# ESTIMATION OF SAND PRODUCTION VOLUME FOR WEAK TO MODERATE STRENGTH SANDSTONE RESERVOIR USING FINITE ELEMENT METHOD

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**ABSTRACT**

The aim of this research work is to develop a new non-liner constitutive model and novel technique to estimate sand production volume for weak to moderate strength sandstone reservoir rocks. Sand production due to rock failure can have a severe impact on the economics of an oil or gas field where the downhole or surface components erosion due to sand production can lead to loss of well integrity and hydrocarbon leakage. Furthermore, if the drawdown increases, sand production volume is becoming more prevalent. To facilitate best sand management over the life of a field, an accurate prediction of sand production volume is required to increase productivity of the well at low operating cost. The current method is unable to fully cater the industry's need as most of the work related to sand production models are developed for onset failure but little on sand production volume estimation. This research work was initiated to fill this industry gap by developing a new technique for sand production volume estimation. The selection of failure criteria has a big impact on accurate predictability on sandstone failure and sand production volume prediction, thus an investigation on the needs for a new non-linear constitutive model has been performed. A new constitutive model has been developed and validated to assist numerical model validation. A new workflow and method have been developed for accurate sand production volume prediction. A novel approach has been developed in this study to enable continuum Finite Element Method (FEM) model to replicate as discontinuum model. This was achieved by creating a new computer code to communicate with FEM solver to remove all failed grid cells (mesh) and allow stress stabilisation around perforation cavity. This technique is known as progressive perforation cavity failure and stabilisation (PPCFS). The invented technique was tested on both laboratory test and field data. A 3D FEM model developed using actual well and field data was used to validate and evaluate the robustness of the developed workflow and method. The outcome of this study shows that the new constitutive model has better predictive capability on both the sandstone failure and sand production volume. The combination of the newly developed Assef-Surej-Ariffin (ASA) constitutive model and the PPCFS FEM method is able to predict onset failure of sandstone and sand production volume accurately within 2.5% and 5% error margin respectively when compared to actual laboratory testing. Meanwhile, field data yields an excellent match with actual observed sand production volume in the field within 3% error margin. The parametric analysis concluded that rock strength has proportional impact on sand production volume. Meanwhile the combination of borehole deviation, smaller perforation diameter, and oriented perforation could reduce the sand production volume. This method also can be used to optimize the controllable parameters (well and perforation design) to eliminate sand production completely provided that the compressive strength and far field stresses of the reservoir permit. Therein, it can be concluded that the developed model is novel and able to assist the oil and gas industry to estimate the possible producible sand volume for their planned drawdown for sandstone reservoirs using the geomechanical properties.

