Petroleum xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Petroleum

journal homepage: http://www.keaipublishing.com/en/journals/petroleum

Sand production: A smart control framework for risk mitigation

Hisham Ben Mahmud[a,*], Van Hong Leong[a], Yuli Lestariono[b]

[a] Department of Petroleum Engineering, Curtin Malaysia, Malaysia
[b] Petronas Carigali Sdn Bhd, PO BOX 1452, Miri, Sarawak, Malaysia

ARTICLE INFO

Keywords:
Sand production
Sand control tools
Sand management
A smart control framework

ABSTRACT

Due to the current global oil price, the sand production is considered undesirable product and the control of sand production is considered as one of the main concerns of production engineers. It can damage downhole, subsea equipments and surface production facilities, also increasing the risk of catastrophic failure. As a result of that it costs the producers multiple millions of dollars each year. Therefore, there are many different approaches of sand control designed for different reservoir conditions. Selecting an appropriate technique for preventing formation sand production depends on different reservoir parameters. Therefore, choosing the best sand control method is the result of systematic study. In this paper the sand production factors and their effects are presented where the emphasis is given towards the sand prediction to determine the probability of producing sand from the reservoir, followed by the correct prevention implementation of sand control method. The combination of these two is presented as a smart control framework that can be applied for sand production management.

1. Introduction

Sand production is worldwide problem. It always has significant consequences on field development. Sand production from unconsolidated formation reservoir is a very challenging issue as it ends the production life of a reservoir and well. In the oil and gas industry, millions of dollars are spent yearly for the cleaning of sand. Sand production also restricts the production flow rate, hence causing huge economical loss. Whenever there is concern about sand production in the field being developed, sand management and control are the main actions to be taken.

The areas of oil and gas production field that face the sand production issue currently are U.S Gulf Coast, the North Sea, China, Canada, California, Venezuela, Western Africa, Indonesia and Malaysia. As shown in Fig. 1, sand control technology is installed by the company, Schlumberger in over 30 countries globally. Sand management is an approach of operating when traditional tools of sand control are not typically applied, and successful production rate is achieved through an appropriate monitoring and control process of sand influx, well pressures, and flow rates. At last 10 years, sand controlling process in conventional formation of oil and gas reservoir is applied on many number of wells worldwide and has showed increased production rates of hydrocarbon. Additionally, different design tools and analysis are necessary to evaluate the possibility of sand production and to quantify the risk of sand reduction, and to found practical operational criteria for safe production window. These design tools depend on the capacity to predict the initial production of sand, and its rates and quantities, equipment erosion risks, and the conditions that allow the sand to be transported thru a production tubing and surface pipelines. Moreover, a critical tool of sand production such as sand monitoring technology can be used to allow real-time quantitative sand flux tracking. The application of tools and how they can help in assessing the risk in sand management are discussed in this paper. Approaches of handling the uncertainties and risks are illustrated. Last not least, implementation of sand management and hybrid completions in challenging environments as high-pressure and high-temperature (HPHT) fields, and marginal fields are considered.

2. Causes and consequences of sand production

Sand production occurs when the stress on the formation exceeds the formation strength and result in rock failure. Rock failure happens due to tectonic activities, overburden pressure, pore pressure, stress induced during drilling and also producing fluid drag force [2]. Factors, which are affected formation tendency to produce sand can be classified into two categories, fluid flow and rock strength effects. Sand particles production can consist of load bearing solids and formation fines. The production of formation fines that does not include in the framework of

Peer review under responsibility of Southwest Petroleum University.

* Corresponding author. Petroleum Engineering Department, Curtin University Malaysia, CDT 250, 98009, Miri, Sarawak, Malaysia.
E-mail address: hisham@curtin.edu.my (H. Ben Mahmud).

https://doi.org/10.1016/j.petlm.2019.04.002
Received 4 March 2018; Received in revised form 10 December 2018; Accepted 10 April 2019

Please cite this article as: Hisham Ben Mahmud, Van Hong Leong and Yuli Lestariono, Petroleum, https://doi.org/10.1016/j.petlm.2019.04.002

Fig. 1. Sand control installed by schlumberger in over 30 countries worldwide [1].

formation mechanical, is beneficiary as they can transport easily within the formation rather than plugging it. Production rate is regularly maintained at low rates to eliminate the production of particles, where in several situations, still the low production rate is uneconomical. These factors can be categorized as follows:

Consolidation degree indicates the capability to keep open perforation holes closely tied to how strongly the single sand grains are bound together. Typically, sandstone cementation occurs by a secondary geological process in which older sediments or deeper formations tend to be more tight than younger sediments or shallow formations. As a result of that sand production is normally a problem when producing from shallow and younger sedimentary formations. Such formations can be found worldwide, for instance in North and South of America (Gulf of Mexico, California, Venezuela), in Africa (Nigeria, Egypt), in Europe (France, Italy), and in Asia (Trinidad, China, Malaysia, Brunei, Indonesia) and others. In general, young tertiary sedimentary formations contain a slight cementation matrix material bonding the sand grains together and such formations are often stated as being “unconsolidated” or “poorly consolidated”. The rock mechanical property that relates to the degree of consolidation is known as “compressive strength”. Acidizing process reduces the compressive strength of the formation, hence weaken the consolidated formation [3,4,and5]]. In general, unconsolidated sandstone formations consist of a compressive strength of less than 6.9 MPa.a [6]. Fig. 2 illustrates the sand failure due to weak rock strength.

Increasing the production rate of reservoir fluid due to a large pressure drawdown between the reservoir pressure and wellbore flowing pressure can cause sand production. Commonly, the production

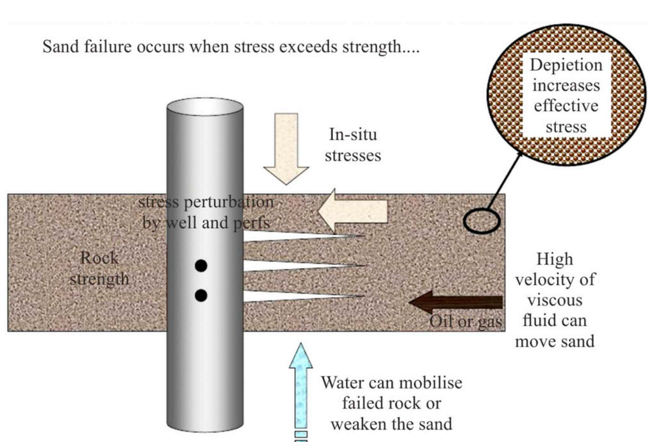

Fig. 2. Sand failure due to weak rock strength [7].

of reservoir hydrocarbon fluid causes pressure frictional loss and frictional forces (due to potential and kinetic energy) that may exceed the formation compressive strength. As a results, most of production wells have a critical flow rate, which is below pressure frictional loss and frictional forces are not high enough to exceed the compressive strength of the formation and leads to sand production. The critical flow rate is obtained through increasing the production rate slowly till the production of sand is detected. On the other hand, one of techniques that can be used to reduce the sand production is choke valve that can reduce the production rate to the critical rate where the sand production has an acceptable level or does not occur. In some circumstances, this flow rate is considerably lower than the acceptable fluid rate of the production well [3,6,and8]].

As the reservoir pressure depletes overtime result from pore pressure reduction, which leads to reduce the reservoir fluid production. Generally, reducing the reservoir pressure can cause increasing the amount of stress that applies on the formation sand, such as increasing the effective overburden pressure. If the formation particles are crushed from its matrix during the reservoir life, sand possibly will be produced along with the reservoir fluid. Also the formation could be damaged if the effective stress exceeds the formation strength because of the reservoir rock compaction from the reduction in formation pore pressure [6].

The frictional force applied on the sand particles is made via the flow of reservoir fluid. The frictional force is proportional to the reservoir fluid viscosity and flow rate. As the reservoir fluid viscosity is high, it usually applies a larger frictional drag force to the formation particles in comparison to a low viscosity fluid. The viscous drag can cause producing sand from heavy oil reservoirs that contain a high specific gravity, high viscosity liquids even though at small flowrates [6].

The sand production increases as the water cut increasing. This incidence is clarified via two mechanisms. When the sandstone formation is water-wet, some of particle-to-particle cohesiveness is provided via the surface tension of connate water that is surround each of sand particle. When water is produced, the connate water has a tendency to adhere the produced water, causing decrease of the surface tension force, which leads to reduce the particle-to-particle cohesiveness. The strength of sand arch surrounding the perforation is limited via the amount of water production resulting in sand particles production [9]. Another water production mechanism has impact on sand production, which is relative permeability. As the percentage of water cut increases, it decreases the relative permeability of oil, which causes increase in the differential pressure being required to produce the hydrocarbon fluid at the same rate. Increasing the differential pressure near the well bottomhole leads to a higher shear force through the

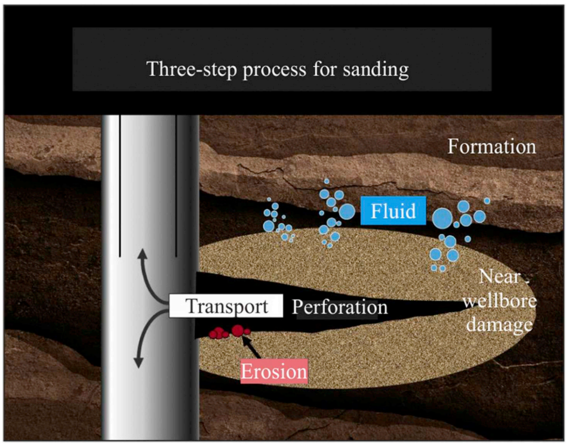

Fig. 3. Sand Production Mechanism [10].

formation sand particles. Therefore, the greater stresses may cause sand arch instability around the perforation that leads to sand production [6].

