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Module 1

FUNDAMENTALS OF SAND MANAGEMENT

CONTENT

- *Introduction*
- *Sand production principles*
- *How does sand production occurs ?*
- *Consequences of sand production*

INTRODUCTION

Sand management is the process by which sand grains and formation particles are produced along with the hydrocarbons, processed and disposed in a cost-effective and environmentally compliant safe manner

The process is labour intensive and to be successful requires the contribution of many disciplines such as geology & geosciences, production technology, flow assurance, geomechanics, management, operating/field knowledge and expertise.

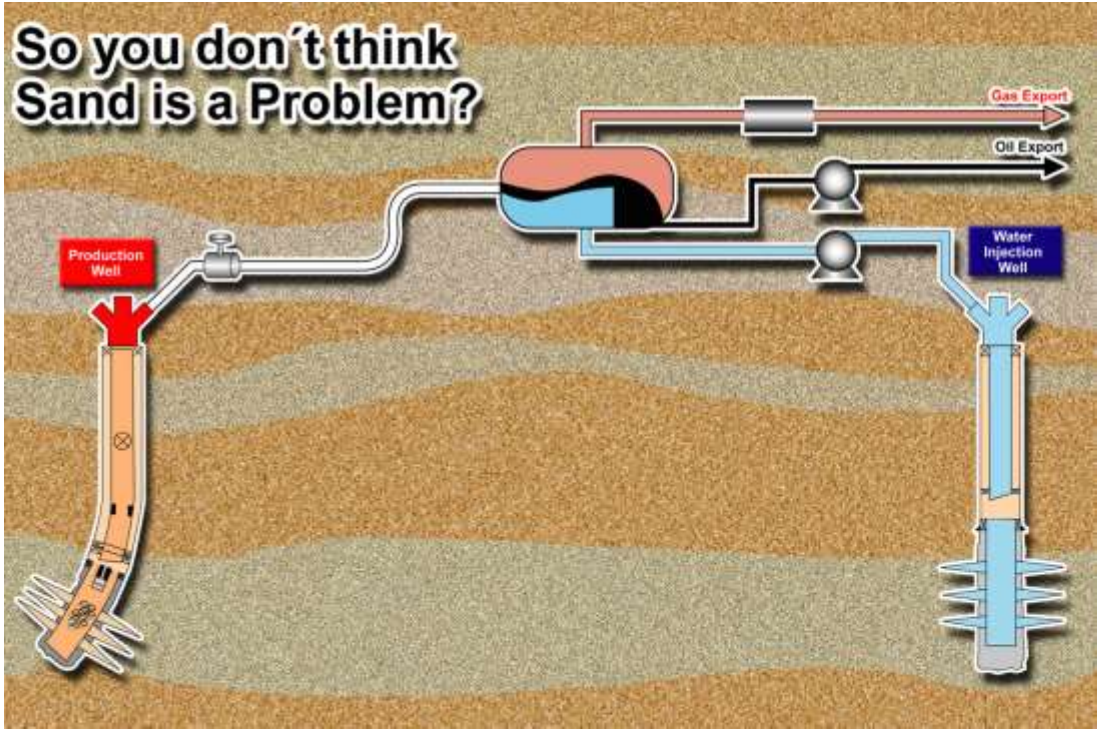
Sand production is considered a detrimental process to production however, *that is not the case*.

Management of sand production can lead to successful and productive field life and improved reserves recovery

INTRODUCTION (Continued)

Sand production impact all aspects of the drilling, completion and production stages in the life of a field.

- Most sandstone reservoirs will produce sand at some point in their productive life
- The sand management process can be planned or a remedial one
- Most fields/wells on sand management are the result of an unplanned event such as completion failure



Courtesy of BP

INTRODUCTION (Continued)

The damage caused by sand production affects all aspects of field's productive life.