# ABSTRAK

Tujuan kajian ini adalah untuk membangunkan satu model juzuk tak linear yang baharu dan teknik asli bagi menganggar isi padu pengeluaran pasir untuk batuan reservoir yang lemah hingga ke sederhana. Pengeluaran pasir yang berpunca daripada kegagalan batuan memberikan kesan ekonomi yang teruk terhadap medan minyak dan gas dengan hakisan yang berlaku pada komponen dalam lubang dan komponen permukaan boleh menyebabkan telaga kehilangan integriti dan bocoran hidrokarbon. Jika surutan meningkat, isi padu pengeluaran pasir menjadi semakin ketara. Demi menghasilkan pengurusan terbaik pasir sepanjang hayat sebuah medan, peramalan yang tepat bagi isi padu pengeluaran pasir adalah diperlukan supaya boleh meningkatkan produktiviti telaga pada kos operasi yang rendah. Kaedah terkini tidak mampu memenuhi keperluan industri memandangkan kebanyakan model dibangunkan untuk kajian kegagalan permulaan dengan tumpuan yang terhad terhadap penganggaran isi padu pengeluaran pasir. Kajian ini dilaksana bagi memenuhi jurang itu dengan membangunkan satu teknik yang baharu untuk penganggaran isi padu pengeluaran pasir. Pemilihan kriteria kegagalan mempunyai kesan yang besar terhadap ketepatan dalam kebolehramalan kegagalan batu pasir dan penganggaran isi padu pengeluaran pasir. Oleh itu, kajian yang memerlukan penggunaan model juzuk tak linear telah dilaksana. Satu model juzuk yang baharu telah dibangun dan disahkan bagi mengesah model berangka. Alir kerja dan kaedah yang baharu telah dibangunkan bagi meramal secara tepat isi padu pengeluaran pasir. Pendekatan yang dibangun adalah untuk membolehkan model kontinum Kaedah Unsur Terhingga (FEM) diulangi sebagai model tak kontinum. Kajian ini berakhir dengan terciptanya satu kod baharu komputer yang boleh berkomunikasi dengan penyelesai FEM bagi menyingkir semua sel grid (jaringan) yang gagal dan membenarkan penstabilan tegasan di sekitar rongga penebukan. Teknik yang dikenali penstabilan dan kegagalan progresif rongga penebukan (PPCFS) itu telah diuji menggunakan data medan dan data uji kaji makmal. Model FEM 3D telah dibangun menggunakan data telaga dengan data medan digunakan bagi mengesah dan menilai kemampuan alir kerja dan kaedah yang terhasil. Hasil kajian menunjukkan bahawa model baharu juzuk mempunyai kemampuan ramalan yang lebih baik tentang kegagalan batu pasir dan isi padu pengeluaran pasir. Gabungan model baharu juzuk Assef-Surej-Ariffin (ASA) dan kaedah PPCFS FEM boleh meramal secara tepat kegagalan permulaan batu pasir dan isi padu pengeluaran pasir dengan masing-masing jidar selisih sekitar 2.5% dan 5% apabila dibandingkan dengan hasil pengujian makmal. Di samping itu, data medan memberikan hasil yang baik berbanding isi padu pengeluaran pasir sebenar di medan dengan jidar selisih sekitar 3%. Analisis parameter menunjukkan bahawa kekuatan batuan mempunyai kesan berkadaran terhadap isi padu pengeluaran pasir. Selain itu, gabungan lencongan lubang, diameter penebukan yang kecil, dan penebukan berarah mampu mengurangkan isi padu pengeluaran pasir. Kaedah ini juga boleh diguna untuk mengoptimumkan parameter-parameter boleh kawal (reka bentuk penebukan dan telaga) bagi menyingkir sepenuhnya pengeluaran pasir dengan bantuan kekuatan mampatan dan tegasan batuan reservoir. Kesimpulannya, model yang dibangunkan adalah asli dan boleh membantu industri minyak dan gas untuk menganggar isi padu pengeluaran pasir berdasarkan surutan yang dirancang bagi reservoir batu pasir menerusi penggunaan sifat-sifat geomekanikal.

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| | | |
|---|---|---|
| BEM | - | Boundary element method |
| BHFP | - | Bottom hole flowing pressure |
| BHFP | - | Bottom hole flowing pressure |
| CDPP | - | Critical drawdown pressure |
| CPP | - | Critical pore pressure |
| DEM | - | Discrete element method |
| DTCO | - | Compressional wave travel time |
| DTSM | - | Shear wave travel time |
| FANG | - | Internal friction angle |
| FD | - | Finite difference method |
| FDEM | - | Finite discrete element method |
| FEM | - | Finite element method |
| FEM | - | Finite element method |
| FVM | - | Finite volume method |
| GR | - | Gamma ray |
| IOC | - | International oil company |
| MEM | - | Mechanical earth model |
| MM | - | Meshless method |
| NOC | - | National oil company |
| PPCFS | - | Progressive perforation cavity failure and stabilisation |
| PPRS | - | Reservoir pore pressure |
| PR | - | Poisson’s ratio |
| RHOB | - | Bulk density |
| TSTR | - | Tensile strength |
| TXSP | - | Total minimum horizontal stress |
| TYSP | - | Total maximum horizontal stress |
| TZSP | - | Total overburden vertical stress |
| UCS | - | Unconfined compressive strength |
| $UCS_{apparent}$ | - | Apparent unconfined compressive strength |
| YME | - | Young’s modulus e |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $\nu, \nu_{sta}, \nu_{static}$ | - | Static poisson's ratio |
| $E, E_{sta}, E_{static}$ | - | Static young's modulus |
| $\sigma_{axial}$ | - | Axial stress |
| $\sigma_{radial}$ | - | Radial stress |
| $\varepsilon_{axial}$ | - | Axial strain |
| $\varepsilon_{radial}$ | - | Radial/lateral strain |
| Diameter $_{original}$ | - | Original diameter |
| Diameter $_{final;}$ | - | Final deformed diameter |
| Length $_{original}$ | - | Original length |
| Length $_{final}$ | - | Final deformed length |
| $E_{dyn}$ | - | Dynamic young's modulus |
| $\nu_{dyn}$ | - | Dynamic poisson's ratio |
| $\rho, \rho_b$ | - | Bulk density |
| $\Delta t_c$ | - | Compressional wave travel time, µsecs/ft |
| $\Delta t_s$ | - | Shear wave travel time, µsecs/ft |
| $\nu_{dyn}$ | - | Dynamic poisson's ratio |
| $G_{dyn}$ | - | Dynamic shear modulus |
| $E_{dyn}$ | - | Dynamic young's modulus |
| $K_b$ | - | Bulk modulus |
| $\beta_b$ | - | Bulk compressibility |
| $LF_{failure}$ | - | Load force at failure |
| A | - | Surface area for the specimen |
| $\phi_{fang}$ | - | Internal friction angle |
| µ | - | Coefficient of internal friction |
| $\tau$ | - | Shear stress |
| $\sigma'$ | - | Effective normal stress |
| $\beta, \beta_{faiure}$ | - | Failure angle |
| $d, D$ | - | Diameter |
| $F$ | - | Failure |

