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Application of Buckingham Theorem in the Prediction of Sand Production Rate for Unconsolidated Sandstone Reservoirs Bounded by Active Water Aquifer

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Abstract

Sand production has been the prime challenge daring the hydrocarbon industry due to its unacceptable influences on oil recovery factor, surface and subsurface production facilities especially in the Niger Delta where the landscape is festooned with unconsolidated sand face. The production of sand reduces the oil recovery volume resulting to deficit economic withdrawal due to shutdown periods for remedial works and replacement cost of damaged equipment. So much exertion has been made on forecasting the sand face breakdown and/or sand production rate, most of these prediction models typified high reliance on geo-mechanistic approach which is hinged on rock mechanism alone. This paper therefore homogenized the rock, reservoir and production data such as compressive strength pressure drawdown, water cut, and production rate, confining pressure, viscosity and sand grain size to develop a simplistic predictive model for sand production rate by applying Buckingham Theorem. The model through its development proved that the collapse of formation sand face does not necessarily translate to sand production but the onset of water-cut triggers sand production. The model was explicit on sand grain size affect on sand production, it nullified the argument expressed in some researches that sand grain size affects sand production; it also showed that viscosity of the fluid is not influential on sand production rate. The model was validated using a real reservoir data from one of the wells in the Niger Delta.

Key words: Sand production; Buckingham theorem; Production rate; Compressive strength; Water cut; Pressure drawdown

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1. INTRODUCTION

Sand production is as a result of flow of sand grains saturated with fluid, Geilikman and Dusseault (1997). The production of sand has cast a humongous challenge on the recovery of hydrocarbons when weighed in terms of oil price worldwide. production of sand from formation during oil and gas exploration comprise rigorous operational setbacks for oil and gas explorers particularly companies producing from unconsolidated sand face and most reservoirs in the Niger Delta are categorized as such O.A Adeyanju and O.A Olafuyi (2011)

The production of sand from unconsolidated reservoirs poses enormous setbacks to the hydrocarbon industry; therefore in predicting the onset of sand production, it is important to precisely ascertain the failure method and the instrumental parameters, sunday Isehunwa and Andrew Farotade (2010).

Problems caused by sanding are much, such as ruination of surface equipment for operations, well work-over strains, well clean up cases and additional cost for sand disposal. These produced sands can generate pipeline blockage, leakage and casing buckling due to formation collapse Addis (1997). Sand production is one of the substantial impasses during production in unconsolidated sandstone reservoirs. Based on sand production features observed during oil production, sand production is categorized into three types: unstable sand production, continuous sand production and catastrophic sand production, Shouwei Zhou and Fujie Sun (2016).

2. LITERATURE REVIEW

An extensive assessment of literature has demonstrated that an astonishing volume of research has been carried out spanning from experimental to analytical, numerical and geomechanistic studies to predict the rate, volume, deformation, and production of rock sands from consolidated and unconsolidated reservoirs. Mohammad Tabaeh Hayavi and Mohmood Abedifar (2016) ran a sensitivity analysis on the influence of reservoir and geo-mechanical parameters including well trajectory, poroelastic stress coefficient, Biot`s factor, maximum horizontal stress, horizontal stress anisotropy ratio, cohesive strength and uniaxial compressive strength on sand production from openhole wells, they concluded that in a normal stress regime, the critical bottom hole flowing pressure of a vertical well is smaller than that of the horizontal well and therefore is less inclined to sand production, as the poroelastic stress coefficient, Biot`s factor, maximum horizontal stress, horizontal stress anisotropy ratio are in direct relationship to the critical bottom hole flowing pressure while the compressive strength is inversely proportional to the bottom hole flowing pressure.

Osisanya. S, (2010) credited sand production to pieces of terrestrial flotsam and jetsam, debris and smaller particles of rocks weathered off other rocks. He stated that the most influencing sand production factors are compressive strength, in-situ stresses and production rate of fluid. He further established that Sand prediction include production test, well log analysis, laboratory mechanical rock testing, acoustic, intrusive sand monitoring devices and analogy. To give credence to these findings, examples and case studies from the Africa, Europe and USA were given. The work underscored data required to predict sand production as production test data, formation strength, rock dynamics elastic constants, and log data.

