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A new approach in calculating porosity of shallow unconsolidated soil based on Archie's Law

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Porosity (ϕ) of soil/rock is frequently approximated using Archie's Law where bulk resistivity (ρ_o) is obtained from resistivity method while pore-fluid resistivity (ρ_w) relies on well/borehole availability. This research proposes a new approach in obtaining ϕ of unconsolidated soil. The study was conducted at Balik Pulau, Minden and Teluk Kumbar. Clay's presence was determined via particle size distribution (PSD) analysis. PSD graphs' curves show that Balik Pulau is composed of elastic silt, while the other two sites consist of sand dominantly. For verification, soil samples' porosities, ϕ_{sample}, were measured to produce 31.93, 32.95 and 26.47% values for the three sites, respectively. The new approach uses saturated layer's resistivity values for porosity calculation, $\phi_{\text{resistivity}}$. The resistivity values generated F_a, ρ_w and ρ_o with constraints applied according to published reports for the parameters' range of values. Conventional and normalized Waxman–Smits models were then employed for $\phi_{\text{resistivity}}$. Conventional model produced $\phi_{\text{resistivity}}$ of 12.66, 25.33 and 12.94%, while normalized model produced better $\phi_{\text{resistivity}}$ values of 30.38, 31.91 and 27.32% for the three sites, respectively. Normalized model significantly outperforms with errors of <5%. Hence, the new approach accurately estimates saturated layer's ϕ with no dependency on physical samplings and is applicable even in clay's presence.

Keywords. Porosity; Waxman–Smits equation; normalization; resistivity method.

1. Introduction

Characteristics of a saturated granular reservoir are frequently studied based on Archie's Law using electrical resistivity method. The law describes the correlation between bulk resistivity of a saturated formation (ρ_o) with its pore-fluid resistivity (ρ_w) and porosity (ϕ) as shown in equation (1):

$$\rho_o = \alpha \rho_w \phi^{-m}, \tag{1}$$

where m represents cementation exponent of the medium which ranges from 1.2 to 3.5 for unconsolidated soils to crystalline rocks, respectively (Archie 1942). Meanwhile, as α parameter is now accepted to signify data quality, this study assumes $\alpha = 1$ which implies high-quality data (Glover 2009; Kelly *et al.* 2016).

The ρ_o term in the equation is conventionally taken from resistivity inversion, whereas ρ_w is measured at wells nearest to the resistivity survey locations. This poses as a problem because well/borehole is often unavailable and expensive to drill. While some sites may have a well, it is frequently far from the survey location. Not to mention, many porosity estimation techniques are restricted when certain information acquired from physical samplings such as hydraulic conductivity, cementation exponent, bulk density and surface conductivity is a necessity to function. Despite having soil/rock samples, many studies still failed

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to obtain an accurate cementation exponent value, consequently causing erroneous porosity estimations as the parameter carries a strong influence on porosity and saturation calculations for reserve estimation (Kadhim *et al.* 2013; Li *et al.* 2013).

Not only that, confusion on the real definition of pore fluid resistivity by researchers further exacerbates the problem in accurately determining porosity of an aquifer as they measure bulk fluid resistivity, whereas the actual concern is on the resistivity of fluids trapped in the pores that it is in physico-chemical equilibrium with the formation. This parameter value is normally obtained through expensive physical samplings and tedious laboratory works, which still poses a risk of high error if the fluid resistivity is not taken immediately due to fluid deoxygenation (Walker *et al.* 2014; Glover 2016). With regard to these issues, an alternative approach to calculate porosity is crucial to meet the demand of industrial and intellectual perspectives in regard to ground water exploration. To counter this, a new technique is presented for porosity calculation of shallow unconsolidated soil that is free from any physical samplings using Archie's Law.