| | | |
|---|---|---|
| $P, P_p$ | - | Pressure |
| $g$ | - | Gravity |
| $\rho_{surface}$ | - | Bulk density for surface formation |
| $z$ | - | True vertical depth |
| $\sigma_v, S_v$ | - | Overburden vertical stress |
| $\sigma_{min}, S_{hmin}$ | - | Minimum horizontal stress |
| $\sigma_{max}, S_{Hmax}$ | - | Maximum horizontal stress |
| $\sigma'_v$ | - | Effective overburden vertical stress |
| $\sigma'_{min}$ | - | Effective minimum horizontal stress |
| $\sigma'_{max}$ | - | Effective maximum horizontal stress |
| $\alpha$ | - | Poroelastic biot's coefficient |
| $\varepsilon_x$ | - | Tectonic strains in minimum horizontal stress directions |
| $\varepsilon_y$ | - | Tectonic strains in maximum horizontal stress directions |
| $r, R$ | - | Radius |
| $L$ | - | Length |
| $U_{strain}$ | - | Total strain energy |
| $W_{load}$ | - | Work done by loads |
| $E_{total}$ | - | Total potential energy |
| $F_i^n$ | - | Normal force |
| $k^n$ | - | Normal stiffness |
| $k^s$ | - | Shear stiffness |
| $F_i^s$ | - | Shear force |
| $\varphi$ | - | Borehole azimuth reference to minimum horizontal stress |
| $\varphi_{min}$ | - | Minimum horizontal stress direction |
| $\psi$ | - | Borehole deviation |
| $\mu$ | - | Mohr friction co-efficient slope |
| $g$ | - | Gravitational constant |
| $z$ | - | True vertical depth |

| | | |
|---|---|---|
| $n_{exp}$ | - | Fitting parameters for overburden vertical stress calculation |
| $\rho_{surface}$ | - | Bulk density for surface formation |
| $E_{total}$ | - | Total potential energy |
| $U_{strain}$ | - | Strain energy |
| $W_{load}$ | - | Work done by applied loads |
| $\sigma_1$ | - | Maximum principal stress |
| $\sigma_2$ | - | Intermediate principal stress |
| $\sigma_3$ | - | Minimum principal stress |
| $\bar{J}_1$ | - | Mean effective stress |
| $J_2$ | - | Deviatoric stress component |
| $P_{bhf}, P_w$ | - | Bottom hole flowing pressure |
| $UCS_{apparent}$ | - | Apparent unconfined compressive strength |
| $\mu_{kappa}$ | - | Pore pressure depletion factor |
| $r_c$ | - | Radius for total collapse |
| $r_1$ | - | Arch spherical radius |
| $r_s$ | - | New spherical radius |
| $S_o$ | - | Cohesive strength |
| $\rho_2, \rho_1$ | - | Gas density |
| $P_{rc}$ | - | Pressure at the face of cavity |
| $\sigma_r, \sigma_{rr}$ | - | Radial stress |
| $\sigma_t, \sigma_\theta, \sigma_{\theta\theta}$ | - | Tangential stress/hoop stress |
| $m_{total}, M_{sand}$ | - | Total sand mass |
| $\phi_{poro}$ | - | Porosity |
| $R^I_{po}$ | - | Radius of plastic zone |
| $R^I_{pL}$ | - | Radius of plastic zone along perforation length |
| $R_i$ | - | Perforation diameter |
| $L_{perf}$ | - | Perforation length |
| $N_{perf}$ | - | Number of perforations |
| $\varepsilon^p_v$ | - | Volumetric plastic strain |
| $\omega$ | - | Damage variable |
| $\ell$ | - | Number of elements |

