:** Saturation; Archie formula; Formation water resistivity; Rock-electro parameters; Geochemical field theory*

I. Introduction

Water saturation calculations are quantitative evaluation of important parameters of reservoir oiliness,at home and abroad to determine the original reservoir oil saturation has both direct and indirect methods,direct method is through the sealed coring or oil-base mud coring,laboratory analysis obtained reservoir original oil saturation, this method is more accurate, but by coring data limitations,can not use in the large-area development wells.The indirect method is by log data to set up the appropriate geological model for calculating to determine reservoir oil saturation.Since Archie from 1942 in the laboratory of pure sandstone reservoir proposed for the classic formula of saturation,many scholars have developed different reservoirs for Archie,on shale in the reservoir conductivity comprehensive analysis and quantitative evaluation[2-6],but as it involves many parameters,the actual scope of application in oilfield development is not widespread.In recent years, many scholars began to Archie parameters influencing factors began to study[7-10],but the method of determining the parameters,most scholars also insisted laboratory method for determining, without taking into account differences in the reservoir.

Western periphery's Gulong Oilfield of Songliao Basin in the multi provenance intersection area, large development area,the local formation water salinity big difference;The content of shale and calcium is heavier, oil and water complex relationship,the same oil and water layer widespread development,Logging interpretation is consistent with the low rate, oilfield development is difficult. In order to quantitatively evaluate the degree of reservoir containing water, guide the development of well perforation,it is necessary to carry out studing of water saturation calculation methods.On the basis of leading in line with the low logging interpretation reason analysis, classic Archie basis, established a high mud and calcium reservoir saturation calculation model,and for the formation water resistivity、formation factor、saturation index and other parameters, proposed a new method of determining. By water saturation established accurately calculate the extent of Gulong oilfield containing water,to improve the area oilfield development effectiveness have practical significance, and high calcium high mud reservoir saturation calculation provides a reference.

II. Difficulties in water saturation calculation

Gulong oilfield construction is located on Songliao Basin Qijia- Gulong Sag, develop the Talaha, Changjiaweizi two syncline, in the north of the syncline develop the Lung Southern nose structure,the western develop Talaha - Halahai fault zone,east of the development of the west nose structure, southeast develop Puxi nose structure. The main purpose of the development of the Upper Cretaceous Yaojia one segment Putaohua reservoir. By the western and northern provenance impact during the deposition,reservoir lithology complex,mainly for the eastern oil fields underwater distributary channel as the main body, interchannel is largely filled with mud, because in the middle of the lake catchment area, sheet sands development,lithology is siltstone or muddy siltstone,western district between underwater distributary channel and distributary channel interbedded appear,a large number of sand and shale intermediate phase development.Reservoir properties quite different, porosity distribution in the range 11.2~24.6%,with an average of 18.2%;Permeability distribution range at 0.45~176.88mD,an average of 14.9mD,belong middle porosity and low permeability reservoirs.

Due to a large number of faults cutting, Gulong oilfield formation of a large number of horst、graben structure and small amplitude,prompting the reservoir water redistribution,resulting in the area's flat water distribution relationship complex, whether on a plane high block or low block, positive or negative tectonic structure all had oil and gas shows, oil and water distribution is mainly affected by lithology,physical properties and structural control,each well no uniform oil-water interface. Portrait on oil and water relations are very complicated,there are mainly six kinds of forms:the whole section of pure oil、the upper oil and lower water（or oil and water same layer）、the upper water and lower oil、oil and water same layer、the whole section water layer、oil and water layer interaction.

Putaohua reservoir depth of between 1000.0~2100.0m,reservoir central depth of 1885.0m,depth of span.Chloride ion content of between 755~3640 mg/L, an average of 2105mg/L,total salinity between 4811 ~ 10200mg/L, an average of 7727mg/L,PH value between 7.1 to 9.0,with an average of 8.1,water type for NaHCO3 type,from Putaohua formation water salinity distribution,placanticline west wing and Longxi area formation water salinity is relatively high,salinity between 8000~10000mg/L. Depression Center partial formation water salinity is relatively high.