Fig. 3 shows the three-step process of sand production mechanism, which include near wellbore damage, perforation and transportation.

The sand accumulated in the surface tools, wellbore, pipelines, tubing and separator result in decreased production, which is unfavourable to the well. Sand settles in the wellbore due to low production velocities, which slowly cover the reservoir section. If the sand trapped is not cleared, they form into sand plugs, which then fall into the wellbore and causing loss of production. In term of facilities, sand production causes erosion to the downhole facilities. When those facilities are exposed to hydrocarbon, corrosion is enhanced. This does not only damage the subsurface equipment but also all the surface facilities such as valves, choke, separator and pipelines. Subsurface safety valve becomes jammed and inoperable after being eroded by sand particles. Then, equipment failure leads to safety and environmental concerns [11]. Furthermore, additional maintenance cost is spent to maintain the surface facilities and downhole equipment being damaged. Work over is required to mitigate the problem. Due to the massive amount of sand production, operating expense also increases for the shut in and clean out operations. Inspection and reinstallment the equipment requires an extra time as well. Sand produced is hazardous waste; hence it should be cleaned before being disposed according to the environment regulations. Sand disposal, which involves cleaning, storage and transportation are very costly. In addition, sand production also causes geo-mechanical problems like formation damage. Severe sand production results in void behind the casing. When this void becomes large enough, the overlying layers' collapse. Eventually, the permeability is reduced due to rearrangement of the sand particles [12].

3. Formation sand characteristic and classification

When compare exclusion approaches, such as production limits or completions, as against surface separation approaches for produced solid particles, it is important to identify the nature of treated solids. Produced solid particles have some characteristics, such as insoluble, inorganic, non-deformable particulate materials that are associated with hydrocarbon fluids production. These particles are produced the reservoir fluid as oil, gas, water, or combination (multiphase). Heavy oils can form a thick particulate matter, such as paraffin waxes or asphaltenes, however; these components are typically colloids, semi-soluble, organic, and deformable and not comprised in the produced particles category [13]. These components have a relative density close to the hydrocarbon liquid and an agglomeration tendency that impedes the effective treatment via either processes, i.e. separators or screening.

Table 1
Physical properties of particles.

Property	Natural Solids		Artificial Solids		
	Sand	Clay	Proppant	Corrosion Product	Gravel Pack
Specific Gravity	2.5–2.7	1.8–2.8	2.6–3.6	5.5–6.0	2.6–3.0
Shape Factor	0.2–0.5	0.1–0.3	0.5–0.9	0.1–0.5	0.5–0.9
Size Range (μm)	25–600	< 20	500–3000	10–10000	250–3500
Concentration (ppmv)	5–100	< 5	to 20000	< 2	0 (unless failure)

Also adding solvent or heat is needed to restore the inflow production or eliminate the materials from pipeline systems and facilities.

When inorganic particulates are produced at a certain size and concentration to involve exclusion or separation treatment are commonly termed "produced solids". This material is classified into two groups: natural and artificial material where the focus of this paper is given to sand particles. The main factor of interest is the physical properties of each solid category that is exploited for either exclusion or separation process. These physical properties consist of particle size, shape and its distribution, density, and concentration. Table 1 shows the average properties of the solids that are utilized in a particle management system design.

The formation of sand is described as a granular material, has a particle diameter between 0.0625 and 2 mm, and consists of mostly silicon dioxide (SiO_2) and some other minerals. In general, there are four types of sand that classified based on the variation of their properties, and can be classified as:

(1) Quicksand
(2) Partially consolidated sand
(3) Friable or semi-competent sand
(4) Consolidated sand

The strength of sandstone is affected by compaction, cementation and dissolution of sand grains at contact points. Sand consolidation is associated with the cementation of minerals such as quartz, calcite and dolomite. The unconsolidated sand is the one which trapped in the environment with insufficient cementing agents. This kind of sand has high porosity and permeability due to weak consolidation. Therefore, sand control is necessary for this kind of sand formation. Whereas, consolidated sand is very well cemented sand; hence does not require sand control. The four classifications of sand are associated with the need for sand control consideration in the completion [14] as shown in Table 2. The natural particles that are producing from the original reservoir minerals are broadly sands. They are detrital particles of clays and mineral oxides that are hydrous aluminum silicates that can be detrital or authigenic [13]. Sand particles are considered as the formation load-bearing particles, while fine particles are not considered as one of the parts of mechanical structure [15].

Most of the produced particles have an averaging relative density of 2.65. The produced sands have great angularity leading to poor shape factors [16]. The advantage of angularity, it assists in grain-to-grain locking required for success gravel pack filtering. Nevertheless, the great surface area as a result of angularity has adversely stabilize oil emulsion, making separation of two-phase oil-water more difficult. Furthermore, increasing particle sharpness increases the potential of erosion [17]. The average sand size varies from production well to another, even in the identical formation, however; typical sand particle sizes are within the range of 50–150 μm. Moreover, sand particles concentration is changing from time to time (every 24 h) at the same well, and even at a good completion job, a sand prone well might yield 5 ppmv sand. At such concentration, if a production well produces 10,000 bpd, it will produce 5 bpd particle that weighs 4630 Ib.

Table 2
Sand type and characteristic.

Sand type	Characteristic
Quicksand	• Completely unconsolidated sand. • No cementing materials. • Have small cohesive force and compaction. • Very difficult for drilling and core sampling operation. • Sand production occurs at the early stage of the well production.
Partially consolidated sand	• Has some cementing agents but still weakly consolidated. • Coring is done easily. • But the core sample obtained is very brittle and crumbles easily. • The open hole condition collapse easily.
Friable or semi-competent sand	• Well cemented. • The core sample is easily obtained. • At the beginning, sand production does not occur. • As the well produces over time, sand production occurs. • It is always hard to make decision whether or not to apply sand control completion in this sand formation.
Consolidated sand	• Very well cemented sand. • Usually do not require sand control method.

Furthermore, clays have a comparable relative density but they have smaller grain sizes that usually present in a low concentration.

Reservoir debris is produced as a result of workover operations, the fluid movement from the reservoir, or due to formation rock degradation. Both operations (production and workover) can lead to residual drilling fragments and damage the formation rock around the wellbore using acid stimulation or hydraulic fracturing. Those natural particles are produced via workover operations could have a high initial concentration (up to 1 vol%) when the production is restarted, but the particle concentration quickly becomes a smaller in a few days to a concentration level < 1 ppmv. Thus, the effects of natural particles are impermanent. On the other hands, those particles are produced by the fluid shear of the formation face degradation or the fluid movement from the reservoir have a longer influence on the fluid production. High fluid rates through the formation pores can remove particles (sand and clay) from the formation matrix and transport them to the wellbore. When the quantity of sand transported reaches a steady state condition leading to a constant production of sand (commonly 5–10 ppmv). Particle production spikes that are associated with multiphase flow where the transient pressure condition influences high instantaneous forces on the formation, or when the fluid front changes to water instead of oil (i.e., water invasion). These situations can increase the concentration of sand up to 100 ppmv at a small period of time.

It is difficult to predict the production rate of natural particles due to the difficulty of obtaining robust data from the formation sand face and surrounding volume. There are many models are available in the literature to predict the sanding onset but the actual rate of sanding has a high level of uncertainty. However, sand measurement and monitoring devices are able to identify catastrophic sanding incidents or provide online measurement of particle concentration. These instruments are required when the gravel pack operation is failed or to predict the beginning of critical sand rates with the pressure drawdown. Failure one of the jobs (gravel pack or screen) will cause a high production of the reservoir materials that built up in the well skin outside the pack plus the associated gravel pack sand. In such situation, the sand production can be catastrophic and lead to facility damage and economical losses.

4. Sand prediction

Sand prediction is an essential step in the reservoir evaluation and analysis to predict the possibility of sand production and choose a proper control method. Some of the analytical techniques used for sand prediction include:

(1) Logging analysis,
(2) Core-based tests,
(3) Numerical simulators, and
(4) Drill stem tests (DST).

4.1. Logging analysis

The sonic log and porosity log are the two important log data, which are used in the formation evaluation for sand prediction. The sonic log records the transit time, which is the time necessary for the sound wave to travel within the reservoir formation.

(1) The shorter travel time less than 50 µm seconds indicates that the sand is hard, has low porosity and high density.
(2) On the other hand, the longer travel time more than 95 µm seconds indicates that the sand is soft, has high porosity and low density.

A common practice used to determine whether the sand control is necessary for known geologic region is to determine the regularities of sand production using the sonic log readings below and above the sand production. Such technique provides a quick screening if sand control is required. Thus, to utilize such method, calibration with specific geologic formations is required.

Some specific well logs, such as the neutron and density devices and sonic log, are indicators of formation hardness and porosity. For some formations, the reading value of low-density designates high porosity. The main purpose of the neutron logs is an indicator of the formation porosity. A number of logging companies compromise the formation properties log that includes the results of density, sonic and neutron logs to identify if the reservoir formation will have the potential to produce sand at certain levels of pressure drawdown. This analysis categorizes the log interval into two intervals that are strong and weak where the weaker intervals are more likely to produce particles. The log of formation properties is used for more than 2 decades, in which the experience has made known that this log generally over predicts the requirement for solid control [18].