$V_{sand}$ - Volume of sand

$\Omega_i$ - Volume of an element

$p^{cap}$ - Mean effective stress at cap

$f, F_{shear}$ - Failure in shearing

$F_{tensile}$ - Failure in tension

$F_{cap}$ - Failure at cap (pore collapse)

$t_{cutoff}$ - Tensile strength cut-off

$d\bar{\bar{\varepsilon}}$ - Incremental total strain tensor

$d\bar{\bar{\varepsilon}}^e$ - Elastic reversible strain component

$d\bar{\bar{\varepsilon}}^p$ - Non-linear plastic irreversible strain component

$\alpha_{thermal}$ - Thermal expansion co-efficient

$\Delta T$ - Differential temperature

$\epsilon_3^{pp}$ - Post failure radial plastic strain

$\epsilon_3^{p}$ - Radial plastic strain at failure

$\epsilon_3^{e}$ - Radial elastic strain

$\epsilon_1^{e}$ - Axial elastic strain

$\epsilon_1^{phard}$ - Axial plastic strain before failure

$\epsilon_1^{psoft}$ - Post failure axial plastic strain

$F_{failure}$ - Failure value

$q'$ - Deviatoric stress

$\bar{\bar{S}}'$ - Deviatoric stress tensor

$\theta_{lode}$ - Lode's angle

$A_\emptyset$ - Represents the coefficient of internal friction

$n_a$ - Dependency of material failure parameter

$\bar{\bar{\delta}}$ - Kronecker tensor

$A_\emptyset$ - Represents the coefficient of internal friction

$n_a$ - Dependency factor of material failure

$\gamma_p$ - Plastic distortion

$\alpha_0$ - Represents onset of yielding

$\alpha_r$ - Represents to residual state

$C_{so}$ - Material cohesion

$\varepsilon_p^f$ - Equivalent plastic strain at failure

| | | |
|---|---|---|
| $\varepsilon_p$ | - | Equivalent plastic strain |
| $\varepsilon_{vol}^{f}$ | - | Volumetric strain at failure |
| $K_{ratio}$ | - | Ratio between the tensile and compressive meridian |
| $W_{sand}$ | - | Mass of the sand |
| $V_{i,j,k}$ | - | Volume of the ijk cell |
| $n_{i.j.k}^{failed}$ | - | Number of failed ijk cell |
| $\rho_{sand}$ | - | Density of the sand grains |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

In 2017 Wang, described that an estimated 50 percent of existing wells require sand control or sand management throughout their lifetime (Wang, 2017). This includes high porosity unconsolidated sandstone in conventional and unconventional reservoirs cause by high stress during the flowback. Most recent major hydrocarbon discoveries, from both transcontinental countries like Tunisia, Morocco, Egypt and countries in Africa (Mozambique, Angola, and Tanzania), North America (United States and Canada) and East Asia (Thailand, Vietnam, Myanmar and Malaysia), are offshore with soft formation sands and high-permeability with half of them being gas-bearing reservoirs. Wang (2017) also concluded that, to ensure a successfully effective sand-management process deployment, a multidisciplinary engagement is necessary, especially the geomechanics modelling. The subsurface and engineering teams should be able to predict the sanding tendencies including volume and rate as well as detecting the sanding locations. This should be followed by selecting appropriate downhole sand-management and/or sand control devices as well as implementing the best operating practices for the life of the well. As the number of existing fields (weak and/or depleted sand reservoirs) around the world increases, these experiences are likely to become more widespread. The United Kingdom based British Petroleum (BP) operator, for example, estimated that more than 60% of its production comes from sand-prone reservoirs (Liou, 2014). To manage the economics of a field and minimize capital expenditure, it is useful to know at the outset whether sand failure is a significant risk. This allows decisions to be made on the most effective completion strategy to manage sand failure for the life of the field.