Statistical regional exploration and appraisal well testing for oil's testing data,the oil and water the same layer accounted for 53% of the total number of test oil layers,67.0% of oil and water the same layer geological reserves account for the total reserves,reservoir water saturation calculation becomes the most difficult for the area to spend,especially oily the same layer、partial water the same layer's identify and calculation of water content of oil and water the same layer reservoirs is more difficult.Meanwhile,due to the impact of multi-material source, resulting in lots of factors such as reservoir lithology, physical properties、thickness and fluid properties integrated together,high clay content、high irreducible water saturation and high shale additional conductive formed the region a low resistivity reservoir,Calcium and the presence of residual oil in the reservoir to form the region of high blocking water layer,leading to the fluid reservoir response characteristics curve is not obvious.

III. Computational model determination for water saturation

Archie as a qualitative interpretation base of logging data,it connect the resistivity and saturation as ties and bridges,has always played an important role in logging interpretation.Classic Archie formula,usually the rock is divided into skeleton、pore and fluid 3 parts, It fails to consider the conductive role of shale or clay, On the basic of Archie equation, Hill 、Waxman and Clavier et al. consider saturation calculation formula of argillaceous conductive mechanism, because of the parameter range and limiting in the actual production data, it is not used in a large area. In general ,focus on containing mud and calcium of Putaohua Oil layer in Gulong Oilfield, on the basic of classical Archie equation, we can conclude Archie equation though calcareous and shale corrected, and then it can be used to calculate the water saturation.

Ama	骨 架	Vma
Ash	灰 质	Vca
Aca	泥 质	Vsh
Aw	水	Φe
Ah	油 气	

Figure1 Simplified volume model of high mud and calcium reservoir

$$\frac{1}{r}=\frac{1}{r_{ma}}+\frac{1}{r_{sh}}+\frac{1}{r_{Ca}}$$

$$\frac{1}{R_t\frac{L}{A}}=\frac{1}{R_{sd}\frac{L}{A_{ma}}}+\frac{1}{R_{sh}\frac{L}{A_{sh}}}+\frac{1}{R_{Ca}\frac{L}{A_{Ca}}}$$

Multiply L^2 on both sides $\frac{L}{R_t \frac{1}{A}} = \frac{L}{R_{sd} \frac{1}{A_{ma}}} + \frac{L}{R_{sh} \frac{1}{A_{sh}}} + \frac{L}{R_{Ca} \frac{1}{A_{Ca}}}$

Multiply $\frac{1}{A * L^2}$ on both sides

$$\frac{LA}{R_t} = \frac{LA_{ma}}{R_{sd}} + \frac{LA_{sh}}{R_{sh}} + \frac{LA_{Ca}}{R_{Ca}}$$

$$\frac{LA}{R_t} = \frac{(1-V_{sh}-V_{Ca})LA}{R_{sd}} + \frac{LAV_{sh}}{R_{sh}} + \frac{LAV_{Ca}}{R_{Ca}}$$

$$\frac{1}{R_t} = \frac{1-V_{sh}-V_{Ca}}{R_{sd}} + \frac{V_{sh}}{R_{sh}} + \frac{V_{Ca}}{R_{Ca}} \qquad (1)$$

About pure rock section using Archie:

$$\frac{R_{sd}}{FR_w} = \frac{b}{S_w^n} \qquad F = \frac{a}{\phi_{sd}^m}$$

$$\phi = \phi_{sd}(1-V_{sh}-V_{Ca})$$

$$R_{sd} = \frac{FbR_w}{S_w^n \phi^m}$$

$$R_{sd} = \frac{abR_w(1-V_{sh}-V_{Ca})^m}{S_w^n \phi^m} \qquad (2)$$

Equation (2) into (1) to give: $\frac{1}{R_t} = \frac{V_{sh}}{R_{sh}} + \frac{V_{Ca}}{R_{Ca}} + \frac{S_w^n \phi^m}{abR_w(1-V_{sh}-V_{Ca})^{m-1}}$

That is: $S_w = \sqrt[n]{(\frac{1}{R_t} - \frac{V_{sh}}{R_{sh}} - \frac{V_{Ca}}{R_{Ca}}) \frac{abR_w(1-V_{sh}-V_{Ca})^{m-1}}{\phi^m})}$ (3)

Formula: V_{sh}—Shale content, decimals; V_{Ca}—Gray matter content, decimals; R_{sh}—Shale resistivity，Take 3Ω·m； R_{Ca}—GRAY resistivity，Take 80Ω·m； ϕ—Effective porosity, decimals; R_w—Formation water resistivity，Ω·m； a、b—Depends on constant lithology； m—Cementation exponent，Related to the degree of rock 's cementation rock； n—Saturation Index.