A formation porosity is utilized as a guideline to indicate whether if the sand control is required. If the porosity is higher than 30%, then the requirement of sand control is needed due to the lack of formation consolidation in contrast with the porosity smaller than 20%, which is unlikely to have sand control due to consolidation. Therefore, the porosity within the range of 20–30% is where ambiguity frequently presents. In the natural porous media, the porosity refers to the degree of cementation in the formation; therefore, the basis of this technique is well understood. Porosity data can be extracted from either laboratory core analysis or well logs [18]. Porosity measured from different log data such as neutron log, density log and sonic log also determine the need for sand control. Sand control is required for sand with high porosity of greater than 30% while not necessary for sand with low

Table 3
Table of sand consolidation based on UCS Test [20].

Description	UCS (psi)	Porosity%	YM[a] (psi)
Zero strength dry sand	0	< 35	< 50,000
Very weak damp sand	< 200	< 30	< 300,000
Weakly cemented	< 500	< 25	< 500,000
Weak more cemented	< 1000	< 22	< 1,000,000
Gray area	< 4000	< 20	< 2,000,000
Consolidated rock	< 5000	< 18	< 3,500,000

[a] YM = Young's modulus.

porosity of smaller than 20% [19].

4.2. Core-based analysis

Core-based tests consist of unconfined compressive strength (UCS) test and Brinell Hardness (BHN) Test. Those tests are applied on the collected core samples and are highly reliable. UCS test measures the resistance of a material to uniaxial deformation based on the concept that the harder the material is the greater force required to deform it [20]. The classification of sand consolidation based on USC test is shown in Table 3.

BHN test measures the hardness and consolidation of the sand by pressing a spherical indenter into a material with a controlled force for 10–15 s to create indentation. Smaller indentation indicates harder material. BHN is calculated as a function of the applied force, indenter diameter and indentation diameter [21]. The classification of the sand consolidation based on the Brinell Hardness Test is shown in Table 4.

4.3. Numerical simulators

Many models are being developed to predict the sand production issue using various strategies such as analytical and empirical relationships, physical model testing, and numerical models. Experiment studies can only capable to predict the sand production onset [22]. Other physical models could predict the volumetric sand production [23] but they are time-consuming and expensive. Furthermore, as the experimental work is usually setup on a small scale, the results are usually affected via boundary effects. However, analytical models have the advantage of fast processing and easy to utilize but they are only appropriate to predict the onset of sand production, nevertheless they have their drawbacks. Most of analytical models can be used to model a single mechanism of sanding through highly simplified boundary and geometrical conditions that are not typically the case in a real field-scale problem. As numerical models are powerful tools where capable to predict the sand production and they also can be integrated with analytical correlations to determine proficient results. The obtained results experimentally can be also employed to validate and calibrate the numerical model. Even though the numerical models have such advantages but there are still some limitations in which extensive efforts have been done to improve model calculations.

There are two mechanisms involve in modeling of sand production, which are mechanical instability including degradation near the wellbore and hydromechanical instability due to flow-induced pressure gradient on degraded material surrounding the cavity such as perforation and open bottomhole. Generally, numerical techniques that include in the mechanical modeling, are classified into two approaches, continuum and discontinuum. In the continuum approach, matters are treated and assumed as continuous in deriving the governing differential equations. In addition, the continuity assumption indicates that the material cannot be divided into smaller fragments. While in the case of discontinuity, the magnitudes of deformation across the discontinuity are approximately the same as the rest of the continuum [24].

Discrete element approach is a valuable tool to simulate the sand production in order to understand the mechanism of sanding. Nonetheless, it should not be utilized for a large-scale problem as it requires an enormous facility capacity and computational time. Moreover, the model calibration is also complicated, it consists of several uncertainties as it is impossible to develop a model with the exact arrangement of particles as the actual physical materials. In the last two decades, the micro properties have been found by calibrating against the actual sand behaviour [25,26]. Therefore, continuum-based models are well-known specifically for field-scale problems but there are advanced models that combine both continuum and discontinuum models to take advantage of both models to get better solution of challenging problems. These models are recognized as hybrid models and are explained into details by Ref. [27]. A comprehensive sand management possibly will require some or all of the above mentioned numerical methods.

4.4. Drill Stem Test (DST)

It is one of the most reliable prediction approaches as it consists of gradually increasing rate and drawdown until the maximum production rate or drawdown is achieved. However, the information about reservoir depletion, water production and other time dependant parameters are still insufficient [28]. In the context of sand prediction, it allows the direct observation of sand particles being detected on the surface at the maximum pressure drawdown, also known as field observation of sanding.

Drill Stem Test (DST) consists of individual well testing through DST. When the production well produces a reservoir fluid under conventional completion, thus the potential sand production can be predicted. As the well flows naturally and gradually increases its production rates through the choke valve till the sand particle is produced or a maximum acceptable rate is achieved. However, an optimum production rate to produce free sand can be attained and the completion sand control strategy can be taken [29].

Pingshuang et al. [30] performed a research on sand production prediction at South of Chine Sea. It was found that most of the China offshore oilfields are producing from unconsolidated sand reservoir and different levels of sand production is experienced across these fields. The reservoir rocks in Beibu Gulf of South China sea are situated between consolidated and unconsolidated. Some particle sands were observed at the surface oil/gas separator during DST operation for two specific wells in the region. The sand was seen to occupy half of the separator volume.

5. Sand monitoring and detection

Sand monitoring is an essential practice of well integrity to access

Table 4
Sand consolidation based on Brinell Hardness (BHN) Test [21].

Classification	Brinell Hardness (kg/mm^2)	Geological Equivalent
Unconsolidated	< 2	No cementing material
Partially Consolidated	2–5	Pieces easily crushed with fingers
Friable	5–10	Pieces crushed when rubbed between fingers
Consolidated	10–30	Pieces can only be crushed with forceps

the need for sand control to maximize the production and ensure the efficiency of the current well completion. Several methods for sand detection are practiced such as wellhead shakeout or grind out test, volumetric sand traps or sand filter, erosion sand probes or safety plugs, fluid sampling, acoustic transducers and erosion monitoring [31]. Sand filter is a common practice where it comes with 20 and 40 µm mesh size is equipped at the upstream part of the test separator. It is utilized during monthly well test as the production flow from the well is diverted to the test separator via the manifold. During the routine monthly well test, the sand filter differential pressure is closely monitored throughout the well test period. From time to time, the sand filter is removed and cleaned to visually check and observe if any sand or debris is produced from the well.

Furthermore, the sand erosion corrosion monitoring (SECM) is an online reading to measure the corrosion or erosion rate in the flow line of each well. The data is extracted periodically from the system for trend analysis to see if there is any suspected sand production as an indication by increased erosion rate. If there is any sand detection, corrective measure needs to be taken immediately. Pressure drawdown control is a common practice to reduce the choke size to the sand production limit.

6. Historical approaches of sand production control

Conventional sand control methods, such as chemical consolidation, wire wrapped screens, gravel packing, frac-and-pack, expandable screens, etc., are implemented based on a sand exclusion philosophy: definitely not any sand in the production equipments can be accepted. On the other hand, to avoid sand influx totally, the conventional method is to minimize the production rate to reduce the amount of sand entering the wellbore. The strategy to control or exclude the sand formation is based on the analysis of sand prediction as mentioned earlier. As a result, it has led to improvement of various numerical approaches to predict the sand production onset [32–35].

Therefore, sand influx is frequently considered as a parameter that limits the production rate (and thereby effects the pay back of the project) through the induced production limitations set via mounted sand control techniques, flowrate losses due to equipment failures and workovers, and induced production restrictions that took place at low maximum sand-free rate limits. Nevertheless, sand influx is associated with a mechanical failure and formation rock dilation and the removal of damaged component [36,37].

The heavy produced oil wells are still to-date the common extensive field validation of the reliability and cost-effectiveness of sand management. This method is considered a modified combination of practices to describe the safety confines at which sanding can be well-thought-out operatively tolerable. In this case, the expenditures of a too-traditional method should be avoided or delayed, and also at the same time improved well productivity from continuous well clean-up is succeeded. Table 5 illustrates a review of various techniques applied to deal with the production of sand. Commonly, sand control signifies high cost and low risk solutions at which sand management can lead to minimize solution cost, but it consists of active risk management. Furthermore, possible sand control and management that can be applied are shown in Table 6 combined with guidelines to different select sand control methods to use and possible application cases.

7. Sand management

Sand management has been recognized as one of the main issues during field development in which contributing to over 70% of the world's oil and gas fields. Sand management is a balance of the threats (environmental, safety, process and cost) of producing sand to the surface and the threats of trying to retain it down in the reservoir. The selections are not always clear or easy to implement. Risk management needs reliable analysis of the “Sand Life Cycle”, starting with predicting formation conditions conducive to sanding, and ending with ultimate disposal of the produced material at surface [38].

Table 5
A review of different sand prevention methods [38].