Haotian Wang, Deepen P. Gala, Mukul M. Sharma (2017) explained that the onset of sanding for different types of reservoir fluid shows diverse values, sand production is prevalent in multi-phase oil reservoir than in a gas reservoir; this is as a result of the effect of water breakthrough and water-cut. Higher compressive stresses are imperative for the onset of sand production in compressible gas flow than in oil flow. According to Gbenga Folorunso Oluyemi and Babs Oyeneyin.M (2010), theoretical modeling has suggested that compressive failure can be triggered by depletion, drawdown pressure and tensile failure.

Musaed N.J. A, Abdel Alim H.E and Saad El-Din M.D (1999) explained that as hydrocarbon fluids are extracted from the reservoir, the production fluid impose a drag force on the formation which when combined with the effect of drawdown pressure will overwhelm the formation compressive strength and therefore results to loosening of the sand grains. This point to a fact that there will be a particular production rate which when exceeded will lead to sand production; this flow rate is referred to as critical flow rate. When wells are produced below the critical flow rate, it does not allow the magnitude of the drag pressure to exceed the rock compressive strength., increasing the production rate beyond the critical rate leads to increasing amount of sand production, therefore establishing that the critical flow rate above which sand production becomes detrimental to economic withdrawal is highly imperative and noteworthy.

Bailin Wu and Chee P. Tan; (2002) conducted perforation collapse experiment on poorly consolidated sandstone modeled from outcrop. The tests were governed by simulated in-situ effective stresses and drawdown conditions. Water-cut was replicated by injecting water into the flowing stream of either oil or gas at different stages of the experiment. The core failure and sand production processes were observed and recorded using a bore scope in real time. The strength of a rock is related to the degree of cementation termed compressive strength. Weakly consolidated sandstone formations are associated with compressive strength less than 1000 psi, Agustawijaya, Didi (2007)

Son Tung Pham, (2017) developed a numerical model that can be used in sand control during production phase in an oil and gas well. He employed the critical bottom-hole pressure derived from geo-mechanical modeling to predict the onset of sand production. by using the hydro-mechanical modeling he was able to predict the mass of sand production versus time as well as the change in porosity versus space and time. The empirical parameters were standardized using the laboratory data and the work presented the sensitivity analysis of drawdown pressure on sand production.

Bell and Culshaw (1998) established an opposite relationship between mean grain size and strength for the Sherwood Sandstone Group, Nottinghamshire, England. sandstones in a formation in Nottinghamshire, showed that the size of grain particle has no influence on the compressive and tensile strength Production of hydrocarbons is often associated with sand production in unconsolidated sandstone reservoirs. Seyed Mostafa Seyed Atashi, Kamran Goshtasbi and Rouhollah Basirat (2018), in their research work "Fluid Properties Effects on Sand Production using Discrete Element

Method", they noted that the flow of fluid is a significant dynamic in sand grain fines conveyance.

Musaed N.J. A, Abdel Alim H.E and Saad El-Din M.D (1999) revealed that if the flow rate and confining pressure are held constant, displacing light oil with water produces smaller amount of sand than when displacing heavy oil, the change in the volume of sand produced is due to more drag force exerted by the more viscous heavy oil on the sand face. Mostafa Seyed Atashi, Kamran Goshtasbi and Rouhollah Basirat (2017), showed that the impact of confining pressure on sand production was investigated after validation of the numerical model. Results showed that rock around the wells are loosed with beginning of the sand production and loosed region is expanded with increasing production. The results also evidenced that in weak formations, confining pressure is high, and more stimulated compared to formations with less stress.

2.1 Buckingham Theorem

Buckingham Pi theorem a mathematical approach to derive the correlation of a system of importance between an actual and simulated model, in other words, it`s application is essential in stating the number of dimensional group needed to depict an event. Buckingham Pi theorem is highly appreciated where the understanding of the influencing parameters in a system is limited; it is mostly applied in designing complex systems where the number of parameters needed to describe a system is more than four. David A. Rubenstein, Wei Yin and Mary Frame (2021).

Dimensionless variables do not have units of measurement due to the fact that their derivations are from the multiplication or division of physical parameters, variable or constants of a known system. The number of independent non-dimensional parameters is derived from the disparity between the number of variables and number of dimensions in a given system. Govind S. Gupta, S. Sarkar, A. Chychko, L. D. Teng, M. Nzotta and S. Seetharaman (2014).