IV. The determination of model parameters by S_W calculated

For obtaining SW, except for building computational model consistent with the geological conditions, one of important measures which is parameters selection is to improve the accuracy of water saturation. The most important parameters are formation water resistivity, formation factor and resistivity increases coefficient. Because of large differences in formation water salinity of Gulong Oilfield and formation water resistivity difficultly calculated, and then we consider from the reason of different formation water salinity, at last, we get variable value accessor methods of formation water resistivity, which is associated with the depth; Simultaneously, Due to pore structure effecting Archie parameters, we classify the reservoir, so pore structure on value is reduced, we also classify to establish value method which is associated with porosity.

A. The determine of formation water resistivity

In the accumulation process, formation water is controlled by diversification of geological environment, which is a comprehensive reflection of hydrodynamic field and chemical field long evolutionary process. Because of dilution effect of atmospheric water infiltration、mudstone compaction and drainage and clay mineral dehydration etc., concentrated action of evaporation and percolation etc., formation water salinity is different in different locations, different depths and different geological periods in basin. Water chemistry is controlled by formation hydrodynamic field and chemical field, which has obvious stages, namely a vertical zonation[11].

In the longitudinal direction, evolution of formation water chemistry can be divided into centripetal flow area, centrifugal flow area and retention area, and the centrifugal flow area is a major exploration depth area in oilfield development, which contained 3 phases, divided into mudstone compaction and drainage、mudstone filter press concentrated segments and clay mineral dehydration segment. When mudstone compaction draining, formation water is diluted by water of mudstone compaction discharge, so salinity is decreasing along with increasing depth; when segment is mudstone pressure filtration and concentration, water of reservoirs is affected by minerals remain in the formation which is result from semipermeable membrane effects of clay minerals, so residual water salinity is increasing along with increasing depth; when segment is clay mineral dehydration, because of smectite to illite transformation releasing large amounts of water, formation water is diluted, so its salinity is decreasing along with increasing depth.

In central depression area of Songliao Basin, formation water also has a vertical zonation. In the structure, Gulong Oilfield lies in the central of Qijia – Gulong depression, where is in the central depression area of Songliao Basin.Though the oilfield drilling data, in the vertical,Putaohua Oil layer is in mudstone pressure filtration and concentration segment,simultaneously,it is aslo in clay mineral dehydration segment.So, by analyzing clay mineral transformation, cementation and other features in Putaohua Oil layer,we can determine depth of cut-off point,which is between mudstone filter press concentrated segment and clay mineral dehydration segment,and then we can build the relationship of formation water resistivity and depth.

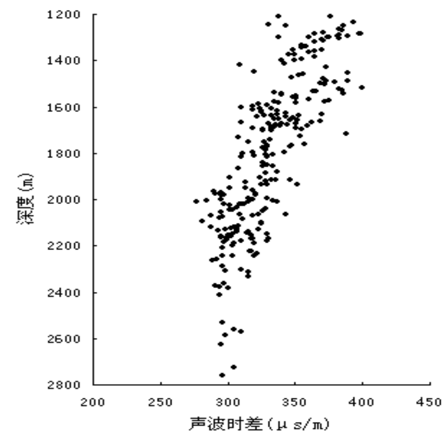
a. Sandstone Diagenesis

During the study, because it is limited by fewer the core analysis data, we use the change of time mudstone acoustic to analysis the change of formations compaction. In full-field different regions,at first, we obtain the value of pure mudstone sonic time difference from 42 wells, whose burial depth is different, and then we can draw out the change diagram (Figure.1) of the relation of pure mudstone sonic time difference and depth ,at last,we can determine compaction inflection point interval of Gulong oilfield. As we can be seen from the figure, the depth of mudstone compaction inflection point interval mianly concentrat between 1900m and 2000m, when the formation depth is less than 1900m, the value of pure mudstone sonic time difference is decreasing along with increasing depth, and it is a linear relationship, when the formation depth is more than 2000m, acoustictime is almost stable at around 300 $\mu s/m$, so we can conclude that the main diagenesis of formation is compaction, simultaneously, it aslo show that the change of mudstone acoustictime is in line with the evolution of formation water in Songliao Basin.

b. Clay mineral transformation stage

Mudstone diagenesis is main that clay minerals evolve along with the change of depth. Illite volume fraction is increasing along with increasing depth. Affected by the montmorillonite and kaolinite towards illite transformation, Iraq - fudge layer volume fraction shows that it increases firstly and then decreases.