Control Method	Major Limitations
Chemical consolidation	• Some permeability reduction • Placement and reliability issues • Short intervals only
Screens, slotted liners, special filters	• Lack of zonal isolation • High placement & workover costs • Longevity of devices • Plugging & screen collapse • Screen erosion • Potential damage during installation
Inside-casing gravel packing	• PI reduction • Placement & workovers difficult • High cost of installation • Positive skin development
Open-hole gravel packing	• PI reduction • Complexity of operation • Necessity for extensive under-reaming in most cases • Costs of installation
Propped fracturing, including Frac-and-pack, Stress-Frac, and use of resin-coated sand	• Permeability recovery • Risks of tip screen-out during installation • Directional control & tortuosity issues (in inclined wells) • Fracture containment control • Proppant flow-back on production
Selective perforating	• Problematic in relatively homogeneous formations • Need for formation strength data • Reduces inflow area
Oriented perforating	• Necessity for full stress mapping • Theoretical analysis required • Perforation tool orientation needed • Limited field validation available
Production rate control	• Erosion of facilities • Sand monitoring required • Separation and disposal required • Potential for lost production

Integrating solids management with surface facility design requires more equipments rather than just installing a separating device. The separated solids may require central collection, cleaning, measurement and monitoring, storage, transport to the disposal location, overboard discharge, or injection disposal. Sand handling mechanism at surface facilities can be classified into five-unit process area: separation, collection, cleaning, dewatering, and transportation [39].

Separation is a unit process of diverting both solid and liquid contained in a multiphase stream to different sites. Solids are separated from well fluids using a gravity vessel (i.e., free water knockout (FWKO) with a sand jet), sand trap desanding, hydrocyclone, or filter system.

When separation completed, solid particles are collected into a central location and physically insulated from the production process. Gathering the particles to a central location reduces the pressure letdown points involving sand (i.e. reduces wear areas), and permits for common subsequent processing. Collection may be completed via a simple device such as a dedicated sump tank or a desander accumulator vessel. Physical segregation from the production process may require significant pressure letdown and therefore, an appropriate wear resistant slurry valve must be installed.

In many locations, sand particles may require cleaning of adsorbed hydrocarbons consequent to disposal. Dedicated sand cleaning systems based on attrition scrubbing with or without chemicals, or thermal

Table 6
Guideline for sand control approach selection [29].

Sand Control Technique	Application Field			
	Highly heterogeneous intervals	Heterogeneous intervals	Horizontal well	Zonal isolation
Standalone screen	Low	Low	High	Medium
Open-hole gravel packs	High	High	Low	Low
Open-hole expandable screen	High	High	Medium	High
Cased hole gravel packs	High	High	Low	Medium
Frac pack	High	High	Medium	Low

treatment, can be used as modular add-on packages or integrated into the separation system [40].

The total volume of sand slurry transported to disposal can be significantly reduced via dewatering. Such process involves removing liquids from the collected (cleaned) solid particles slurry. A range of equipments are available for dewatering including a filter press, sand drainage bag, or centrifuge. The final product should contain less than 10 vol% liquid.

Transportation process of the solid particles comprises three stages, which are the removal, hauling, and disposal. The design of the haulage system will be dependent upon the site (land-based or offshore) and disposal requirements (i.e. landfill, injection disposal well, overboard discharge, road surfacing). In some cases, the particles may be mixed with water and injected into wells or disposed overboard [41]. The Surface facility is usually designed to incorporating solids handling unit processes for onshore and offshore fields where they have been well recognized in the last decade as approaches are taken to minimize downtime and increase equipment robustness [42,43]. This outcome has led to the recognition of facilities sand handling as its own interest area in a previous SPE production systems and facilities technical interest group as well as workshops.

Regardless downhole sand control equipment work properly, fine sand is still produced to the surface and make some trips/shutdowns at surface facilities including crude oil pumps. In order to reduce downtime, some operators introduce holistic sand management system to include real time surface sand monitoring which expects reliable and accurate measurement in detecting sand and provide early alarm/notification to avoid unnecessary production shutdown.

8. Guidelines provide framework for controlling sand production

The Control Framework is a structured and documented process for the application to verify that sand production control information is of good quality, accurate and complete. Different tools are available to the field production engineer for monitoring produced solid particles. These consist of production limits to reduce sand inflow at a level below the destructive threshold, set up downhole equipment to prevent sand ingress from the reservoir formation, conventional facilities for taking out sand particles that reach to the surface, and placement of a separation equipment at the surface facilities to improve the robustness of the topside operation.

8.1. Production limits

The simplest approach of particles management is to implement a conservative method of "Zero Sand Production" [44–47]. This method provides a minimum sand production rate based on the pressure drawdown criteria. The well testing approach is used to determine the areas of sand free production through obtaining the relationship between the reservoir pressure and bottomhole pressure. In a number of cases, Permanent Downhole Gauge (PDG) could be installed in selective wells to have real time drawdown limit to reduce sand production. Although this method requires a minimal CAPEX, it has its weakness of reducing inflow, therefore; directly reducing the fluid production. Moreover, the solid particle production map is a target to any variation in the production profile of the well; it requires to re-define the map boundaries. Sand measurement and monitoring instruments can detect fluctuations of produced sand. These instruments are utilized as a go/no-go gauge for optimizing pressure drawdown while reducing the sand production [48–51]. Alternative approach can be used by diluting the produced sand. For instance, if a large field consists of a single or few wells, which are heavily sand producers, then they can be calmingly produced with less sanding wells to reduce the complications of sand influence.

8.2. Downhole equipment

The most common technique of sand control to maximize hydrocarbon production is to install an equipment, which excludes sand particles from entering the bottomhole. As mechanical barrier, sand screens or slotted liners restrains solids from flowing with the reservoir fluid. However, spherical sand particles shall not flow continuously through non-circular slots twice as wide as the particle diameter when they flow in an appropriate concentration [18]. A sand screen or slotted-liner is commonly utilized with gravel packing, which is cleanly placed and accurately sized around the periphery of the screen permits for a larger screening site. Furthermore, the gravel is more robust to erosion compared to the slotted-liner/screen material. Since the gravel pack equipment and techniques are popular and frequently installed, they have been well studied and are chosen as the primary option for sand particle control [52–54]. Even though such sand control equipment were installed in the wells, however they have life time of failure in controlling the sand not to produce to the surface as this relates to what production rates were made. In many cases, it requires another sand control installed thru tubing called Thru Tubing Sand Screen (TTSS) such as strata coil; and recently ceramic sand screen installed at nipple or nipple-less as it is believed this ceramic sand screen has stronger material against sand erosion, expecting less wireline well intervention. Another technique of sand control uses chemicals, which allow to bonding the produced sand grains together for a radius several feet from the wellbore. Plastic consolidation method uses either furans, epoxies, or phenolic resins to create a bond between the formation particles forming a filter barrier to sand inflow [18]. This technique requires multiple stages to implement, such as acid clean, pre-flush, and injection of the resin and catalyst.

Several combinations of previous methods may be utilized for effective sand control. Both expandable and multi-path screens can provide better flexibility compared with conventional screen liners [54,55]. Moreover, pre-coated gravel can be added to provide better placement of the consolidating resin. Frac pack combines the benefits of hydraulic fracture stimulation using gravel packing. All of these methods cannot be utilized as they seek out to eliminate the reservoir materials from entering the wellbore.

8.3. Surface facilities: conventional design

Using conventional surface facility is to control ordinary sand production, but performing workovers are still required. Some of these measures include profile instrumentation in separators, erosion resistant choke valve design and materials, sacrificial tees in flow lines, and sand jet or suction devices for FWKO, heater-treater separators and multiphase separators. All of these systems, despite the fact that increasing in robustness with proper material selection and improvement in fluid flow design, still need physical intervention for maintenance. Although, the sand particle is produced at a steady-state rate with low concentration (less than 5 ppmv), conventional facilities design shall work adequately between maintenance intervals. Nevertheless, at transient solid production condition such as gravel pack failure, frac flow-back, reservoir subsidence causing formation sand spikes, etc. where solid particles concentration can increase to 1000 ppmv, these issues need immediate action to avoid well shutdown. Therefore, flowlines and choke valves have to be protected from erosion states that can result in catastrophic damage. The industrial standard API RP 14E guideline establishes a limit of flow production velocity where the increase in particles concentration causes reducing the flow production velocity. Thus to maintain conventional well operation when the solid particles concentration increases and to prevent erosion failure, fluid flow rates are usually reduced [56].

Moreover, solid particles can cause various problems in production facilities such as gravity separators. When large solid particles (higher than 50 μm) settle down in the separating vessel, the residence time required for separating liquid-liquid (oil-water) flow is reduced and leading to a reduction in the production. Periodic shutdown requiring manual removal of particles could be required to bring back the production rate. In addition, settled solid particles in a layer form where sulfate-reducing bacteria can grow and accelerate the corrosion process. While small sands with a range of 10–30 μm may present in the interface of oil-water flow and they lead to stabilize emulsions, further reducing equipment efficiency [17].

8.4. Surface facilities: solids separation design

The best place to remove surface particles is prior entering the choke valve as can be seen in Fig. 4. Using such approach will protect entirely downstream equipments, such as flowlines and piping, choke and control valves, heat exchangers, production separators and treaters. Solid particles that available at upstream of the choke valve can be present at a high temperature of the facility that keep it clean from produced chemicals rendering these particles can be easily cleaned once separated prior to the choke valve. In cyclonic technology, solid particles are easily separated from multiphase lines as the increased gas void fraction (GVF) decreases the viscosity of continuous phase where its density permitting increased solids settling velocity. The wellhead desander, presented in next section, is a particular tool designed to remove solid particles from multiphase fluids and is installed prior to the choke valve. The wellhead desander normally uses some of the pressure taken through the valve bean, therefore, reducing the erosion problem and adapts the pressure as an energy in separation process.