Following Archie's Law, the ratio ρ_o/ρ_w is equivalent to intrinsic formation factor, F_i, only if the medium follows the original Archie's Law of clay-free condition. The ratio is then implemented into equation (1) to form equation (2) (Soupios *et al.* 2007).

$$\phi = e^{(1/m)\ln(\alpha)+(1/m)\ln(1/F_i)}. \qquad (2)$$

If the medium does not comply with Archie's Law, the ratio is known as apparent resistivity formation factor, F_a and not intrinsic formation factor, F_i as shown in equation (3). When a medium is a mixture of clay and sand/rubble/gravels, a modification to Archie's equation is needed to correct the effect of clay's conductivity (Patnode and Wyllie 1950; Worthington 1993). The effects of conductive materials in a reservoir, cause the calculated F_a values to be smaller than F_i values which are supposedly unaffected by conductive solids. The errors that may come up in F_a due to presence of conductive matrix must be eliminated in order to get the correct F_i. Therefore, the Waxman–Smits model was used in this study to approximate porosity of unconsolidated soil as it associates F_a with F_i (Vinegar and Waxman 1984). This leads to equation (4):

$$F_a = \frac{\rho_o}{\rho_w}, \qquad (3)$$

$$F_a = F_i(1 + BQ_v\rho_w)^{-1}, \qquad (4)$$

where BQ_v is due to surface conductivity effects that are primarily caused by clay to very fine sandy grain size materials (Soupios *et al.* 2007). By rearranging equation (4), a linear relationship between $1/F_a$ and ρ_w is obtained as in equation (5):

$$\frac{1}{F_a} = \frac{1}{F_i} + \left(\frac{BQ_v}{F_i}\right)\rho_w. \qquad (5)$$

Thus, F_i is obtained by plotting $1/F_a$ against ρ_w, which will then be inserted in equation (2) for calculation of the medium's porosity (Huntley 1986; Worthington 1993).

The m coefficient can be calculated for each site using equation (6) which relies on ρ_w, where m decreases as ρ_w increases (Kelly *et al.* 2016).

$$m = 1.19\exp^{0.033/\rho_w}. \qquad (6)$$

The pore fluid is one of the main conductors in a reservoir, thus ρ_o is greatly influenced by the amount of saturation (Hersir and Árnason 2009). It is important for the pores to be interconnected and saturated with water for fluid conduction to occur. Archie's Law would only be valid if the value of $\rho_w \leq 2\ \Omega$m as electrical flow is dominantly influenced by pore-fluid's resistivity, whereas considerably higher resistivity would raise doubts (Flóvenz *et al.* 1985; Purvance and Andricevic 2000). This is because the ρ_o of fluid-saturated rocks having resistivity of $\geq 2\ \Omega$m at room temperature is essentially no longer dependent on the fluid's resistivity, but is reliant on temperature and porosity instead, where the primary conductivity is influenced by its mineral and surface conductivity. Nevertheless, Archie's Law is still a reasonably good estimation when the saturating fluid predominates the resistivity (Árnason *et al.* 2000).

Another key element of this paper is simple data management and data transformation in enhancing porosity calculation's accuracy. Based on many geophysical and non-geophysical studies, data mining and transformation have proven to be an effective tool in establishing a data that is clean, noise free and consistent (Al Shalabi *et al.* 2006; Patel and Mehta 2011; Mohamad and Usman 2013).

2. Study area and geology

This research was conducted at three sites in Penang Island, Malaysia, which are Balik Pulau, USM Minden and Teluk Kumbar (figure 1). All sites are at close proximity to the coastal areas (<1 km from sea) with flat terrain, hence was presumed to be of saline to brackish setting. The island's geological settings are relatively homogenous where it is entirely made of granitic rock (figure 2) (Ong 1993). This reduces potential errors in our research as the geology is incomplex. All three sites overlie quaternary deposits composed of unconsolidated marine clay, sand and gravel, further indicating that the areas are composed of conductive materials.

Figure 1. Locations of the three sites on Penang Island.

3. Methodology

This research encompasses two ways in obtaining ϕ of soil; ϕ measurement from soil samples (ϕ_{sample}) and ϕ calculation from the new approach using resistivity data ($\phi_{\text{resistivity}}$). Three soil samples taken from each site were subjected to particle size distribution analysis (PSD) and saturation porosimetry where the measured ϕ_{sample} will act as true porosity and used as reference. On the other hand, 2-D resistivity method were conducted at all sites where the data was used in calculating porosity from Archie's Law to get $\phi_{\text{resistivity}}$. Lastly, $\phi_{\text{resistivity}}$ values were compared to ϕ_{sample} values to certify the new version of $\phi_{\text{resistivity}}$ calculation method.