Clay minerals of Gulong oilfield contain mainly montmorillonite, illite, illite / smectite, followed by chlorite and kaolinite, clay mineral content is generally less than 20% [13-14]. As we can see from oilfield realation diagram (Figure 2)of Iraq - fudge layer content and depth, when the depth is in the range of 1900±50m, eamonn mixed-layer content reaches the maximum, so we can conclude, in this range, that majority of smectite transform to illite transformation, which can be used as boundary segment of mudstone filter press concentrate and clay mineral dehydration segment.



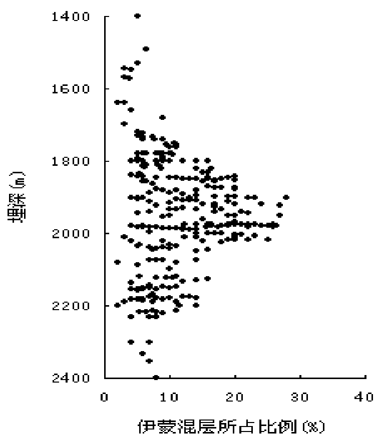


Figure 2 Relationship between the acoustic travel time of pure mudstone and depth in Gulong oil field
Figure 3 Relationship between the content of illite/smectite interlayer and depth in Gulong oil field

c. Sandstone cementation

During diagenesis, cementation mainly show the cementation of authigenic-calcite, authigenic-quartz and feldspar-increase, Authigenic-quartz increase refers to siliceous cement around detrital quartz grains to grow, and quartz overgrowth is filling intergranular porosity during the reservoir evolution, which result in porosity reduction and porosity decreases, so it makes the contact relationship among quartz grains to show line contact and suture contact. Quartz- increase usually exist[15], but along with the depth increasing and temperature increasing, quartz overgrowth content also increases. Therefore, the thin and thick of the quartz overgrowths edge reflects the intensity of diagenesis.

Take a statistics on 626 pieces of slice identification data of 66 wells, including 322 pieces of identification data of 45 wells has significant quartz secondary growth phenomenon. Observing from the statistics of depth of Gulong oilfield and frequency of quartz secondary growth(Fig.4),the numerous phenomenon of quartz secondary growth which appears when the depth of burial is above 1900m has a significant correlation, indicating that when the depth is above 1900m, cementation is further strengthened. The section of depth can also be used as a secondary basis for depth division of the section of mud filtration and enrich.

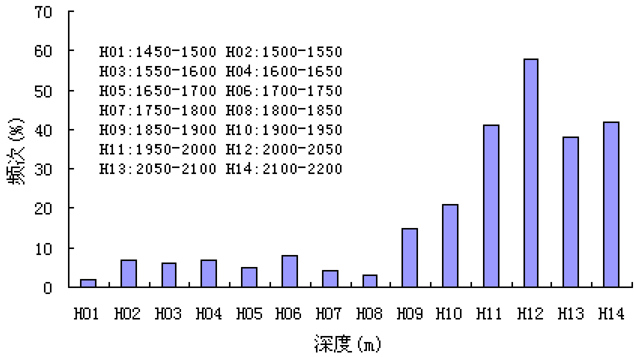


Figure 4 Increasing frequency of secondary quartz in different depth range of Gulong oil field

d. Result of vertical segmentation for geology model

Take a statistics on sample point which have a formation water test data, when formation depth is below 1900m, resistivity of formation water decreases with depth increases, when formation depth is above 1900m, resistivity of formation water increases with depth increases(Fig.5). That is, when the depth of burial is 1000m~1900m, degree of mineralization increases with the depth of burial increases, belongs to the section of mud filtration and enrich; when the depth of burial is above 1900m, degree of mineralization decreases with the depth of burial increases, belongs to the section of clay dehydration, there is a good regression relation between the data points.

Upper section: $R_w = 0.9269e^{-0.005D}$ （Relative Coefficient R=0.93） （4）

Under section: $R_w = 0.0033e^{0.0024D}$ （Relative Coefficient R=0.92） （5）

In the formula above: R_w -Resistivity of formation water; D -Depth of oil layer.