If the location of facility or space constraints prohibit removal of solids from upstream; however, a multiphase desander should be mounted downstream before the separator as presented in Fig. 4. Such location has same benefits to that listed earlier; however, the choke shall not be protected. The lower pressure at such location allows a lower rating of vessel pressure, thus it increases the actual flow rate, which leads to increase the equipment size. Solid particles collected at this location are usually easy to clean and handle.

Solid particles that found in the separator are still treatable with a separation equipment but unable to retain the advantages of removal at the choke. Fine particles (less than 25 μm) in the production separator can flow through and out with the liquid (oil) phase or flow to the interface of oil-water stabilizing the emulsion layer. These particles are typically vanished with the oil phase forming part of the BS&W. Large particles (higher than 200 μm) settle down in the separator and need removal via keep cleanout with spray or cyclonic jetting equipment.

On other hand, medium particles between 25 and 200 μm ultimately flow through and out with the liquid (water) phase to the water treatment system. These particles can cause plug oil removal equipment and also contribute to the oil and grease content through hydrocarbon coating. Moreover, solid particles in the produced water can be typically removed through a liquid desander placed on the separator outlet and upstream of the level control valve as seen in Fig. 4. At such location, a separator pressure can energize the cyclonic separation and the suspended particles still have appropriate temperature assist in subsequent handling.

Generally, low pressure processes of particles removal are utilized at the end of produced water treatment unit where flowing temperature and pressure are reduced to nearby atmospheric pressure. These processes consist of different devices such as nut shell filters (NSF), corrugated plate interceptors (CPI), and cartridge filters (CF). All these devices have substantial weight and large footprint compare to cyclonic technologies and are mainly used in onshore applications. CPI devices can provide coarse particles (> 25 μm) removal at a low operating pressure. Meanwhile, NSF and CF devices are typically deployed in water injection units to reduce the particles size to 2–5 μm [57].

8.5. Wellhead desander design

The motivating parameter for the wellhead desander (WHD)

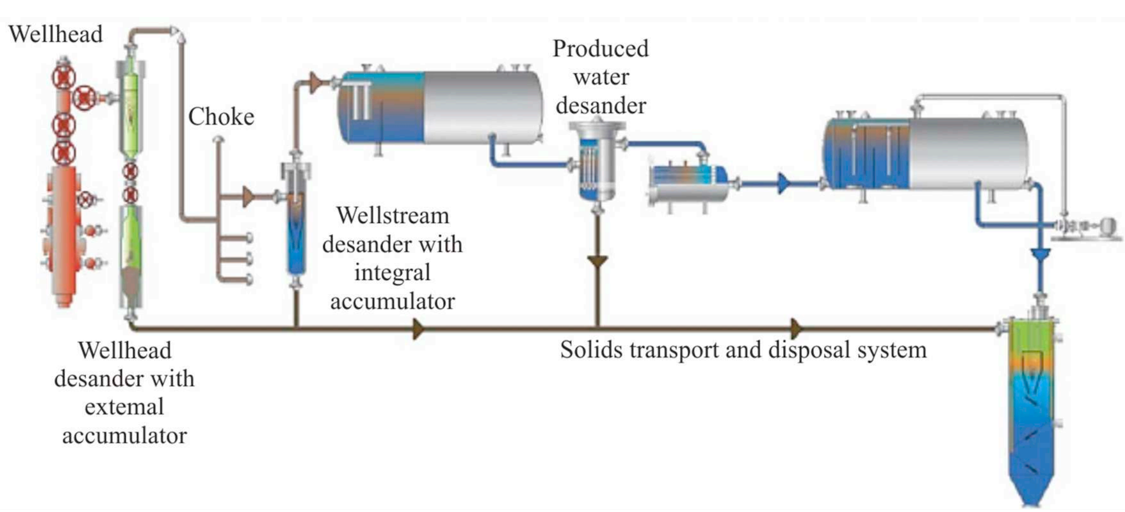

Fig. 4. Cyclonic location based solids separation equipment at surface facilities [56].

development was to improve the operability of cyclonic technology to accommodate the multiphase flow regime. Since the mid-twentieth century, desanding hydrocyclones have been significantly utilized to remove particles from produced water before injection; however, their operability in two–phase (gas-liquid) flow was unidentified. In 1995, the first wellhead desanding hydrocyclone was used and tested by British Petroleum Farm production facility [58,59]. Such test culminated the work of a joint industry development to improve a multiphase version of a liquid desanding hydrocyclone for continuous removal of particles before entering the choke valve and lead to an understanding of its design and operation.

The primary applications of WHD are established on well cleanup applications for instance frac flowback capture and coiled tubing wash [42,58]. At wellhead operating conditions, these units were installed to maintain a pressure up to 68,950 kPa and managed up to 15,000 BPD condensate and 105 MMSCFD gas. When these units use for managing up to 1 lb/bbl of solids, they can separate between 95 and 98% of solids down to 10 μm. Therefore, multiphase desanders have now been built in many surface facilities, both offshore and onshore applications. These installations have been done in downstream and upstream applications of the wellhead choke, in heavy oil, gas-condensate, HPHT, and gas-only.

The operation mechanism of multiphase desanders based on both hydraulic and pneumatic cyclonic principles [60]. As with all cyclonic devices, the pressure energy is transformed into radial and tangential acceleration to contribute to centrifugal forces on the contained fluids. As forces increased leads to accelerate the phases separation with different densities. When using a multiphase desander, solids are segregated from the fluid (gas-liquid) mixture. The forces conveyed are 400–5000 times higher than gravity force, which can cause quick separation of solid particles from fluids and also provide the cyclone unaffected by external motion. The separated particles are collected into a collector chamber (external or integral) for periodic isolation and batch discharge whereas the well fluids retain continuous flow as displayed in Fig. 5, which shows a wellhead desander with oversized accumulator integrated into the well bay of a production spar. Thus cyclonic technology has the utmost throughput-to-size ratio of any category of static separation unit resulting in a minimal installed footprint and weight [61].

Furthermore, surface multiphase desanding has been effectively used as a service tool and as a part of the processing system. As a service tool, it is built upstream of the choke in order to remove solid particles during workover operations, such as coiled tubing washout, acid washing, well testing, frac flowback, or under-balanced drilling. Using multiphase desander as part of surface facilities, it is installed either before or after the choke valve and leads to only different in pressure rating design of the vessels. Workability of the multiphase desander is similar regardless of the pressure rating. Removal of solid particles before the wellhead protects surface facilities (i.e. choke valve, flow line, separation unit). Meanwhile, removing particles after the valve permits for a lower pressure rating design even though protecting separation system. The initial few installations of multiphase desanders took place in critical applications in which downhole tools providing inadequate protection to topsides equipment. Through grown utilize and improved prediction models, multiphase desanders come to be a significant tool in general sand management.

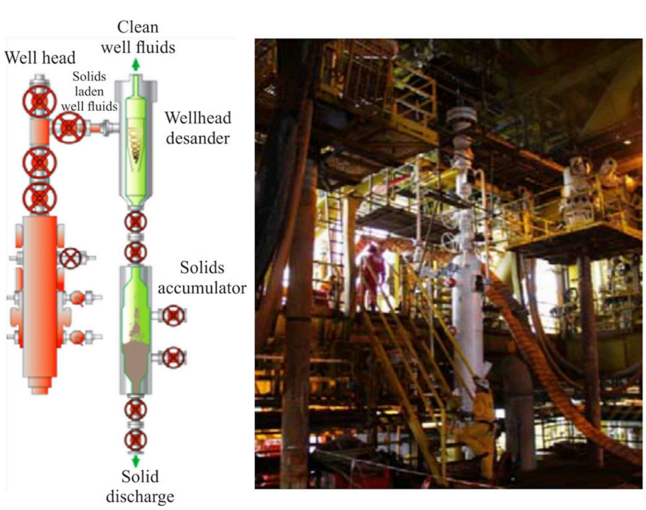

Fig. 5. (left) Schematic of wellhead desander operation, and (right) wellhead desander with oversized accumulator integrated into well bay of spar facility [56].

8.6. Chemical consolidation treatments

Approximately 70% of the total world's hydrocarbon fluids are to be found in poorly consolidated formation reservoirs [62,63]. Typically, these formations are relatively young in geologic age, and are unconsolidated since natural processes have not cemented the rock grains together via mineral deposition [66]. Many sand consolidation techniques have been developed to prevent sand movement with oil or gas fluids produced from hydrocarbon-bearing earth formations. Storing the formation with resin-coated particulated solid particles, saturating the unconsolidated sand formation with a bonding resin, and placing resin-treated sand between the free sand in the well bore and formation to form a screen are considered as chemical techniques. These approaches have met with varying grades of achievement.

A dispersion sand consolidation mixture is one in which a consolidating fluid is made up of a hydrocarbon carrier, a resin or a resin-forming mixture dispersed in it together with a quantity of particulated solid particles [64,65,67]. The processes of resin consolidation have been categorized in different techniques. Low injection pressure, minimum preparation time at the well site, short treatment time before restoring the production, high compressive strength of resulting matrix, good resistance to deterioration from well fluids and usually utilized treating fluids and high retained permeability are necessary characteristics for a consolidation practice [74]. Some types of resins have been currently used in the sand control operation. Some examples of hardenable organic resins that can be suitably used, are polyester resins, phenol–formaldehyde resins, epoxy resins, furan resins, urea–formaldehyde resins, urethane resins and combinations of such resins [64,65,67–73].