Sand production phenomenon can be described as hydrocarbon fluid production accompanied by sand grain particles when reaching the surface. In the event that the velocity of fluid production is not sufficient to carry the sand particles to surface, then the sand grain particles will fill up the wellbore. As a result, this eventually acts as gravel pack which may lead to loss of production (Subbiah *et al.*, 2014; Fuller *et al.*, 2017). Sand failure can have a severe impact on the economics of an oil or gas field. Erosion of downhole or surface components by sand can lead to loss of integrity and hydrocarbon leakage. Production rates from screenless completions may need to be reduced to limit solids either flowing to surface or filling the wells. Sand handling, either at surface or flushed from a downhole, adds expense to lifting costs and significant disposal difficulties. Therefore, the sand production phenomenon either needs to be controlled or avoided in any circumstance.

The sand production phenomenon is normally a two-stage process. The first stage is onset of failure caused by stresses acting on the rock which result in failure of the rock. The second stage is that the failed/spalled sand grains/solid are transported by producing hydrocarbon fluid to the surface or becomes deposited within the well system. With the onset of formation failure and evidence of mobilized sand (or solid particulates) through the formation, operators can opt to reduce flow to rates incapable of carrying solids, manage produced sand or create a barrier (a filter) to prevent sand movement from formation to wellbore. Stopping, or at least slowing, the flow of sand, while minimally impacting production, requires the operator to choose from among mechanical exclusion techniques such as cased-hole gravel packs, high-rate water packs, frac packs, open hole gravel packs or stand-alone screens. Additionally, screenless completions such as oriented perforation or a chemical consolidation can be applied (Acock *et al.*, 2004). Therefore, the best completion strategy and field scale production development plan for each well of the reservoir can be further optimized by predicting both the locations and conditions that lead to the onset of sand production and the volume of sand that will be produced.

During the ARMA (American Rock Mechanics Association) annual conference in 2017 at San Francisco, United States, a discussion was held on the topic of sand production volume and rate predictions and the industry’s current practises on this subject. It was concluded that the current technology is good for initial sandstone failure but poses an unsolved challenge in predicting sand volume and rate. All delegates agreed that sand production volume and rate is very important for sand management. There is no proper toolkit and simulator currently available. However, a number of oil and gas operators and consulting organisations are using standard analytical models and Finte Element Method (FEM) code and are yet still unable to find a holistic solution to predict the volume of sand that will be produced (Cook, 2017). On another occasion, during a technical meeting held in Schlumberger Gould Research at Cambridge, UK, divulged that they worked a lot on sand production volume and rate prediction using FEM codes and were still unable to accurately predict the severity of sand production (Cook and Moffet, 2017).

Sand control methods must be used if the well will be producing more than 5 lb of sand per 1000 bbl/day (five pounds of sand per thousand barrels, pptb) of oil and much lesser for gas wells in the range of 0.3 to 0.5 lb for mmscf/day (Cook and Fuller, 2005). Therefore, estimating the sand volume will be critical for many oil and gas operators for their CAPEX planning.

## 1.2 Problem Statement

Sand production erodes hardware, blocks tubulars, creates downhole cavities and must be separated and prior to disposal. Petroleum industry has been struggling for a robust and accurate modeling technique to predict or estimate sanding propensity (volume and rate). The sand volume quantification has a big impact for field development planning, i.e., requiring an initial investment and its own rate of return (ROI). Cost for sand control remedial can range between 50,000 to 1 million US Dollars. This cost normally varies depending on field location such as onshore, offshore and deep-water (Cook and Fuller, 2005). Thus, the decision must be made based on sand production severity and long-term durability i.e., life of the field. Therefore, workflow and a computer simulator or modeling toolkit to predict and quantifying sand volume that will be produced is very essential for field developing planning in the petroleum industry.

As described, sand production can cause a loss of millions of dollars for oil and gas operators. This unwanted phenomenon needs to be quantified for (i) an optimum sand control method selection, (ii) operation planning and (iii) decision on overall field development plan investment and economic feasibility. Considerable efforts have been made in the past few decades in investigating the mechanisms and modelling approach involved in sand production while producing hydrocarbon fluid.