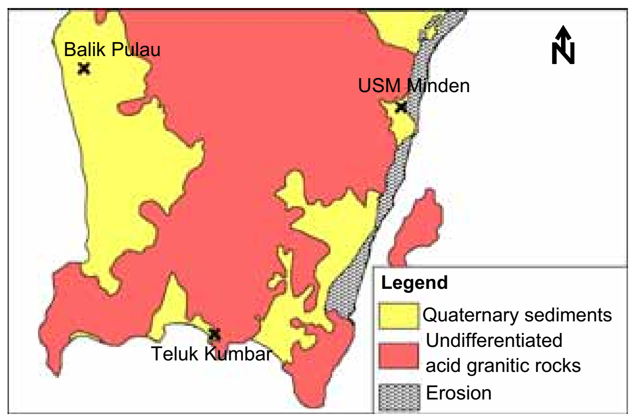

Figure 2. Geology of Penang Island. Modified from Almayahi *et al.* (2012).

3.1 *Particle size distribution analysis (PSD)*

Soil samples from Teluk Kumbar and Minden were subjected to dry sieving analysis in accordance to ASTM (2007) whereas the samples from Balik Pulau site was subjected to hydrometer method in accordance to Standard (1990) due to high clay percentage. These tests provided information on each grain size class' percentage in the soil where fine-grained sediments, which exhibit surface conduction can be determined (Glover 2016). With this test, the distribution of grain sizes can be identified from PSD curve and the curve can then be used to determine coefficient of curvature, C_c and coefficient of uniformity, C_u, thus subsequently determining its soil class. The equations used were shown in equations (7 and 8):

$$C_c = \frac{(D30)^2}{D60 \times D10}, \tag{7}$$

$$C_u = \frac{D60}{D10}, \tag{8}$$

where D10 is the diameter corresponding to 10% finer, D30 is the diameter corresponding to 30% finer, and D60 is the diameter corresponding to 60% finer.

3.2 *Porosity of soil samples*

Porosity of soil/rock from samples taken from sampling or coring are the most accurate known measurement as ϕ is measured directly using physical samples. Thus, saturation porosimetry method were done on all soil samples to measure its effective porosity (Mikhail and Robens 1983; Klobes and Munro 2006). The measured ϕ_{sample}

will be used as true porosity for comparison with calculated $\phi_{\text{resistivity}}$ using the new approach.

Soil porosity was calculated based on the relationship between unit weight and volume (Cheney and Chassie 1993). The unit weight is also known as bulk density, ρ_b, and is defined as shown in equation (9):

$$\text{Bulk density}, \rho_b = \frac{\text{Weight of sample (g)}}{\text{Volume of sample (cm}^3\text{)}}. \quad (9)$$

Porosity of soil samples, ϕ_{sample}, is obtained from void volume of saturated soil samples, V_v and total volume of soil sample, V_T defined as shown in equation (10);

$$\phi_{\text{sample}} = \frac{V_v}{V_T} \times 100\%. \quad (10)$$

3.3 *2-D resistivity imaging*

This is the first step in estimating $\phi_{\text{resistivity}}$ using the new approach where 2-D electrical resistivity method was employed to maximize the area of coverage and number of datums measured. Multi-electrode resistivity meter system (ABEM SAS4000) was used together with a computer-controlled system that automatically selected the active electrodes for each measurement (Griffiths and Barker 1993). Wenner–Schlumberger electrode array was chosen due to its high sensitivity to both lateral and vertical changes (Loke 2004). Analysis of the obtained data was done with reference to tables 1 and 2, which show resistivity values of several common soil types and fluid salinities (Braga *et al.* 2006; Ravindran *et al.* 2013). Data from RES2DINV inversion was extracted to plot a resistivity profile in Surfer software for flexibility in data processing and presentation.

Table 1. *Resistivity values of unconsolidated soil types (Braga et al. 2006).*

Type of soil	Lithology	ρ_o (Ωm)
Unsaturated soil	Uncertain	7–1440
Saturated soil	Clay	≤20
	Sandy-clay	20–40
	Clayey-sand	40–60
	Sand	≥60

Table 2. *Resistivity values of fluids with their respective TDS (Ravindran et al. 2013).*

Types of fluid	TDS (ppm)	ρ_w (Ωm)
Fresh water	100–400	25–200
Brackish water	400–7500	7–25
Saline water	7500–30000	1–7

3.4 *Porosity from resistivity method*

The saturated layer distinguished from resistivity data was further processed by implementing restriction on parameters ρ_o, ρ_w and F_a. This data constraint was applied with reference to previously reported values for unconsolidated soil where the reports provide the ceiling and floor values for these parameters (Winsauer *et al.* 1952; Soupios *et al.* 2007; Kelly *et al.* 2016). Any outliers from these range were taken out from consideration in calculating $\phi_{\text{resistivity}}$ to reduce potential errors.