The process of resins polymerization is made with catalysts or curing agents. Using resins for sand consolidation has been implemented for many years. Resins are directly applied into the formation using high pressures when pressures are released from tubing in wells or when perforations are made in the casing [64,65]. Chemical techniques have a number of significant advantages over mechanical techniques; however, the high cost of resins and the difficulties in finding suitably uniform injection of chemicals have limited application to relatively short intervals of perforations [66]. The hardenable resin on the deposited particulate solids caused or permitted to harden whereby a consolidated permeable particulate solid pack is formed between the well bore and loose or incompetent sand in the formation.

Among the commercial processes for consolidating incompetent formations some are developed by both service and research companies, whose major business is the production, refining and marketing of petroleum. For instance, "Sanset process" is developed by Esso Production Research Co. It is also well-known as Base Catalyzed Process (BCP) where phenol–formaldehyde resin is used in this process. Moreover, it can be used to reservoir formations with a temperature range from 29.5 to 94 °C. It may also be used at higher temperatures under some limitations. The consolidated formation could have a compressive strength of 200 atm. and maintain 50% of the formation original permeability. The pumping or placement time is controlled by

Table 7
Various commercial consolidation processes.

Inventor	Year	Base of applied resin	Range of temperatures (°F)	Range of compressive strength (Psi)	Permeability to original (%)
Sain	1962	Phenol–formaldehyde	85–200	> 3000	50
Dees et al.	1992	Epoxy	100–220	> 5000	67
Dees	1993	Epoxy	50–250	> 7000	50
Jennings et al.	1994	Phenol–formaldehyde	280	> 3000	70
Shu	1994	Epoxy	175	–	–
Todd et al.	2001	Furan	40–400	> 3000	90
Appah	2003	Furan–phenolic	–	3000	–
Nguyen	2004	Furan	80 to > 300	> 3000	70
Nguyen	2006	Furan	40 to 400	> 3000	70
Talaghat et al.	2009	Modified phenol–formaldehyde		> 3000	67–83
Riyanto et al.	2016	An aqueous based consolidation	145		

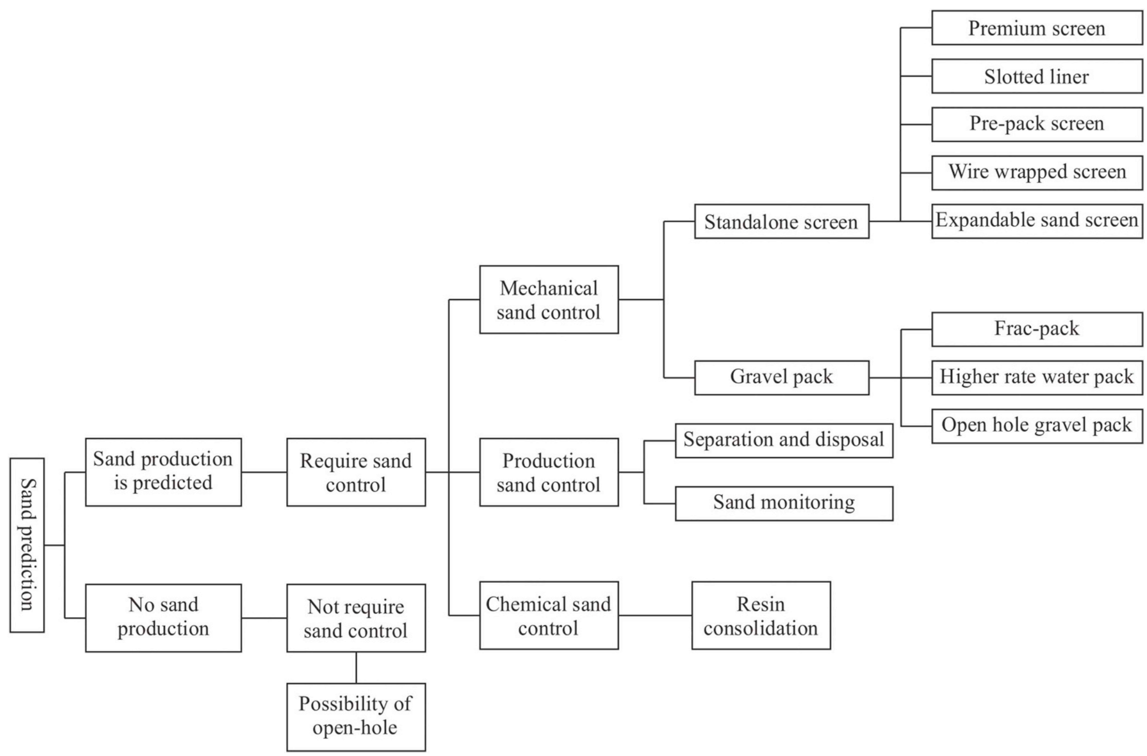

Fig. 6. Sand management strategy flow chart.

the added quantity of curing agent when the resin is mixed. Thus the chemical reaction in which involves in this process is called exothermic and the resin constituents should be refrigerated instantaneously before and through the mixing operation. At lower temperatures, several days may be required. An enriched formulation is available for greater strength [74]. Further commercial available processes for consolidation formations are listed in Table 7 [65,73–80]. Fig. 6 illustrates the events flow after the quantification of risk to analysis the best fit sand management approach.

Mahmoud et al. presented a full scenario on the mitigation methods taken to solve a sandstone production issue [81]. Several techniques that can be adopted to predict the potential of sanding as well as its rate included the field observations, experimental works and theoretical model to correlate the data. An application criteria of three different sand control methods had been presented as shown in Table 8. Meanwhile, a comprehensive pros and cons evaluation of different sand control techniques had been tabulated in Table 9. It is clearly remarked that an improved sandstone control methodology is deserved to maintain the hydrocarbon production from the wells. The application criteria presented in this study as well as comparison between sand control techniques had consolidated the conclusion made at the end of this paper.

Table 8
Application criteria of sand control techniques [82].

Criteria	Resin Injection	Resin coated Gravel without screens	Gravel Pack
Pressure (psi)	≤3300	2500–3300	> 1000
Temperature (°F)	< 250	< 250	> 150
Percentage of Sand Control (%)	10	5	75

Gjedrem conducted a study to investigate the effects of rate constraints on the performance of reservoir caused by an erosion of the sand screens in a cased hole [84]. An analytical sand screen erosion model had been integrated with a NETool completion model as well as an ECLIPSE reservoir model. A sensitivity analysis had been presented in this work to study the effect of different particle size and concentration of produced sand on the safe velocity and the subsequent well recovery factor as represented in Table 10. A comparative study on Standalone Sand Screen (SAS), Screens with packers and Expandable Sand Screens (ESS) was then made. The results of study indicated that

Table 9
Comparison among different sand control techniques [83].

	Resin injection	Grave Pack without screens	Screen with open hole gravel pack
Advantages	● Leaves wellbore open. ● No necessity for screens and liners.	● Offers economical methods of sand control. ● Gravel packing covers long interval up to 500 ft.	● Low drawdown and high productivity. ● Excellent longevity. ● No casing or perforating expense.
Disadvantages	● Limited zone height. ● Longevity limited. ● Temperature sensitivity $< 250\,^{\circ}F$. ● Very difficult to evenly apply. ● Reduces permeability by 10–60%	● Expensive fishing job ● Cause pressure drop ● Erosion failure of the slotted liner or screen. ● Plugging will eventually occur. ● Reduce the production capacity of the well.	● Difficult to exclude undesirable fluids such as water and/or gas. ● Not easily performed in shale and erode or slough when brine is pumped past them. ● Requires special fluids for drilling the open hole section.

Table 10
Design of sensitivity analysis and results of safe velocity [84].

Particle size (micron)	Particle concentration (ppm)	Ultimate recovery factor ESS	Ultimate recovery factor SAS	Ultimate recovery factor SAS-Packers	Ultimate recovery factor Gravel
50	200	0.529	0.127	0.127	0.722
	400	0.492	0.111	0.111	0.722
	1000	0.409	0.094	0.094	0.722
	10 000	0.219	0.062	0.062	0.599
	50 000	0.142	0.047	0.047	0.546
75	200	0.509	0.118	0.118	0.722
	10 000	0.197	0.058	0.058	0.588
	50 000	0.127	0.044	0.044	0.530
100	200	0.492	0.111	0.111	0.722
	10 000	0.182	0.055	0.055	0.579
	50 000	0.118	0.042	0.042	0.509

the gravel pack is the most suitable sand control method for the erosion prevention of the sand screens. This method was found to ensure a highest well production rate. Therefore, a gravel pack sand screens well completion would lead to a higher potential of production. Meanwhile, ESS and SAS had a poor performance in sand erosion resistance. Erosion was found to be more severe at large particle sizes and high concentrations, hence deserving a more robust and efficient sand control method.