Less effort has been put on modelling sand production volume and rate and few researchers investigate both analytical and numerical methods (Ranjith *et al.*, 2013; Rahmati *et al.*, 2013).  Therefore, there is still room in improving the existing modelling methods in predicting sand production volume and rate. Rock failure that leads to sand production is a continuous and dynamic process and is discontinuous in nature. Such dynamic process is not captured by the models that are based on continuum approaches (FEM). Physical and mechanical rock properties appear to greatly influence the sand production volume and rate. Previous works are inconclusive in generating best methods in predicting sand production volume and rate as the work was either done using only the analytical or continuum approach or only the discontinuum approach. Therefore, effort required to investigate turning 3D FEM continuum method to discontinuum and allow stress stabilisation after failure.

## 1.3 Research Objectives

The objectives of the research are:

1. To investigate reliable constitutive models for sandstone failure prediction and sand volume estimation.
2. To develop a new reliable constitutive model for sandstone failure prediction and sand volume estimation.
3. To develop a new workflow and method for accurate sand production volume prediction.

## 1.4 Scope of The Work

1. To conduct series of laboratory tests according to ASTM/ISRM standard on the weak to moderate strength sandstone to investigate if non-linear constitutive model is required for better sand production failure and volume prediction. The laboratory tests conducted for various loading mechanism and standard core specimen size.

2. Using the laboratory test results to develop a new non-linear constitutive model honoring full spectrum of sandstone mechanical behavior (elastic, plasticity/hardening, failure and softening). Followed by validation of developed model (ASA) using Finite Element Method (FEM) to reproduce the stress strain rock mechanical behavior.

3. To develop a new workflow and computer simulation techniques to turn FEM continuum medium to discontinuum medium by newly implemented grid cell removal method during the simulation (known as progressive perforation cavity failure and stabilization namely PPCFS). Estimate sand production volume using PPCFS method and validate/verify numerically estimated sand production volume with both laboratory test data and actual field data.

4. To develop customize subroutines codes for the numerical model simulation and analysis work, while industry recognized/commercial software such as Techlog, VISAGE, Petrel and GiD to ease field deployment of the proposed method.

## 1.5 Significance of Study

This study has its own uniqueness and novelty as it considered non-linearity behavior together with simulation techniques to turn FEM continuum medium to discontinuum medium. For this study, grid cell (mesh) removal technique has been used in FEM for sand production volume prediction. In other word turning conventional continuum FEM to replicate discontinuum method (as example, DEM is discontinuum method). A common FEM code or engine is not able to do this. Thus, an additional computer program code has been programed to communicate with VISAGE software to achieve the requirement known as PPCFS method (perforation cavity failure and stabilization). Furthermore, selection of the constitutive model is important for non-liner (plastic) sandstone rock. Most of researchers in petroleum geomechanics still using commonly available failure models which are not able to capture a proper post-yielding and post-failure (plasticity/hardening and softening) behavior. Capturing and modeling this behavior is important for onset sand production and sand production volume (stress at failure and stress stabilization after failure). In this study in order to honor a full spectrum of stress strain behavior in a single equation, a new/modified constitutive law for sandstone has been developed. The intention is to simulate for better failure estimation honoring the elasto-plastic non-linear behavior. In other word failure criterion that can handle both hardening and softening aspect of mechanical behavior of weak to moderate strength rock using single equation. These are two new additional contribution from this study to petroleum geomechanics, which has been validated using both laboratory test results and field data.

As for sand production from onset failure, a new software has been developed using Python language for both open-hole and perforated cased hole completion. Three different constitutive models have been implemented in the software including the newly developed model from this study. Eventually, after satisfied with newly developed constitutive model validation, algorithm has been implemented within VISAGE software engine for finite element analysis.

Combination of new constitutive model and PPCFS has been used for sand production volume estimation. Where, its honors the stress stabilization around the failed perforation cavity, and newly developed PPCFS method able to remove for any failed material (grid cells). This study able to improve the prediction/estimation of producible sand volume more precisely for any given or planned drawdown pressure.