Failed Completion

Eroded sand screen

Sand deposition at the flowlines

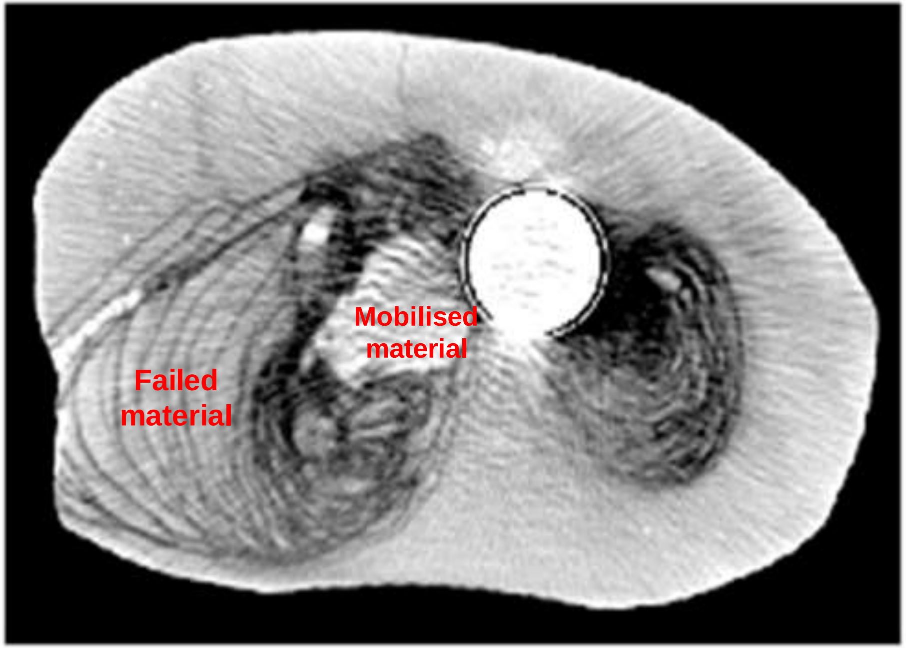
SAND PRODUCTION PRINCIPLES

Sanding occurs in all types of wells, oil & gas producers, injectors and storage wells

- Intact rock failure, granular material failure and grain mobilisation are the mechanisms that lead to sand production

- Intact rock failure and granular material failure are driven by the stresses acting at the near wellbore and area

- In many cases sand production can increase productivity/injectivity from/to a reservoir