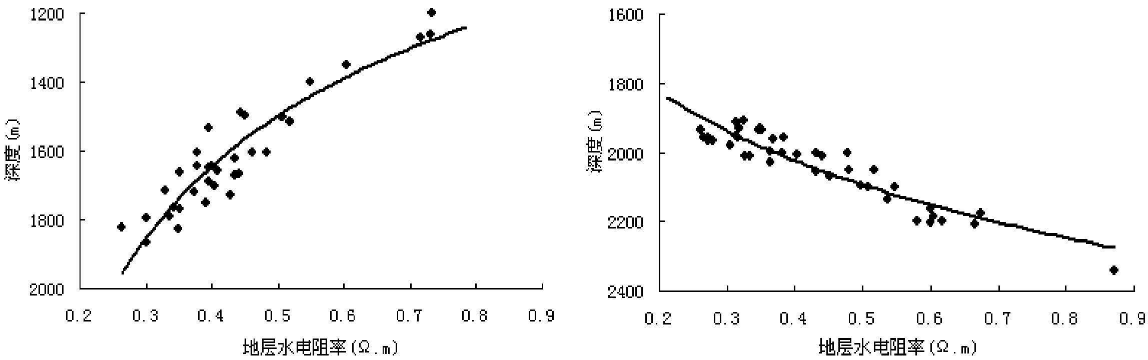


Figure 5 Relationship between formation water resistivity and depth in Gulong oil field

B. Determination rock electricity parameter

In log interpretation, parameter a 、 b 、 m 、 n is the composite reflection of many kinds of geology factors, there are of great differences between each area, layer and lithology, therefore, it is not reasonable to use a fixed parameter when different lithology exists in the same layer. A great amount of production practice prove that parameter a 、 b 、 m 、 n in Archie equation change relatively great, and is hard to choose especially in low porosity-permeability layer .The resulting water saturation would be more accurate if log data can be directly used to acquire these changeable parameters.

In order to improve accuracy of porosity, layer factor and saturation index, reduce the reflect for parameter calculating of pore structure of the layer, using mercury penetration and core analysis data, divides reservoir of Gulong oilfield into three classes(Table 1). It is easy to find by counting, F 、 n have a good relation to porosity, calculation model divided into different types are built by using porosity.

Table 1 Classification of effective reservoir in Gulong oil field

Classification	Porosity（%）	Permeability（mD）	Average pore radius（um）	Index of pore structure	Saturation median pressure（MPa）
I	>14	>5	>1	>5	<1.5
II	12～20	1～5	0.5～1	3.5～5	1.5～3.5
III	<12	0.03～5	0.1～0.5	1.2～3.5	3.5～20

I 、II class reservoir：

$$F = 10087\phi^3 - 5284.1\phi^2 + 911.13\phi - 50.434 \qquad (6)$$

$$n = -18559\phi^3 - 9959.1\phi^2 - 1767.7\phi + 105.36 \qquad (7)$$

III class reservoir：

$$F = -2015.7\phi^3 + 886.581\phi^2 - 132.24\phi + 8.1221 \qquad (8)$$

$$n = 3237.4\phi^2 - 1854.94\phi + 57.811 \qquad (9)$$

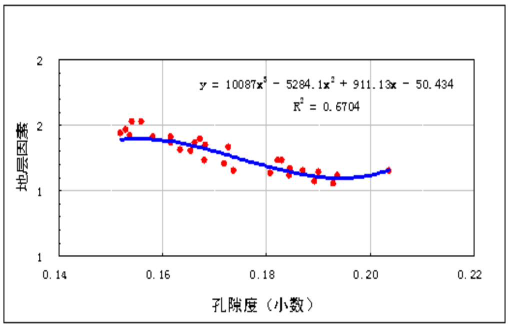


Figure 6 Relationship between formation factors and porosity (Class I, II)