Waxman–Smits model was then used on the constrained data as it considers the effect of clays' surface conductivity. From the model, F_i was obtained from F_a as the clay's effect had been removed as required by Archie's Law. The datasets were further subjected to two types of processing Waxman–Smits forms; conventional Waxman–Smits model and normalized Waxman–Smits model to observe the impacts of normalization towards the generated $\phi_{\text{resistivity}}$. The conventional model calculates F_i directly from the datasets, whereas normalized model transforms the datasets prior to finding F_i for a better best fit line (Juhasz 1981; Gomez *et al.* 2010; Okiongbo and Oborie 2015). The transformation done was according to equation (11).

$$y_{\text{normalized}} = \frac{y - y_{\text{mean}}}{SD}, \quad (11)$$

where $y_{\text{normalized}}$ is the normalized datum, y is the original datum, y_{mean} is the average y dataset and SD is standard deviation.

3.5 *Validation of $\phi_{\text{resistivity}}$*

Using ϕ_{sample} obtained from an established and well-accepted method for porosity measurements, ϕ_{sample} was used as the true porosity to compare and verify the accuracy of the calculated $\phi_{\text{resistivity}}$ at each site. Using equation (12), the accuracy of $\phi_{\text{resistivity}}$ can be determined.

$$\text{Error} = \frac{|\phi_{\text{sample}} - \phi_{\text{resistivity}}|}{\phi_{\text{sample}}} \times 100\%. \quad (12)$$

4. Results and discussion

Results from PSD analysis, saturation porosimetry, 2-D resistivity imaging and calculated porosity were discussed. The measured ϕ_{sample} was compared to $\phi_{\text{resistivity}}$ for all sites and the new approach for ϕ was certified.

4.1 *PSD analysis*

PSD analysis indicated that Balik Pulau is composed of a significant percentage of fine-grained soils (silt and clay) unlike the other two sites. Table 3 shows the PSD analysis on the three soil samples at each of the survey areas. At Balik Pulau, the dominant grain sizes are silt, followed by clay and sand, and is classified as elastic silt. In contrast, soil samples at USM Minden and Teluk Kumbar suggest that the areas are composed of gravel, sand and silt/clay, and are classified as poorly graded sand based on Folk and Ward (1957). PSD analysis showed that surface conductivity from fine grain soil is present in all sites, thus correction on surface conductivity effects on bulk resistivities must be dealt with before using Archie's Law, especially at Balik Pulau site.

4.2 *Porosity from saturation porosimetry*

Results from saturation porosimetry on the three soil samples obtained at Balik Pulau, USM Minden and Teluk Kumbar sites generated ϕ_{sample} as shown in table 4. The soil samples at Balik Pulau gave ϕ_{sample} ranging from 29.70 to 35.77%, giving an average ϕ_{sample} of 31.92%. Contrarily, ϕ_{sample} from USM Minden varied from 29.58 to 35.06% with average ϕ_{sample} of 32.95%, while 25.37–27.54% with average ϕ_{sample} of 26.47% at Teluk Kumbar. These average ϕ_{sample} values that were measured

Table 4. *Measured ϕ_{sample} at the three sites based on three soil samples.*

Site	ϕ_{sample} (%)	Average ϕ_{sample} (%)
Balik Pulau	35.77	31.92
	33.28	
	29.70	
Minden	29.58	32.95
	34.21	
	35.06	
Teluk Kumbar	25.37	26.47
	26.47	
	27.54	

Table 3. *Types of soil and clay percentage from PSD analysis.*

Site	Soil sample	Composition	Percentage (%)	Coefficient	Soil classification
Balik Pulau	1	Sand	1.50	–	Elastic silt
		Silt	84.02		
		Clay	14.48		
USM Minden	1	Gravel	3.85	$C_c = 1.25$	Poorly graded sand
		Sand	94.80	$C_u = 5.00$	
		Silt/clay	1.35		
	2	Gravel	23.51	$C_c = 1.03$	Poorly graded sand
		Sand	75.90	$C_u = 5.78$	
		Silt/clay	0.59		
	3	Gravel	28.04	$C_c = 0.94$	Poorly graded sand
		Sand	70.94	$C_u = 5.78$	
		Silt/clay	1.02		
Teluk Kumbar	1	Gravel	8.65	$C_c = 1.56$	Poorly graded sand
		Sand	89.13	$C_u = 4.00$	
		Silt/clay	2.22		
	2	Gravel	5.07	$C_c = 1.47$	Poorly graded sand
		Sand	93.74	$C_u = 4.25$	
		Silt/clay	1.19		
	3	Gravel	6.00	$C_c = 1.45$	Poorly graded sand
		Sand	91.62	$C_u = 3.50$	
		Silt/clay	2.38		