After Palmer I. 2000

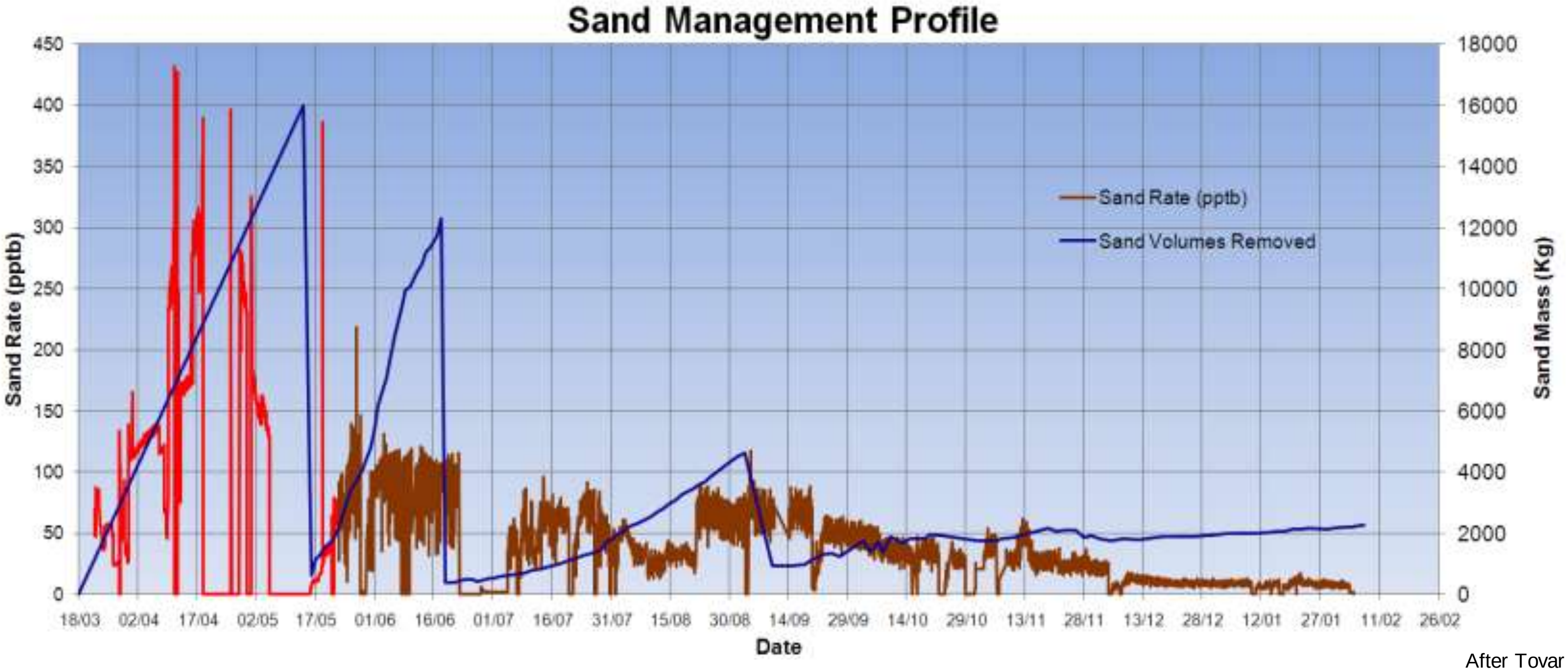
SAND PRODUCTION PRINCIPLES (Continued)

It is common to *identify* the severity of sand production by the mode of sanding (Rate) and volumes measured at surface. The table below presents four(4) modes of sanding based on liquid hydrocarbon production i.e. lbs of sands per 1000 bbls of fluids

MODE	VOLUMES* [lbs/1000 bbls]	WHEN DOES IT OCCUR	CHARACTERISTICS
Initial / Start up	< 700	Well start up, initial flow(DST), clean out	Large volumes of sand & associated mud particles
Transient	< 100	Change of operating conditions	Also known as “sand bursts” that occur sporadically
Continuous	< 50	Anytime but it increases from there	Low “tolerable” volumes on a continuous basis
Catastrophic	-	Start up or any other time	Sudden event that is sometimes associated with an increase in WOR

SAND PRODUCTION PRINCIPLES (Continued)

Sanding is perceived as an erratic process both from open hole or cased/perforated completions



After Tovar et al 2010

HOW DOES SANDING OCCURS ?

Sand production occurs when the mechanical loads acting on the wellbore exceeds the capability of the rock matrix to withstand these loads. At this point two (2) conditions must be present for sanding to occur:

1. Mechanical failure of the rock at the near wellbore occurs, this implies that an intact reservoir rock matrix ”breaks” transitioning into clusters or granular material as part of the deformation process

2. This failed material must be ***mobilised*** from the near wellbore along with the produced fluids into the wellbore and up to surface.

The production fluids generate capillarity, seepage and drag forces that can overcome the cohesive forces keeping the failed material in place. Water production has been identified with the initiation of sand production.

HOW DOES SANDING OCCURS ? (Continued)

Due to the direction of flow (into the reservoir) in *water injection wells* the sequence of events is different but the engineering principles causing sanding remains similar

1. Mechanical failure of the rock at the near wellbore, reservoir rock matrix ”breaks” transitioning into clusters or granular material as part of the deformation process. *Such a failure occurs during the shutdown of the injector due to a pressure pulse* (Water hammer effect) *generated during the sudden injection of fluids*

2. This failed material is ***mobilised*** from the near wellbore. The transient equalisation of reservoir pressures at the near wellbore area and zones of varying permeability allow cross-flow of water prior to the “equalisation” of pressure at the sand face.