9. Conclusions

Sand production from reservoir formations can take place if the reservoir fluid flow exceeds a certain threshold influenced via factors for instance stress state, consistency of the formation grain and the completion strategy used around the well. Sand control of producing oil and gas well is an essential step to ensure high production by removal of solid particles along with produced fluids, but these particles could be present in inadequate quantities (less than few grams per cubic meter of reservoir fluid), concentrations or sizes, causing only minor problems, or if a significant amount accumulated over a short period of time can result in equipment and/or pipe erosion and in some situations filling and blocking of the wellbore. When the amount or size of solids causes lost production because of reduced inflow or the equipment downtime, a control technique is essentially required to restore the fluid production rate to an economically level. Sand prediction models provide a better evaluation of the sanding potential and the real-world knowledge of formation sand production behaviour. Many research studies either experimentally or numerically have been conducted in which highlighting the importance of sand control in produced reservoir formations. Most of developed models are based on either discrete element model or the continuum hypothesis. Some models have only the potential to assess the conditions that cause sanding, while others have the ability to make volumetric predictions. Some of developed models utilize analytical formulae, mainly those used for determining the sanding onset, but other models apply numerical models, particularly in obtaining sanding rate. Even though, the major improvements have been made previously, but sanding tools are still not capable to predict the sanding rate and mass for all field problems in a reliable procedure. Many different exclusion techniques of sand control are developed, applying mechanical retention (slotted liner or screen), chemical consolidation, gravel packs, or a mixture of these techniques to prevent sand from entering the wellbore, but still there are some limitations like not completely stopping sand production. An alternative to allowing solid particles in the reservoir formation is to produce with reservoir fluids and then separate phases at the downstream facility. Such a multiphase desander segregates solid particles from the produced hydrocarbons at the choke valve either before or after or prior to the separator unit. The selection of the best technique relies on a comprehensive knowledge on the reservoir and well conditions, production life, intervention costs, and the well treatment that will deliver the maximum sustained well productivity. Nevertheless, there is no particular sand control scheme, which can work for any type of unconsolidated reservoirs. Applying a new sand control technology will broaden up our knowledge on sand control methods and will assist in selecting a specific fit for a particular reservoir condition.

References

[1] Schlumberger, Alternate path technology–global track record, http://www.slb.com/services/completions/sand_control/transcend/openhole_gravel_pack_completions/alternate_path_gravel_pack_services/alternate_path_technology.aspx?t=2, (2015).
[2] O.N. Vincent, S.O. Abiola, O.O. Felix, J.A. Ajienka, Sanding in Oil Well Reservoir Completions, SPE, 2012 163010-MS.
[3] J.M. Cook, I.D.R. Bradford, R.A. Plumb, A Study of the Physical Mechanisms of Sanding and Application to Sand Production Prediction, SPE, 1994 28852-MS.
[4] M.U. Shafiq, H. Ben Mahmud, Sandstone matrix acidizing knowledge and future development, J. Petrol. Explor. Prod. Technol. (2017), https://doi.org/10.1007/s13202-017-0314-6.
[5] V.H. Leong, H.B. Mahmud, A comparative study of different acids used for sandstone acid stimulation: a literature review, IOP Conference Series: Material Science *and Engineering*, vol 217, 2017, p. 012018 IOP Publishing https://doi.org/10.1088/1757-899X/217/1/012018.
[6] Completion Technology for Unconsolidated Formations, Revision 2, (June 1995).
[7] H.H. Abass, H.A. Nasr-El-Din, M.H. BaTaweel, Sand Control: Sand Characterization, Failure Mechanisms and Completion Methods, SPE, 2002, p. 77686.
[8] H. Ben Mahmud, A. Abdullah, Investigate a Gas Well Performance Using Nodal Analysis, International Conference on Materials Technology and Energy, Curtin University Malaysia, 2017, pp. 20–21. April.
[9] J. Carlson, D. Gurley, G. King, C. Price-Smith, F. Waters, Sand Control: Why and How? Completion Simulation, Oilfield Review, (1992), pp. 41–53.
[10] K. Amos, Sand control mechanism and its impact on mature fields, http://halliburtonblog.com/sand-control-mechanism-and-its-impact-on-mature-fields/, (2012).
[11] K.C. Tummala, K.P. Roberts, J.R. Shadley, E.F. Rybicki, F.A. Shirazi, Effect of Sand Production and Flow Velocity on Corrosion Inhibition under Scale Forming Condition, NACE, 2009, p. 09474.
[12] A. Younessi, V. Rasouli, B. Wu, The Effect of Stress Anisotropy on Sanding: an External Study, ARMA, 2012 2012-374.
[13] F. Civian, Reservoir Formation Damage: Fundamentals, Modeling, Assessment, and Mitigation vol 10, Gulf Publishing Company, Houston, TX, 2000.
[14] K. Sampach, P.L. Randol, Measurement of Formations Characteristics for Western