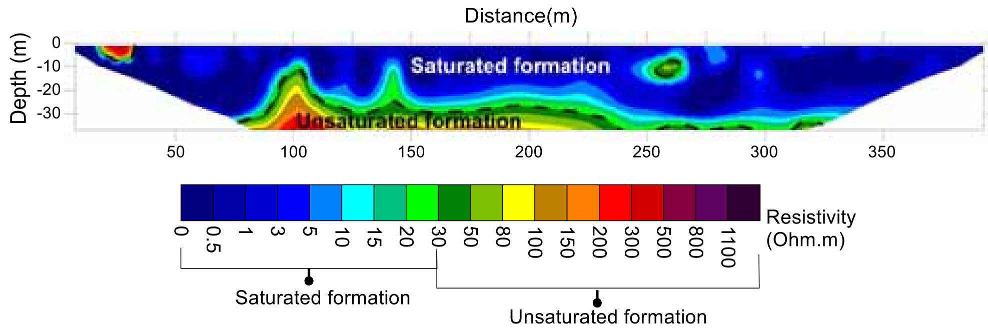

Figure 3. Resistivity profile at Balik Pulau that was separated into saturated and unsaturated mediums.

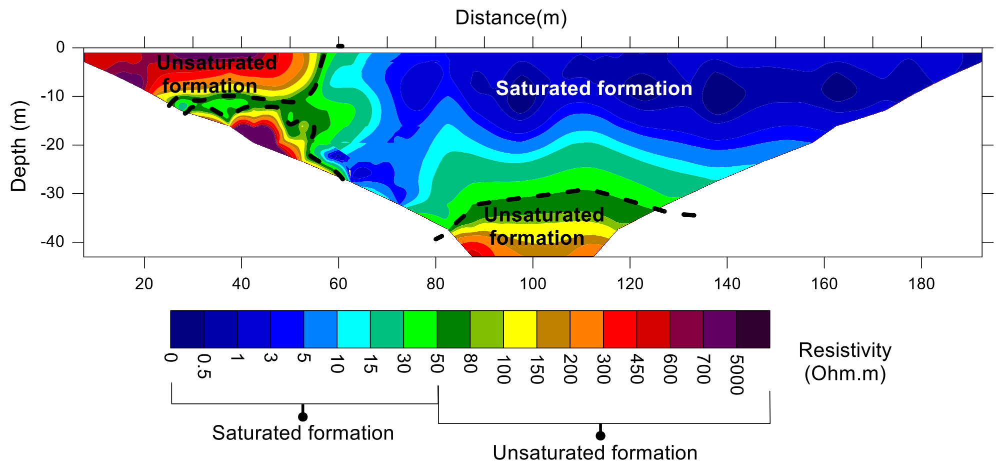

Figure 4. Resistivity profile at USM Minden that was separated into saturated and unsaturated mediums.

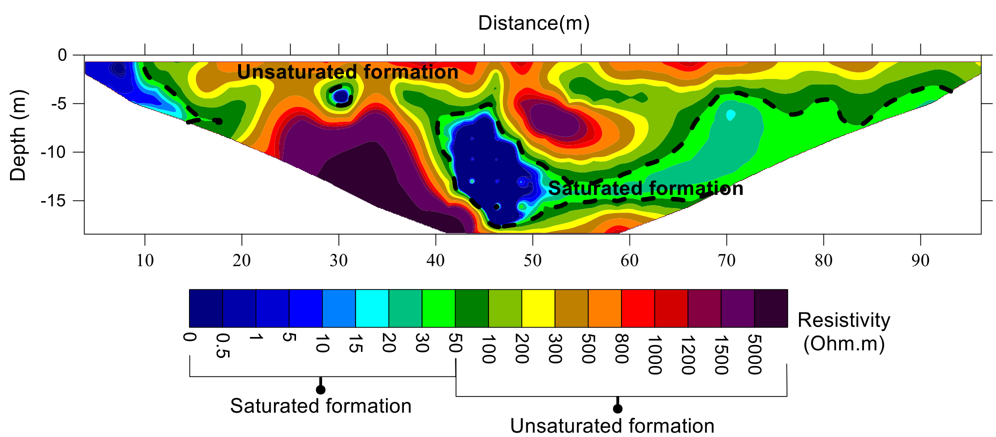

Figure 5. Resistivity profile at Teluk Kumbar that was separated into saturated and unsaturated medium.

using well-accepted method acted as the true porosity and were used as reference to validate porosities obtained from the new approach.