3. METHODOLOGY

The Buckingham pi-theorem is a method of obtaining the relationship between given variables. If there are n-variables in a problem, and these variables contain m-primary dimensions M, L, T, the equation relating all variables will have (n-m) dimensionless group as Л groups. This theorem will be applied to develop an analytical model for sand production rate, the factors considered to influence sand production rate as mentioned below were termed as variables. Each independent and dependent variable is assigned the corresponding dimensional unit. The Response is the dependent variable

Variable;

1. Viscosity (μ)- $ML^{-1}T^{-1}$ **2**. Water Cut (W_c)-$M^0L^0T^0$ **3**. Compressive Strength (C_s)-$ML^{-1}T^{-2}$ **4.** Confining Pressure (P_c)-$ML^{-1}T^{-2}$ **5.** Production Rate (Q)-L^3T^{-1} **6**. Drawdown Pressure (P_D)-$ML^{-1}T^{-2}$ **7**. Sand Particle Size(S)– L

Response;

Sand Production Rate (SPR)-L^3T^{-1}

Sand production rate is expressed as a function of the independent variables

SPR = $f(\mu, W_c, C_s, P_c, P_D, q, S)$

No of variables, m=8

No of fundamental Dimensions, n=3 (i.e. dimensional quantities to consider – mass(M), length(L) and time(T))

The recurring set must contain variables that cannot be formed into dimensionless group;

1. Sand particle size, S= L
2. Compressive Strength, $C_s = ML^{-1}T^{-2}$
3. Viscosity, $\mu = ML^{-1}T^{-1}$

No of π terms = 8-3 = 5

$\Pi_1 = S^{a1} \quad C_s^{\ b1} \quad \mu^{c1} \quad S.P$

$\Pi_2 = S^{a2} \quad C_s^{\ b2} \quad \mu^{c2} \quad P_c$

$\Pi_3 = S^{a3} \quad C_s^{\ b3} \quad \mu^{c3} \quad P_D$

$\Pi_4 = S^{a4} \quad C_s^{\ b4} \quad \mu^{c4} \quad q$

$\Pi_5 = S^{a5} \quad C_s^{\ b5}\mu^{c5}\ W_c$

Expressing each term dimensionally in terms of M L T, we have;

$\Pi_1 = M^0L^0T^0 = S^{a1} \quad C_s^{\ b1} \quad \mu^{c1} \quad S.P$

$\Pi_1 = M^0L^0T^0 = (L)^{a1}\ (ML^{-1}T^{-2})^{b1}\ (ML^{-1}T^{-1})^{c1}\ \ L^3T^{-1}$

M: 0 = b + c--------------------- (1)

L: 0 = a -b -c+3--------------- (2)

T: 0 = -2b – (-c) ----------------- (3)

From Equation 1, we determine that

b= -c

Substituting (1b = -1c) in equation 3, we have;

0 = -2b-c-1

0 = -2(-c)-c-1

0 = 2c-c-1

0 = c-1, therefore c = 1, b= -1

From equation 2

0 = a-b-c+3

0 = a-(-1)-1+3

0 = a+3

a = -3

a = -3, b = -1, c = 1

$\Pi_1 = S^{-3} \quad C_s^{\ -1} \quad \mu^1 \quad S.P$

$\Pi_1 = \mu\ S.P/S^3\ C_s$

$\Pi_2 = M^0L^0T^0 = S^{a2} \quad C_s^{\ b2} \quad \mu^{c2} \quad P_c$

$\Pi_2 = M^0L^0T^0 = (L)^{a2}\ (ML^{-1}T^{-2})^{b2}\ (ML^{-1}T^{-1})^{c2}\ \ ML^{-1}T^{-2}$

M: 0 = 2b+2c+1------------------------- (1)

L: 0 = 2a-2b-2c-1----------------------- (2)

T: 0 = -2(2b)-2c-1------------------------ (3)

From equation (1)