As a result, the two (2) conditions are met for water injectors and sand is produced into the wellbore. This occurs during well’s shutdown

CONSEQUENCES OF SAND PRODUCTION

PROCESS	CONSEQUENCE	RISK	OBSERVATIONS
Drilling	Increase in NPT, poor hole quality and increased drilling and completion time	**Medium**	Higher rig and materials cost
Completion	Well requires frequent well intervention	**Low**	High cost associated with intervention & recompletion
	Completion failure and loss of the well	**High**	Screens, tubing and DHSV failure
Production	Erosion of surface equipment	**High**	Tree valves, chokes, flowlines
	Poor separation of gas/fluids/solids	**Low**	Increased OPEX due to extended maintenance programs
	Increase in hydrocarbon production	**Low**	Improved reserves recovery
Disposal	Higher environmental cost & risk	**Medium**	To meet local regulations
	Additional monitoring, testing	**Low**	Data gathering and processing programs.

CONSEQUENCES OF SAND PRODUCTION (Continued)

Quartz is one of the hardest natural minerals on earth and the damage it causes to equipment is significative

Courtesy of Dragon Oil

MODULE 1 - SUMMARY

Sand production is a phenomena that occurs in all types of sandstone reservoirs during their productive life. In stronger rocks this might occur at a later stage in the field’s life.

Managing sand production is a complex process that increases the risk to completion and production operations in oil, gas, storage and injection wells.

Such a risk vary between very severe to moderate and low. In all cases it might cause mechanical integrity problems, environmental issues all leading to higher cost.

Wellbore filling, failed screens, eroded tubing and valves are the result of sand production in wells. Failed chokes, valves, flowlines, poor separator performance and corroded flowlines are some of the potential consequences of sand production

Improved well, reservoir performance and reserves recovery are some of the positive outcomes of effective and efficient sand management

MODULE 1 – SUMMARY (Continued)

Sand production is caused by the loading being applied to the reservoir rock that induces mechanical failure of the intact reservoir matrix

Fluid production/injection then mobilises the failed material from the near wellbore into the wellbore and up to surface. These two (2) conditions must be met (Rock failure and mobilisation) for sanding to occur

In water injectors the same engineering principles apply but the sequence of events which generates the two (2) conditions (Rock failure and grain mobilisation) varies

A similar situation occurs in gas producing wells however, the tolerance of gas wells to sand is much lower than that in oil producers and water injection wells.

In wells producing heavy crudes, such a potential risks are mitigated by the viscosity of the crude