4.3 *2-D resistivity imaging*

Porosity calculations using the new approach started with 2-D resistivity imaging where resistivity data was obtained on site. Resistivity profiles of the three sites were presented in figures 3–5, where the saturated layer of the unconsolidated soil was distinguished. The resistivity values of the saturated layer were used in calculating the layer's porosity using Archie's Law.

4.4 *Porosity from resistivity*

The results from data restriction and Waxman–Smits model applications (conventional and normalized

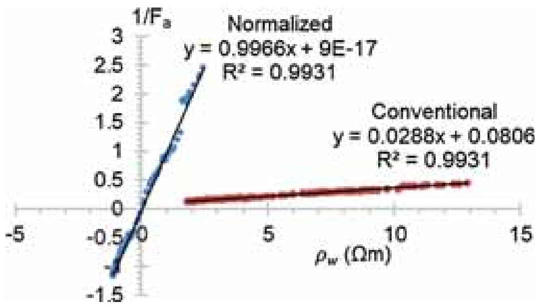

Figure 6. Models comparison between conventional and normalized resistivity data at Balik Pulau.

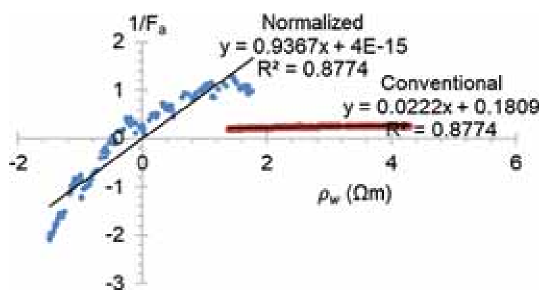

Figure 7. Models comparison between conventional and normalized resistivity data at USM Minden.

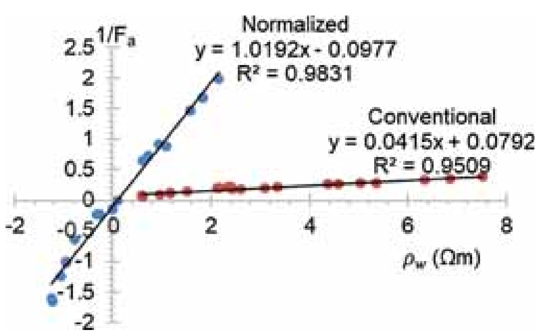

Figure 8. Models comparison between conventional and normalized resistivity data at Teluk Kumbar.

forms) for surface conductivity's effect correction were presented in graphs where corrected F_i was obtained for all sites (figures 6–8).

Table 5. *The difference between the two Waxman–Smits models' $\phi_{resistivity}$.*

Site	Waxman–Smits model	m	$\phi_{\text{resistivity}}$ (%)
Balik Pulau	Conventional	1.22	12.66
	Normalized		30.38
Minden	Conventional	1.25	25.33
	Normalized		31.91
Teluk Kumbar	Conventional	1.24	12.94
	Normalized		27.32

With known F_i, $\phi_{\text{resistivity}}$ can now be calculated using Archie's Law where the $\phi_{\text{resistivity}}$ values generated were tabulated in table 5. The $\phi_{\text{resistivity}}$ obtained from conventional form of Waxman–Smits are significantly different compared to the normalized $\phi_{\text{resistivity}}$. The conventional form produced $\phi_{\text{resistivity}}$ of 12.66, 25.33 and 12.94% at Balik Pulau, USM Minden and Teluk Kumbar sites, respectively. In contrast, the normalized form produced $\phi_{\text{resistivity}}$ of 30.38, 31.91 and 27.32%, respectively. It is clear that the two forms have significant difference in the $\phi_{\text{resistivity}}$ output using the same data input. Thus, it is crucial to determine the Waxman–Smits form that works most accurately with reference to the true porosity from ϕ_{sample}.