0 = 2b+2c+1, therefore 2b= -2c-1

Substituting in equation (3), 0 = -2(-2c-1)-2c-2, 0 = 2(2c) +2-2c-2, 2c = 0

Recall 2b=-2c-1, 2b=0-1, therefore 2b =-1

Using equation (2), 0 = 2a-2b-2c-1, 0 = 2a+1-0-1

2a = 0, therefore a = 0, b = -1, c = 0

$\Pi_2 = S^{a2} \quad C_s^{\ b2} \quad \mu^{c2} \quad P_c$

$\Pi_2 = S^0 \quad C_s^{\ -1} \quad \mu^0 \quad P_c$

$\Pi_2 = P_c / C_s$

$\Pi_3 = M^0L^0T^0 = S^{a3} \quad C_s^{\ b3} \quad \mu^{c3} \quad P_D$

$\Pi_3 = M^0L^0T^0 = (L)^{a3}\ (ML^{-1}T^{-2})^{b3}\ (ML^{-1}T^{-1})^{c3}\ \ ML^{-1}T^{-2}$

M: 0 = 3b+3c+1------------------------- (1)

L: 0 = 3a-3b-3c-1----------------------- (2)

T: 0 = -6b-3c-1------------------------ (3)

From equation (1), 0 = 3b+3c+1, 3b= -3c-1

Substituting in equation (3), 0 = -2(-3c-1)-3c-2, 3c = 0

Recall 3b = -3c-1, 3b = 0-1, therefore 3b = -1

Using equation (2), 0 = 3a-3b-3c-1, 0=3a+1-0-1

3a= 0 therefore a = 0, b =-1, c =0

$\Pi_3 = S^{a3} \quad C_s^{\ b3} \quad \mu^{c3} \quad P_D$

$\Pi_3 = S^0 \quad C_s^{\ -1} \quad \mu^0 \quad P_D$

$\Pi_3 = P_D / C_s$

$\Pi_4 = M^0L^0T^0 = S^{a4} \quad C_s^{\ b4} \quad \mu^{c4} \quad q$

$\Pi_4 = M^0L^0T^0 = (L)^{a4}\ (ML^{-1}T^{-2})^{b4}\ (ML^{-1}T^{-1})^{c4}\ \ L^3T^1$

M: 0 = 4b+4c----------------------------- (1)

L: 0 = 4a-4b-4c+3----------------------- (2)

T: 0 = -8b-4c-1------------------------- (3)

From equation (1)

0 = 4b+4c, therefore 4b = -4c

Substituting in equation (3)

0 = -8b-4c-1

0 = -2(-4c)-4c-1

0 = 8c-4c-1

0 = 4c-1, therefore 4c = 1, 4b = -1

From equation (2), 0 = 4a-4b-4c+3, 0 = 4a+1-1+3

4a = -3, a=-3/4

b=-1, c=1

$\Pi_4 = S^{-3} \quad C_s^{\ -1}\mu^1 \quad q$

$\Pi_4 = \mu\ q / C_s\ S^3$

$\Pi_5 = M^0L^0T^0 = S^{a5} \quad C_s^{\ b5}\mu^{c5} \quad W_c$

$\Pi_5 = M^0L^0T^0 = (L)^{a5}\ (ML^{-1}T^{-2})^{b5}\ (ML^{-1}T^{-1})^{c5}\ M^0L^0T^0$

M: 0 = 5b+5c+0------------------------- (1)

L: 0 = 5a-5b-5c+0----------------------- (2)

T: 0 = -2(5b)-5c+0----------------------- (3)

From equation (1)

0 = 5b+5c, 5b = -5c

Substituting in equation (3), 0 = -2(-5c)-5c, 5c = 0

Recall 5b = -5c, therefore 5b=0

From equation (2), 0 = 5a-5b-5c+0, 5a = 0, therefore a = 0, b = 0, c = 0

$\Pi_5 = S^0 \quad C_s^{\ 0}\mu^0\ W_c$

$\Pi_5 = W_c$

$\Pi_1 = f\ (\Pi_2, \Pi_3, \Pi_4, \Pi_5)$

$\mu\ S.P/S^3\ C_s = f\ [\ (P_c/ C_s), (P_D/ C_s), (\mu q/ C_s\ S^3), (W_c)]$

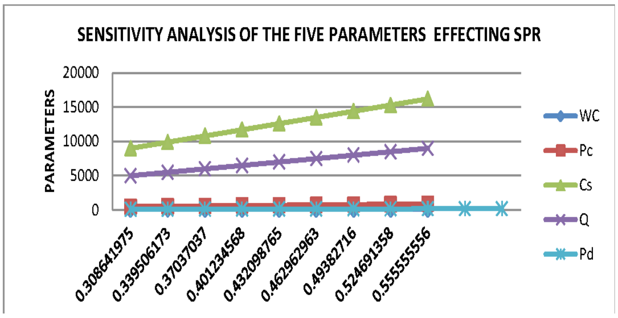
$\mu\ S.P/S^3\ C_s = f\ [P_c P_D\ \mu q\ W_c/ C_s^{\ 3}S^3]$