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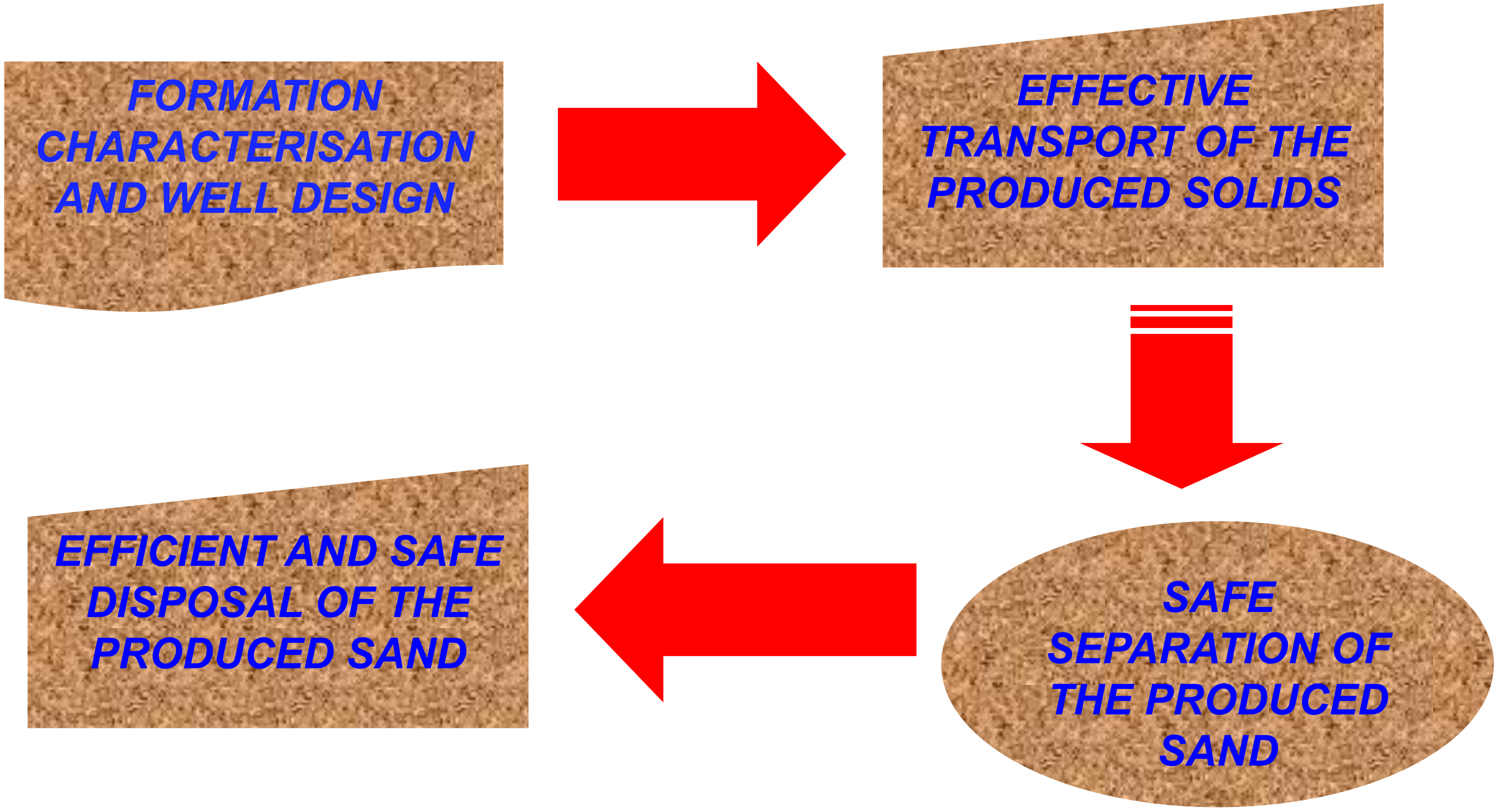
Module 2

THE PROCESS OF SAND MANAGEMENT

CONTENT

- *The process and its components*
- *Formation characterization*
- *Transport of the produced solids*
- *Safe separation of the sand at surface*
- *Efficient and safe disposal of the produced solids*

SAND MANAGEMENT PROCESS



SAND MANAGEMENT PROCESS (Continued)

It is a process that requires a detailed knowledge of the reservoir, well completion, flowlines, plant and storage facilities. It has the following characteristics:

- It requires participation from many disciplines to be successful
- Success is defined in this case as a safe, environmentally compliant and commercially efficient reservoir management and operations
- The process is composed of four (4) main elements:
    - Detailed formation characterization
    - Efficient transport of the produced and processed fluids
    - Safe separation of the produced solids and fluids
    - Safe disposal of the produced sand