Tight Sands, (1980) DOE/BC/00042-20.
[15] N. Morgan, Saving sand dollars, Frontiers 6 (2006) August.
[16] S. Zwolle, D.R. Davies, Gravel Packing Sand Quality-A Quantitative Study, SPE Formation Damage Control Symposium, Lafayette, (1982), pp. 24–25 March.
[17] Emulsions: Fundamentals and Applications in the Petroleum Industry Advances in Chemistry Series, L.L. Schramm (Ed.), vol 231, American Chemical Society, Washington, DC, 1992.
[18] W.L. Penberthy Jr., C.M. Shaughnessy, Sand Control SPE Series on Special Topics vol 1, Society of Petroleum Engineers, Richardson, TX, 1992.
[19] J. Alford, M. Blyth, E. Tollefsen, J. Crowe, J. Loreto, S. Mohammed, V. Pistre, A.R. Herrera, Sonic logging while drilling – shear answers, Oilfield Rev. Spring 24 (2012) (2012) 1.
[20] Z. Szczepanik, D. Milne, C. Hawkes, The Confining Effect of End Roughness on Unconfined Compressive Strength, (2007) ARMA-07-098.
[21] P.M. Halleck, E. Poyol, F.J. Santarelli, Estimating Perforation Flow from Variation in Indentation Hardness. SPE-24769-PA, (1995).
[22] Y. Xiao, H.H. Vaziri, Import of strength degradation process in sand production prediction and management, Proceedings of the 45th, U.S. Rock Mechanics/ Geomechanics Symposium, San Francisco, Calif, USA, 2011.
[23] E. Papamichos, P. Cerasi, J.F. Stenebråten, et al., Sand production rate under multiphase flow and water breakthrough, Proceedings of the 44th U.S. Rock Mechanics Symposium and the 5th US/Canada Rock Mechanics Symposium, Salt Lake City,Utah, USA, 2010.
[24] L. Jing, O. Stephansson, Fundamentals of Discrete Element Methods for Rock Engineering, Theory and Applications, Elsevier, 2007.
[25] N. Belheine, J. Plassiard, F. Donzé, F. Darve, A. Seridi, Numerical simulation of drained triaxial test using 3D discrete element modeling, Comput. Geotech. 36 (1) (2009) 320–331.
[26] P.H.S.W. Kulatilake, B. Malama, J. Wang, Physical and particle flow modeling of jointed rock block behavior under uniaxial loading, Int. J. Rock Mech. Min. Sci. 38 (5) (2001) 641–657.
[27] H. Rahmati, M. Jafarpour, S. Azadbakht, A. Nouri, H. Vaziri, D. Chan, Y. Xiao, Review of sand production prediction models, J. Pet. Eng. 2013 (2013) 16.
[28] W.R. Moore, Sand Production Prediction, SPE-29331-PA, BJ Services Co, 1994.
[29] O.M. Aborisade, Practical Approach to Effective Sand Predication, Control Management, Department of Petroleum Engineering, African University of science and Technology, Thesis, 2011.
[30] W. Pingshuang, Z. Jianliang, L. Ming, Sand Production Prediction of Weizhou 12-1 Oilfield in Beibu Gulf in South China Sea. SPE International Oil and Gas Conference and Exhibition, vol 64623, SPE, Beijing, 2000 2000.
[31] N.A. Braaten, T. Blakset, R. Johnsen, R. Birkeland, Field Experience with a Subsea Erosion Based Sand Monitoring System, SPE, 1996 35551-MS.
[32] C.A.M. Veeken, D.R. Davies, C.J. Kenter, A.P. Kooijman, Sand Production Prediction Review: Developing an Integrated Approach, SPE, 1991, p. 22792.
[33] J.S. Weingarten, T.K. Perkins, Prediction of Sand Production in Gas Wells: Methods and Gulf of Mexico Case Studies vol 24797, SPE, Washington, 1992, pp. 4–7 October.
[34] F. Sanfilippo, M. Brignoli, D. Giacca, F.J. Santarelli, "Sand Production: from Prediction to Management." European Formation Damage Conf. Proc. SPE, The Hague, 1997 #38185.
[35] N. Morita, D.L. Whitfill, I. Massie, T.W. Knudsen, Realistic sand production prediction: numerical approach, 62nd Annual Technical Conference and Exhibition of the Society of Petroleum Engineers Proc., Dallas, TX, 1987, pp. 27–30 Sept.
[36] J. Tronvoll, N. Morita, F.J. Santarelli, Perforation cavity stability: comperhensive laboratory experiments and numerical analysis, SPEAnnual Technical Conference and Exhibition, Washington DC, 1992, pp. 4–7 October.
[37] J. Tronvoll, E. Fjaer, Experimental study of sand production from perforation cavities, Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 31 (5) (1994) 393–410.
[38] J. Tronvoll, M.B. Dusseault, F. Sanfilippo, F.J. Santarelli, The tools of sand management, SPEAnnual Technical Conference and Exhibition, New Orleans, 30 Sepetember–3 October, 2001.
[39] C.H. Rawlins, I. Wang, Design and installation of a sand separation and handling system for a Gulf of Mexico oil production. facility, Paper 63041 Presented at the SPE Annual Technical Conference and Exhibition, October, Dallas, 2000, pp. 1–4.
[40] M. Hess, A. Sinker, H. Rawlins, Treatment of solids at oil production installations, Presented at the IBC Conference on Meeting Environmental Standards for the Offshore Industry, Aberdeen, December, 1997.
[41] M. Arfie, E. Marika, E.S. Purbodiningrat, H.A. Woodard, Implementation of slurry fracture injection technology for E&P wastes at duri oilfield, SPE Asia Pacific Health, Safety, and Environmental Conference and Exhibition, Kuala Lumpur, 19-20 September, 2005.
[42] J.D. Kaura, A. Macrae, D. Mennie, Clean up and well testing operations in high-rate gas-condensate field result in improved sand management system, SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, 2001, pp. 17–19. April.
[43] F.J. Wohlfart, New Approach to Sand Production in Mature Oilfields and Cost Optimization for Sand Problems. Presented at the Spring Meeting of the German Society for Petroleum and Coal Science and Technology (DGMK), Celle, 21 April, (2006).
[44] F. Selfridge, M. Munday, O. Kvernvold, B. Gordon, Safely improving production performance through improved sand management, Paper 83979 Presented at Offshore Europe, Aberdeen, 2-5 September, 2003.
[45] D.L. Tiffin, M.H. Stein, X. Wang, Drawdown guidelines for sand control completion, SPE Annual Technical Conference and Exhibition, Denver, 2003, pp. 5–8 October.
[46] G.K. Wong, P.S. Fair, K.F. Bland, R.S. Sherwood, Balancing act: Gulf of Mexico sand control completions, peak rate versus risk of sand control failure, SPE Annual Technical Conference and Exhibition, Denver, 2003, pp. 5–8 October.
[47] I. Palmer, H. Vaziri, S. Willson, Z. Moschovidis, J. Cameron, I. Ispas, Predicting and managing sand production: a new strategy, Paper 84499 Presented at the SPE Annual Technical Conference and Exhibition, Denver, 2003, pp. 5–8 October.
[48] H. Vaziri, R. Allam, G. Kidd, C. Bennett, T. Grose, P. Robinson, J. Malyn, Sanding: a rigorous examination of the interplay between drawdown, depletion, start-up frequency and water cut, SPE Annual Technical Conference and Exhibition, Houston, 2006, pp. 26–29 September.
[49] C.J. Balgobin, Sand management of ultra-high-rate gas wells, Paper SPE 94896 presented at the SPE Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, 2005, pp. 20–23 June.
[50] M.H. Stein, A.A. Chitale, G. Asher, H. Vaziri, Y. Sun, J.R. Colbert, F.A. Gonzalez, Integrated sand and erosion alarming on Na kika, deepwater Gulf of Mexico, SPE Annual Technical Conference and Exhibition, Dallas, 2005, pp. 9–12 October.
[51] L.A. Musa, T. Temisanren, W. Appah, D. Appah, Establishing actual quantity of sand using an ultrasonic sand detector, The Niger Delta Experience, 29th Annual SPE International Technical Conference and Exhibition, Abuja, 2005, pp. 1–3. August.
[52] G.E. King, P.J. Wildt, E. O'Connell, Sand control completion reliability and failure rate comparison with a multi-thousand well database, SPE Annual Technical Conference and Exhibition, Denver, 2003, pp. 5–8 October.
[53] C. Price-Smith, M. Parlar, C. Bennett, J.M. Gilchrist, E. Pitoni, R.C. Burton, R.M. Hodge, J. Troncoso, S.A. Ali, R. Dickerson, Design methodology for selection of horizontal openhole sand-control completions supported by field case histories, SPE Drill. Complet. 18 (3) (2003) 235.
[54] C.G. Williams, B.N. Richard, D. Horner, A new sizing criterion for conformable and nonconformable sand screens based on uniform pore structures, SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, 2006, pp. 15–17 February.
[55] T. Iversen, D. Soskice, Electoral institutions and the politics of coalitions: why some democracies redistribute more than others, Am. Pol. Sci. Rev. 100 (2006) 165–181.
[56] C. Hank Rawlins, Sand management methodologies for sustained facilities operations, The North Africa Technical Conference & Exhibition Held in Cairo, Egypt, 15–17 April, 2013.
[57] C.H. Rawlins, A.E. Erickson, C. Ly, Characterization of Deep Bed Filter Media for Oil Removal from Produced Water, SME Annual Meeting, Phoenix, 28 February – 3 March, (2010).
[58] D. Hadfield, Wellhead desanders-cyclonic sand removal from multi-phase wellstreams, Presented at the NIH Seminar on Offshore Separation, Kristiansand, 1996, pp. 11–13 November.
[59] D. Hadfield, Solving the sand production problem at source: the wellhead desanding hydrocyclone, Presented at the IBC Production Separation Systems Forum, Oslo, May, 1997, pp. 28–29.
[60] C.H. Rawlins, Application of multiphase desander technology to oil and gas production, Paper Presented at the BHR 3rd International Conference on Multiphase Technology, Banff, 2002, pp. 3–5 June.
[61] C.H. Rawlins, The case for compact separation, J. Pet. Technol. 55 (5) (2003) 77–79.
[62] A. Nouri, H. Vaziri, H. Belhaj, R. Islam, Comprehensive transient modeling of sand production in horizontal wellbores, SPE Annual Technical Conference and Exhibition, Denver, Colorado, 2003.
[63] A. Nouri, H. Vaziri, H. Belhaj, R. Islam, Effect of volumetric failure on sand production in oil-wellbore, SPE Asia Pacific Oil and Gas Conference and Exhibition, Jakarta, Indonesia, 2003.
[64] J.M. Dees, Sand Control in the Wells with Gas Generator and Resin', United States Patent 5101900, (1992).
[65] J.M. Dees, W.J. Begnaud, N.L. Sahar, Sand Control with Resin and Explosive', United States Patent 5145013, (1992).
[66] J.M. Dees, Method of Sand Consolidation with Resin', United States Patent 5178218, (1993).
[67] D. Appah, Sand consolidation experience in Niger Delta', IE (I), J. – CH 84 (9) (2003) 14.
[68] H.H. Sain, Sand Consolidation with a Base – Catalyzed Plastic', API Paper No. 926-7-F, Spring Meeting, Southern District, Houston, Texas 11, 1962.
[69] A.R. Jennings, E.S. Sprunt, R.S. Timmer, Method of sand consolidation, U. S. Pat. 5363 (1994) 917.
[70] P. Shu, 'Consolidation Agent and Method', United States Patent, (1994) 5362318.
[71] B. Todd, B.F. Slabaugh, R.J. Powell, J.G. Yaritz, Resin Composition and Methods of Onsolidating Particulate Solids in Wells with or without Closure Pressure', United States Patent, (2001) 6311773.
[72] P.D. Nguyen, 'Methods of Completing Wells in Unconsolidated Formations', United States Patent, (2004) 6776236.
[73] P.D. Nguyen, Methods for Forming a Permeable and Stable Mass in a Subterranean Formation, United States Patent, (2006) 6997259.
[74] J.A. Hugh, J. Ramos, Guidelines to Sand Control, Report, Halliburton Services from Halliburton Co, 1995.
[75] D.D. Sparlin, A New Sand Control Technique for Old Sand Problems. API Paper No. 906-12-H, Spring Meeting, Southwestern District, (1976).
[76] J.W. Graham, A.R. Sinclar, J.L. Brandt, Method of Treating Well Using Resin-Coated Particles. United States Patent, (1982) 4336842.
[77] P.D. Nguyen, R.G. Dusterhoft, Methods of Completing Wells in Unconsolidated Subterranean Zones. United States Patent, (1999) 6003600.
[78] B.T. Dewprashad, P.D. Nguyen, K.L. Schreiner, Compositions and Methods for Consolidating Unconsolidated Subterranean Zones. United States Patent, (2000) 6016870.
[79] S. Danican, G. Salamat, A. Pena, E. Nelson, Method of Completing Poorly Consolidated Formations. United States Patent, (2006) 7013973.
[80] L. Riyanto, M. Saleh, K. Goh, J. Ambrose, T. Kristanto, C.Y. Hong, Novel aqueous-

based consolidation restores sand control and well productivity: case history from east Malaysia, SPE International Conference & Exhibition on Formation Damage Control Held in Lafayette, Louisiana, USA, 2016, pp. 24–26 February.
[81] M.N. Mahmoud, M.Z.B. Sultan, N. Yousuf, Scenario of sand production from hydrocarbon reservoir and its mitigation, J. Recent Act. Prod. 3 (1) (2018) 1–8.
[82] E.K. George, J.W. Pat, O. Eamonn, Sand control completion reliability and failure rate comparison with a MultiThousand well database, SPE Annual Technical Conference and Exhibition, 2003, pp. 5–8 October 2003, Denver, Colorado.
[83] J.A. Leone, M.L. Mana, J.B. Parmley, Gravel Sizing Criteria for Sand Control and Productivity Optimization, SPE California Regional Meeting, Ventura, California, 1990, pp. 4–6. April 1990.
[84] C. Gjedrem, Effect of Screen Erosion on Reservoir Performance, Master's Thesis University of Stavenger, Norway, 2017.