$SPR = [S^3\ C_s / \mu]\ f\ [P_c P_D\ \mu q\ W_c/ C_s^{\ 3}S^3]$

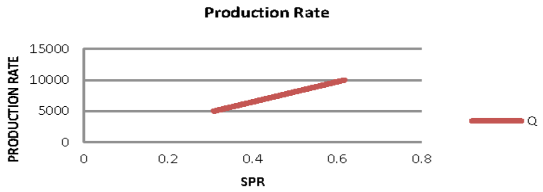
$\mathbf{SPR = [(P_c P_D\ q\ W_c) / C_s^{\ 2}]}$

Where: P_c = Confining Pressure [-], P_D = Drawdown Pressure [-], Q = Production Rate [-], W_c = Water cut [-], C_s = Compressive Strength **[-]** **(all parameters are dimensionless)**

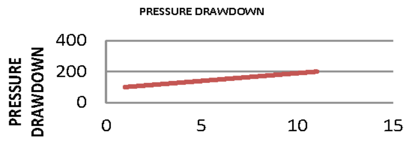
4. RESULTS AND DISCUSSION



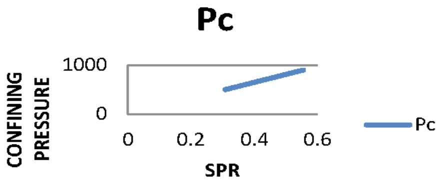
Graph 1
Sensitivity Analysis of the Five Parameters Effecting Sand Production Rate



Graph 2
Production rate versus sand production rate



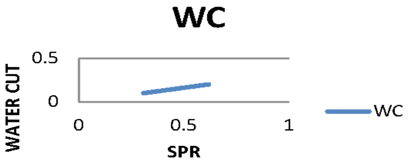
Graph 3
Pressure Drawdown versus SPR



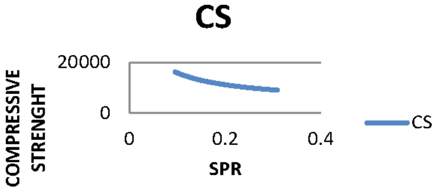
Graph 4
Confining pressure vs SPR

4.1 Validation of the Developed Model.

Raw field data obtained from onshore wells prone to sanding in the Niger Delta were compared to the predicted sand Production rate using the developed model.



Graph 5
Water cut vs SPR



Graph 6
Compressive strength Vs SPR

4.2 Reservoir data for reservoir x of well F 10

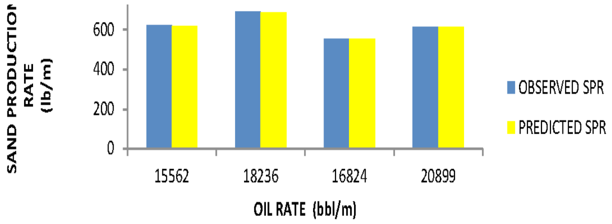
Reservoir pressure (psi)	3412
Compressive strength (psi)	4863
Overburden pressure (psi)	0.978 psi/ft
Reservoir depth (ft)	7631

Table 1
Production data of reservoir X of well F 10

Unique ID	Date	Oil bbl/m	Sand production rate Ib/m	Pressure drwadown psi	Water cut %
F-10-X	01-JUL-05	15562	625	175	72
F-10-X	01-NOV-05	18236	691	210	57
F-10-X	01-MAR-06	16824	555	200	52
F-10-X	01-AUG-06	20899	613	212	44

Table 2
Production and reservoir data of reservoir X of well F-10 with predicted SPR

ID	Date	Oil rate bbl/m	Confining pressure psi	Pressure drawdown Psi	Water cut %	Compressive strength Psi	Observed SPR Ib/m	Predicted SPR Ib/m	Error
F-10-X	01-JUL-05	15562	7463.12	175	72	4863	625	618.79	0.99
F-10-X	01-NOV-05	18236	7463.12	210	57	4863	691	688.87	0.31
F-10-X	01-MAR-06	16824	7463.12	200	52	4863	555	552.17	0.51
F-10-X	01-AUG-06	20899	7463.12	212	44	4863	613	615.21	-0.36