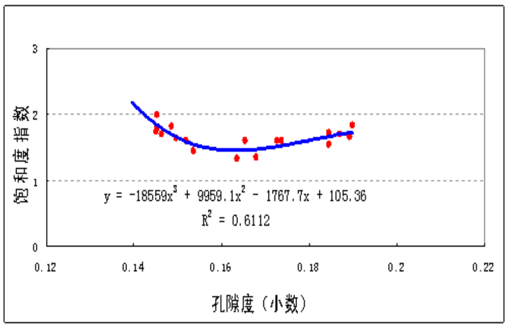


Figure 7 Relationship between saturation exponent and porosity (Class I, II）

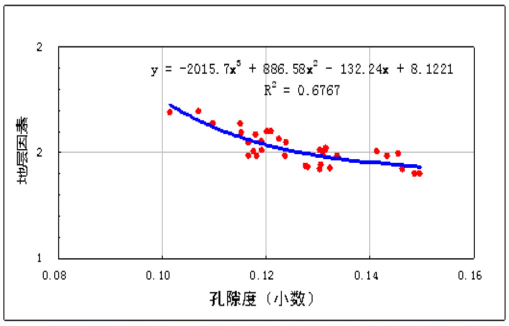


Figure8 Relationship between formation factors and porosity （Class III)

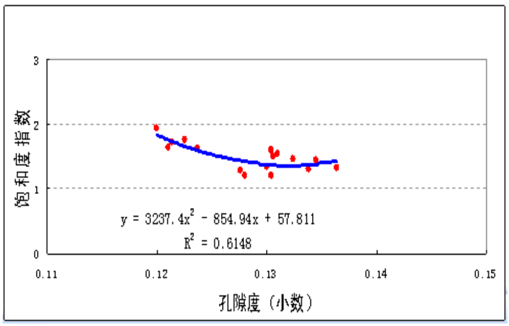


Figure 9 Relationship between saturation exponent and porosity（Class III）

C. Analysis for application effect

In order to test the correctness and effectiveness of model above and parameter value method, calculating water saturation on 6 layers of 2 wells with sealed coring data in Gulong oilfield, and compare them with analysis result in laboratory, the average absolute error is 6.91%, relative error is 5.87%. In additional, calculating on 15 layers of 10 wells with logging data in Gulong oilfield, and compare them with water saturation analyzed by logging, the average absolute error is 5.76%, relative error is 5.18%. Calculating result of 21 layer of 12 wells have a good effect in comparison with sample measuring result(Fig.10), It can be found in calculating data table(Tab.2), the average absolute error is 6.09%, relative error is 5.38%,the accuracy of value method and calculating model for saturation built by this paper is adequate proved.

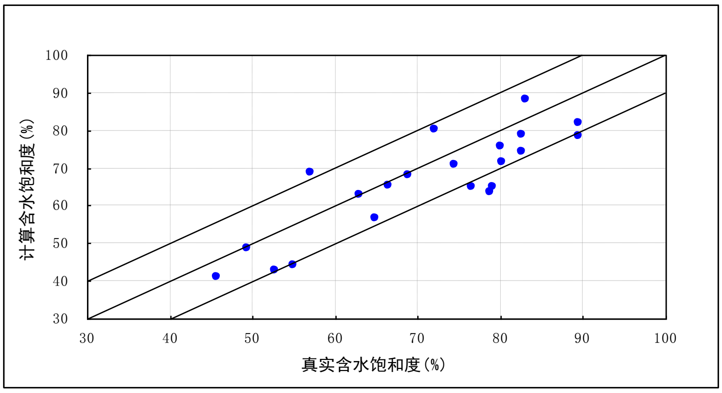


Figure 10 Cross plot of water saturation from core analysis and calculated saturation in Gulong oil field

Table 2 Error statistical table of calculated water saturation calculation in Gulong oil field

Sample source	Well	Layer	absolute error（%）	relative error（%）
Sealed coring	G139	4	6.56	5.50
	G12-94-108	2	7.61	6.63
Logging data	Glb456-562 et al	15	5.76	5.18
Total/Average		21	6.09	5.38

V. Conclusions

1. Electric conductivity of mud bound water in high volume mud reservoir results a drop of log response to oiliness sensitive of reservoir, there is a large error in water saturation calculating by using classical Archie equation, based on classical Archie equation, derives a water saturation calculating model using relatively fewer parameters, have an application value to oilfield development.

2. Resistivity of formation water calculated by common logging curve, using formation water chemical field theory, starting with the causes of degree of mineralization difference, resistivity value method built that varies with depth has a less error, and interference of man factor in the process of formation water assay, has a guide signification for resistivity calculation in low permeable reservoir.

3. Rock electricity parameter in Archie equation, suffers a relatively great influence by pore structure in low permeable reservoir, after reservoir classification by analyzing core data, built a varying value and value method of rock electricity parameter and pore, can effectively reduce the influence of calculating accuracy that pore structure towards water saturation.

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