FORMATION CHARACTERIZATION

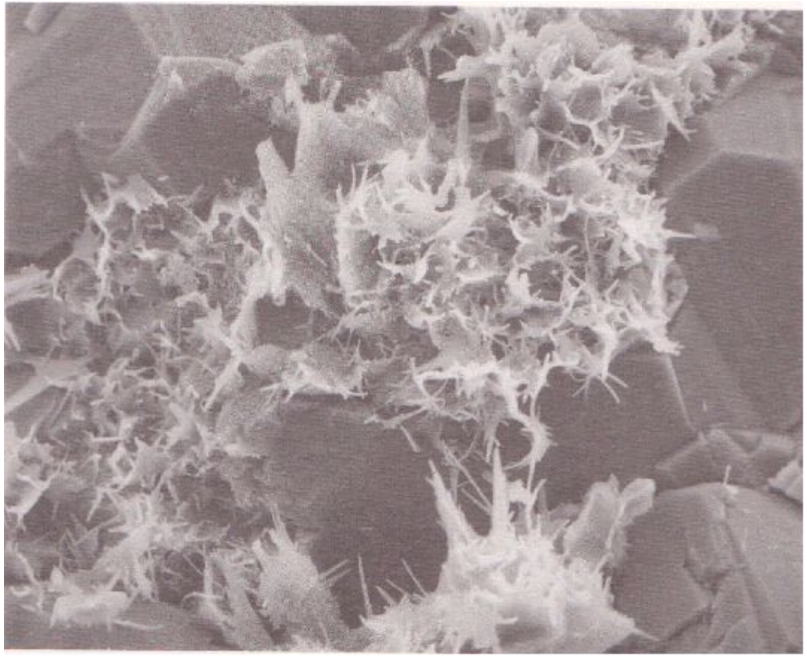
Requires collection, organization, analysis of data/results and its input into the relevant models use. The types of formation characterization are:

1. **Mineralogy** characterization to define the elements that compose the reservoir matrix, their size and quality. Typical tests used include SEM/EDAX and PSD
2. **Reservoir fluids** using typical PVT type of test for well performance applications and determination of fluids rheology
3. **Mechanical** characterization through testing including UCS, TWC, tri-axial test to obtain static properties such as strength and deformation parameters

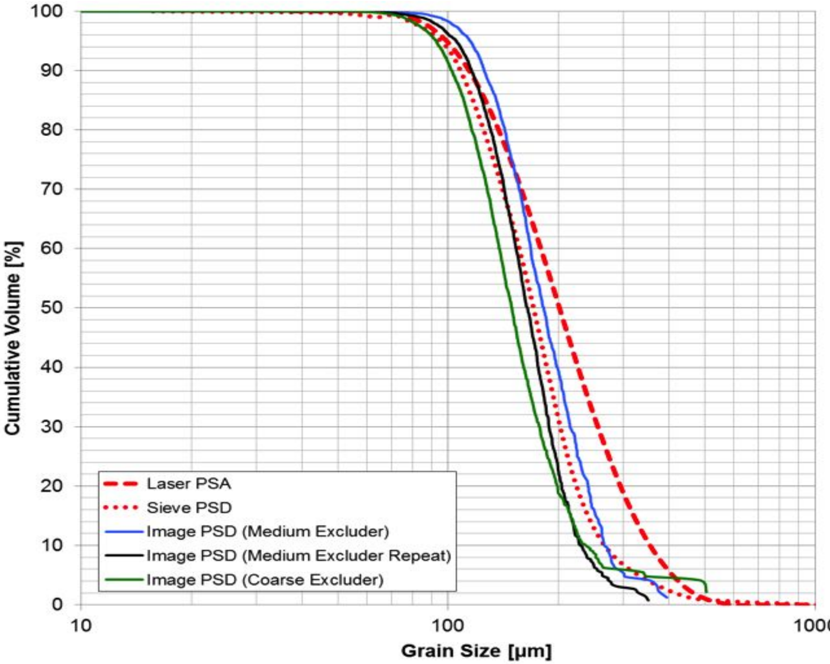
This process along with modelling and analysis should answer the following questions: What size and volume of sand is to be produced ?. Where will it come from (Location and orientation) ?. What are the mechanical limits of the reservoir ? What modes of sand production are expected ?, Can it be transported/separated ?

FORMATION CHARACTERIZATION (Continued)

Grain size distribution and mineral content are measured, at least three(3) different PSDs methods are available, sieving, laser diffraction and optical.