4.5 *Validation of $\phi_{resistivity}$*

The $\phi_{\text{resistivity}}$ of the saturated layers at Balik Pulau, USM Minden and Teluk Kumbar sites obtained from calculations were compared to ϕ_{sample} at each site respectively and tabulated as in table 6.

The comparisons show that the conventional Waxman–Smits models at the three sites produced errors ranging 20–60% which are too high to be accepted. However, the normalized models

Table 6. *Verification of $\phi_{resistivity}$ based on ϕ_{sample}.*

Site	Method	$\phi_{\text{resistivity}}$ (%)	ϕ_{sample} (%)	Error (%)
Balik Pulau	Conventional	12.66	31.92	60.33
	Normalized	30.38		4.84
Minden	Conventional	25.33	32.95	23.14
	Normalized	31.91		3.15
Teluk Kumbar	Conventional	12.94	26.47	51.21
	Normalized	27.32		3.23

Table 7. *Best porosity results with reference to soil samples.*

Site	$\phi_{resistivity}$ (%)	ϕ_{sample} (%)	Error (%)
Balik Pulau	30.38	31.92	4.84
Minden	31.91	32.95	3.15
Teluk Kumbar	27.32	26.47	3.23

produced errors that are <5% for all sites which are promising as they are comparable to the ϕ_{sample}. In general, the normalized Waxman–Smits model outperforms the conventional model by a significant margin of accuracy.

5. Conclusion

From PSD analysis, Balik Pulau site has a large percentage of fine-grained soil (>95%) and was considered as dirty formation whereas USM Minden and Teluk Kumbar sites have <5% of fine-grained soil, thus can be considered as clean formations. However, all data from each site were subjected to data constrained and clay-correction analyses.

It was clear that normalized Waxman–Smits model gave better $\phi_{resistivity}$ results than the conventional model for all sites. Normalized model generated $\phi_{resistivity}$ with <5% error for all sites in comparison to <60% error produced from the conventional model (table 7). This study proves that normalized Waxman–Smits model can calculate porosity of a saturated subsurface that is both accurate and comparable to the true porosity from soil samples, ϕ_{sample}, yet is more cost efficient than drilling or sampling.

Not only that, the new approach is also compatible for clean formations such as in USM Minden and Teluk Kumbar that are composed of <5% fine-grained soils and for dirty soil formations as Balik Pulau with >90% fine-grained soils as well. Using this new approach, porosity determination can now be obtained without wells/boreholes with >95% accuracy using a method that is more feasible, inexpensive with less hassle.

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References

Al Shalabi L, Shaaban Z and Kasasbeh B 2006 Data mining: A preprocessing engine; *J. Comput. Syst. Sci.* **2**(**9**) 735–739.

Almayahi B, Tajuddin A and Jaafar M 2012 Effect of the natural radioactivity concentrations and ^{226}Ra/^{238}U disequilibrium on cancer diseases in Penang, Malaysia; *Radiat. Phys. Chem.* **81**(**10**) 1547–1558.

Archie G E 1942 The electrical resistivity log as an aid in determining some reservoir characteristics; *Trans. AIME* **146**(**01**) 54–62.

Árnason K, Karlsdottir R, Eysteinsson H, Flóvenz Ó G and Gudlaugsson S T 2000 The resistivity structure of high-temperature geothermal systems in Iceland; In: *Proceedings of the World Geothermal Congress 2000*, Kyushu–Tohoku, Japan.

ASTM D 2007 Standard test method for particle-size analysis of soils.

Braga A C D O, Malagutti Filho W and Dourado J C 2006 Resistivity (DC) method applied to aquifer protection studies; *Rev. Bras. Geofis.* **24**(**4**) 573–581.

Cheney R S and Chassie R G 1993 *Soils and foundations workshop manual*, National Highway Institute.

Flóvenz Ó G, Georgsson L S and Árnason K 1985 Resistivity structure of the upper crust in Iceland; *J. Geophys. Res.-Sol. Ea.* **90**(**B12**) 10,136–10,150.

Folk R L and Ward W C 1957 Brazos River bar [Texas]: A study in the significance of grain size parameters; *J. Sedim. Res.* **27**(**1**) 3–26.

Glover P 2009 What is the cementation exponent? A new interpretation; *Lead. Edge* **28**(**1**) 82–85.