Graph 7
Sand production rate(SPR) Vs Oil Rate

4.3 Reservoir Data for Reservoir X of Well F 12

Reservoir pressure (psi)	2774
Compressive strength (psi)	4698
Overburden pressure (psi)	0.978/ft
Reservoir depth (ft)	7417

Table 3
Production Data of Reservoir Y IN WELL F-12

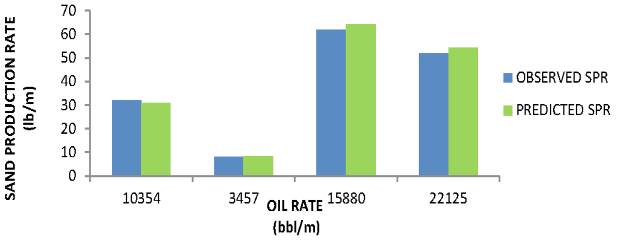
	Date	OIL bbl/m	Sand production rate Ib/m	Pressure drawdown psi	Water cut %
F-12-Y	01-APR-02	10354	32	35	26
F-12-Y	01-JUN-02	3457	8	26	30
F-12-Y	01-SEPT-02	15880	62	41	30
F-12-Y	01-N0V-02	22125	52	44	17

Table 4
Production and reservoir data of WELL F12 with predicted SPR

Unique ID	Date	OIl rate bbl/m	ConfiniNG Pressure psi	Pressure drawdown psi	WateR Cut %	Compressive strenght psi	SPR S Observed Ib/m	SPR Predicted Ib/m
F-10-X	01-JUL-05	10354	7254	35	26	4698	**32**	30.97
F-10-X	01-NOV-05	3457	7254	26	30	4698	**8**	8.35
F-10-X	01-MAR-06	15880	7254	41	30	4698	**62**	64.19
F-10-X	01-AUG-06	22125	7254	44	17	4698	**52**	54.39

Table 5
Comparison of Observed SPR with Predicted SPR OF Reservoir X in WELL F12

OIl rate bbl/m	Confining pressure psi	Pressure drawdown psi	Water cut %	Compressiv E Strenght psi	Sand production rate observed Ib/m	Sand production rate predicted Ib/m	% Error
10354	7254	35	26	4698	**32**	30.97	3.22
3457	7254	26	30	4698	**8**	8.35	4.34
15880	7254	41	30	4698	**62**	64.19	3.53
22125	7254	44	17	4698	**52**	54.39	4.60



Graph 8
Bar Chart of Observed and Predicted SPR at Different Oil Rates

4.3 Discussion of Result

For the seven parameters that were used in developing the model, sand grain size and fluid viscosity were nullified in the model indicating that their effects on sanding rate are negligible which means they do not affect sanding rate as often mentioned in literature. Results of the degree of influence of other variables appearing in the developed model were obtained by carrying out sensitivity analysis in Microsoft excel to evaluate the impact of each of the parameter on sand production using the final equation obtained from the Buckingham Pi-theorem, compressive strength has the greatest influence on sand production rate. The other parameters have equal effects on sand production but the model shows that without the production of water, sand will not be produced therefore water cut is a critical factor to sand production from the reservoir.

The percentage of the predicted sand production rate using the model formed in this research from the actual or observed sand production rate from the reservoir is encouraging. The deviation from the actual in both wells are below 5 percent

All the parameters in the model have direct relationship to sand production rate except Rock Compressive Strength which is inversely proportional to sand production rate

5. CONCLUSION

Conclusions derived from the formulated model shows that water production in indeed the major factor for sand production, sand grain size does not contribute to sand production. More research should be carried out on ways to improve the compressive strength of the rock to withstand the burden of pressure hydrocarbon withdrawals impose on the rock. More research is also required to show technological ways to reduce water production which will in effect reduce sand production. This model can not be effective if there is no water production.

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NOMENCLATURE

μ--	viscosity
Wc---	Water cut
Cs --	Compressive Strength
Pc --	Confining Pressure
Q-	Production Rate
Pd---	Pressure Drawdown
S--	Sand Particle Size
L--	Length
T--	Time
M--	Mass
SPR--	Sand Production Rate
lb/m--	Pound per Month
psi--	Pound Per Square Inch
bbl/m---	Barrel per Month