Having better and accurate volume of sand production estimation is essential for decision making process for best type of completion option, which has direct impact on the CAPEX planning and its Return of Investment (ROI). Some operators nowadays also opt to produced sand to the surface. The produced sand accumulated in vessels later will be cleaned and disposed. For this, they need to know accurately the quantity/volume of sand production. On other hand it is very important to estimated accurately the volume of sand production during well testing operation. Knowing the quantity of sand is key to mitigate any risk of operation failure and non-productive time (NPT). Sand filters can be blocked due to high amount of sand produced volume. Knowing this ahead of time using modelling, the well testing and completion engineers able to prepare the correct quantity and sizing of filters, this is essential especially for deep water operation.

## 1.6 Research Gaps

Despite the numerous efforts in sand production and modelling, there are still some significant gaps in knowledge that require to be filled. After studying the current projects reported in the literature, there is still much that can be done to improve sanding models. Some are listed below:

1. Most of the conducted sand production study/research are mainly related to onset failure and not much work has been done on estimating the volume of sand production.

2. Majority of sand production related work was done or simulated in 1D and 2D domains and used plan strain and axisymmetric assumption.

3. No work was conducted in FEM using element or grid cell removal techniques and stabilization which could be more appropriate for sand production.

4. Constitutive Model: Most of the models used were elastic model and a few modified to elasto plastic. No single researcher considered a full spectrum of rock mechanical behaviour such as elastic, hardening and softening which can provide more realistic representations of sand production (stress stabilisation).

## 1.7 Study Limitations

This study has its own limitation listed below:

1. Erosion aspect and bifurcation were not analysed.
2. Sand production validation is for weak to medium rock strength only (approximately to 32 MPa).
3. Effect of water-cut and capillary pressure are not considered in modelling the sand production volume.

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# LIST OF PUBLICATIONS

## Journal with Impact Factor

1. **Subbiah, S.K**; Samsuri,A. ; Mohamad-Hussein,A,. ; Jaafar; M.Z., Chen,Y.R. Kumar,R.R (2020). Root cause of sand production and methodologies for prediction. Petroleum, Volume 7, Issue 2 263-271. https://doi.org/10.1016/j.petlm.2020.09.007. **(Q1,IF: 4.44).**

## Indexed Conference Proceedings

1. **Subbiah, S.K.,** Samsuri,A. ; Mohamad-Hussein,A, Jaafar; M.Z., Chen,Y.R. Pearce.A., Paramanathan.R. (2020) . New Novel Constitutive Model for Solid Production Prediction with Laboratory Test Validation (SPE-203130-MS) Abu Dhabi International Petroleum Exhibition & Conference, 2020. https://doi.org/10.2118/203130-MS **(Indexed by SCOPUS).**

2. **Subbiah, S.K.,** Samsuri,A. ; Mohamad-Hussein,A, Jaafar; M.Z., Chen,Y.R. Pearce.A., Kumar,R.R , Paramanathan.R. (2020). Sanding Propensity Prediction Technology and Methodology Comparison" (SPE-203238-MS) Abu Dhabi International Petroleum Exhibition & Conference, 2020. https://doi.org/10.2118/203238-MS (**Indexed by SCOPUS).**

3. **Subbiah, S.K.,** Samsuri,A. ; Mohamad-Hussein,A,. Jaafar; M.Z., Chen,Y.R. Pearce.A., Kumar,R.R , Paramanathan.R **(2021).**Development of new novel constitutive model for deep reservoir sandstone rock for sand production application. IOP Conference Series: Materials Science and Engineering 1051 (1): 012093. http://dx.doi.org/10.1088/1757-899x/1051/1/012093.

4. **Subbiah, S.K.,** Samsuri,A. ; Mohamad-Hussein,A,.Jaafar; M.Z., Chen,Y.R. Pearce.A., Kumar,R.R , Paramanathan.R. (2021). Solution for Sand Production Problem in Oil and Gas well. IOP Conference Series: Materials Science and Engineering 1051 (1): 012050. http://dx.doi.org/10.1088/1757-899x/1051/1/012050.

5. **Subbiah, S.K.,** Samsuri,A. ; Mohamad-Hussein,A., Jaafar; M.Z., Chen,Y.R. Pearce.A., Kumar,R.R , Paramanathan.R . Groot. D.L. (2021). Managing Sanding Risk in Sandstone Reservoir Through a New Constitutive Model. SPE Middle East Oil & Gas Show and Conference, 2021. https://doi.org/10.2118/204666-MS **(Indexed by SCOPUS).**