Glover P W 2016 Archie's Law – a reappraisal; *J. Geophys. Res.-Sol. Ea.* **7**(**4**) 1157–1169.

Gomez C T, Dvorkin J and Vanorio T 2010 Laboratory measurements of porosity, permeability, resistivity, and velocity on Fontainebleau sandstones: Laboratory measurements on sandstones; *Geophysics* **75**(**6**) E191–E204.

Griffiths D and Barker R 1993 Two-dimensional resistivity imaging and modelling in areas of complex geology; *J. Appl. Geophys.* **29**(**3–4**) 211–226.

Hersir G P and Árnason K 2009 Resistivity of rocks; In: *Short Course on Surface Exploration for Geothermal Resources*, El Salvador, UNU-GTP, LaGeo, Santa Tecla.

Huntley D 1986 Relations between permeability and electrical resistivity in granular aquifers; *Groundwater* **24**(**4**) 466–474.

Juhasz I 1981 Normalised Q_v-the key to shaly sand evaluation using the Waxman–Smits equation in the absence of core data; In: *SPWLA 22nd Annual Logging Symposium*, Society of Petrophysicists and Well-Log Analysts, Texas.

Kadhim F S, Samsuri A and Kamal A 2013 A review in correlation between cementation factor and carbonate rock properties; *Life Sci. J.* **10**(**4**) 2451–2458.

Kelly R, Pineda J and Suwal L 2016 A comparison of *in-situ* and laboratory resistivity measurements in soft clay; *Dep* **8** 10.

Klobes P and Munro R G 2006 *Porosity and specific surface area measurements for solid materials*; National Institute of Standards and Technology, Washington DC.

Li X, Qin R, Liu C and Mao Z 2013 The effect of rock electrical parameters on the calculation of reservoir saturation; *J. Geophys. Eng.* **10**(**5**) 055007.

Loke M 2004 Tutorial: 2-D and 3-D electrical imaging surveys.

Mikhail R S and Robens E 1983 *Microstructure and thermal analysis of solid surfaces*; Wiley, New York.

Mohamad I B and Usman D 2013 Standardization and its effects on K-means clustering algorithm; *Res. J. Appl. Sci. Eng. Tech.* **6**(**17**) 3299–3303.

Okiongbo K and Oborie E 2015 Investigation of relationships between geoelectric and hydraulic parameters in a quaternary alluvial aquifer in Yenagoa, southern Nigeria; *IJS* **17**(**1**) 163–172.

Ong W S 1993 *The Geology and Engineering Geology of Penang Island*; Geological Survey of Malaysia.

Patel V R and Mehta R G 2011 Impact of outlier removal and normalization approach in modified k-means clustering algorithm; *IJCSI* **8**(**5**) 331.

Patnode H and Wyllie M 1950 The presence of conductive solids in reservoir rocks as a factor in electric log interpretation; *J. Pet. Technol.* **2**(**02**) 47–52.

Purvance D T and Andricevic R 2000 On the electrical-hydraulic conductivity correlation in aquifers; *Water Resour. Res.* **36**(**10**) 2905–2913.

Ravindran A, Ramanujam N and Sudarsan R 2013 Delineation of saltwater and freshwater interphase in beach groundwater study using 2D ERI technique in the northern sector of the Gulf of Mannar Coast, Tamilnadu.

Soupios P M, Kouli M, Vallianatos F, Vafidis A and Stavroulakis G 2007 Estimation of aquifer hydraulic parameters from surficial geophysical methods: A case study of Keritis Basin in Chania (Crete–Greece); *J. Hydrol.* **338**(**1–2**) 122–131.

Standard B 1990 Methods of test for soils for civil engineering purposes; *BS1377*.

Vinegar H and Waxman M 1984 Induced polarization of shaly sands; *Geophysics* **49**(**8**) 1267–1287.

Walker E, Glover P and Ruel J 2014 A transient method for measuring the DC streaming potential coefficient of porous and fractured rocks; *J. Geophys. Res.-Sol. Ea.* **119**(**2**) 957–970.

Winsauer W O, Shearin Jr H, Masson P and Williams M 1952 Resistivity of brine-saturated sands in relation to pore geometry; *AAPG Bull.* **36**(**2**) 253–277.

Worthington P F 1993 The uses and abuses of the Archie equations. 1: The formation factor-porosity relationship; *J. Appl. Geophys.* **30**(**3**) 215–228.

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