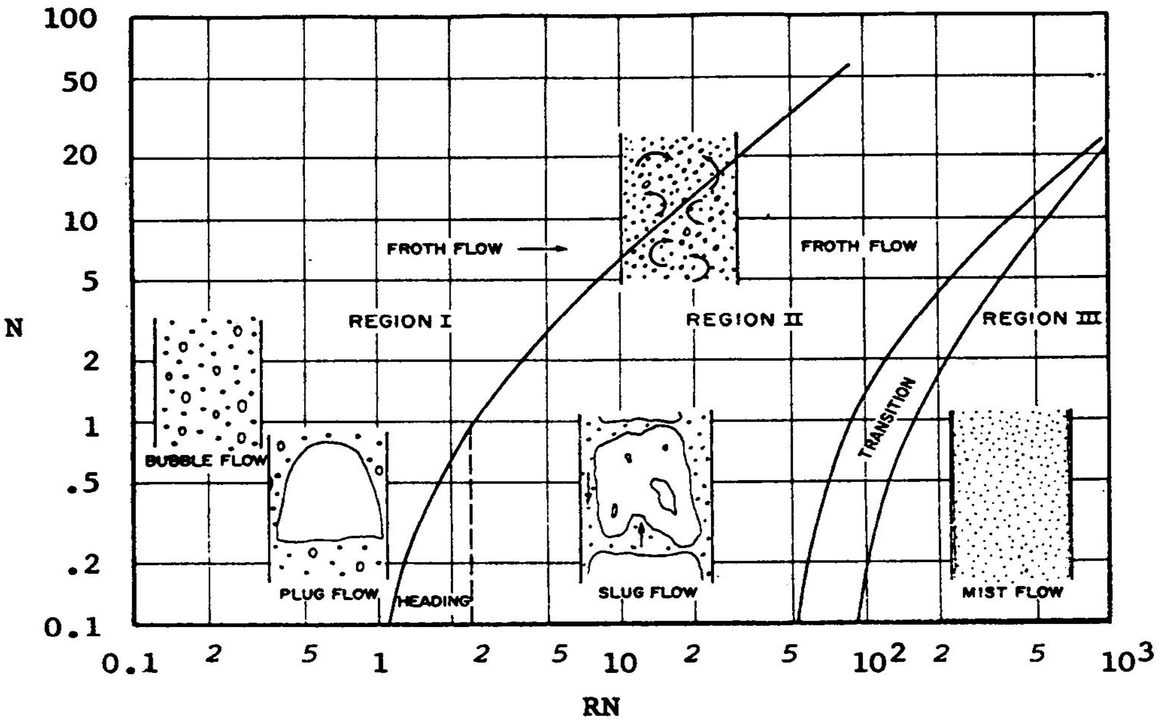
After Bertaux J. 1986



SOLIDS TRANSPORT

Efficient lifting and transport of the produced sand is required in the well and flowlines

- Specific flow rates and flow regimes required for effective transport
- Rheology of the produced fluids plays an important role
- Impact of well configuration on the lifting conditions needs to be determined



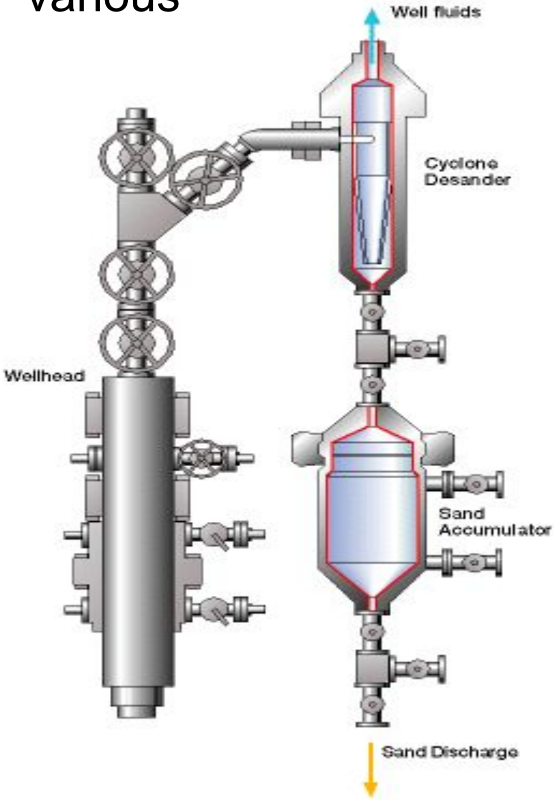
FLUID/SOLIDS SEPARATION

Removal of the solids is carried out at surface using various separation methods such as:

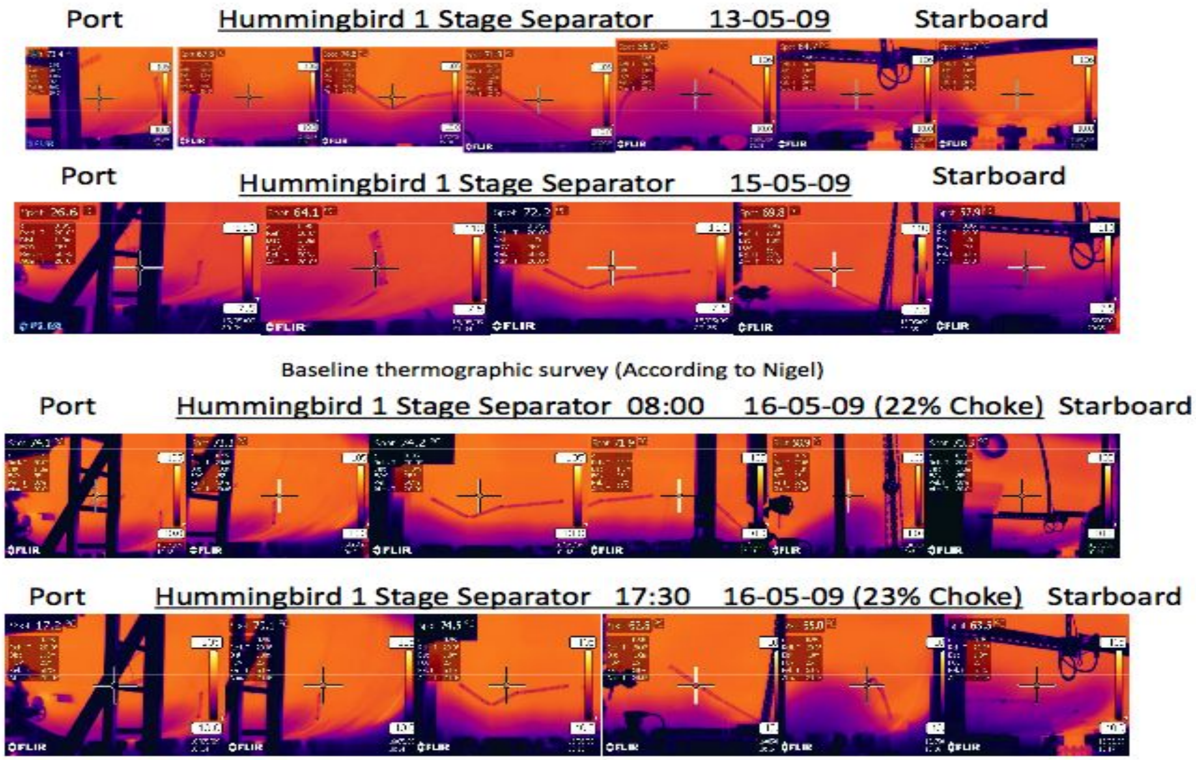
1. Gravity based on conventional production separators
2. Centrifugal forces based which might require special equipment

Solids in the plant and process can impair severely the gathering, separation and storage operations.

- Solid's settlement impacts separation efficiency because the residence time of the fluids in the separator is reduced
- Regular cleaning for the separation increases OPEX



FLUID/SOLIDS SEPARATION (Continued)



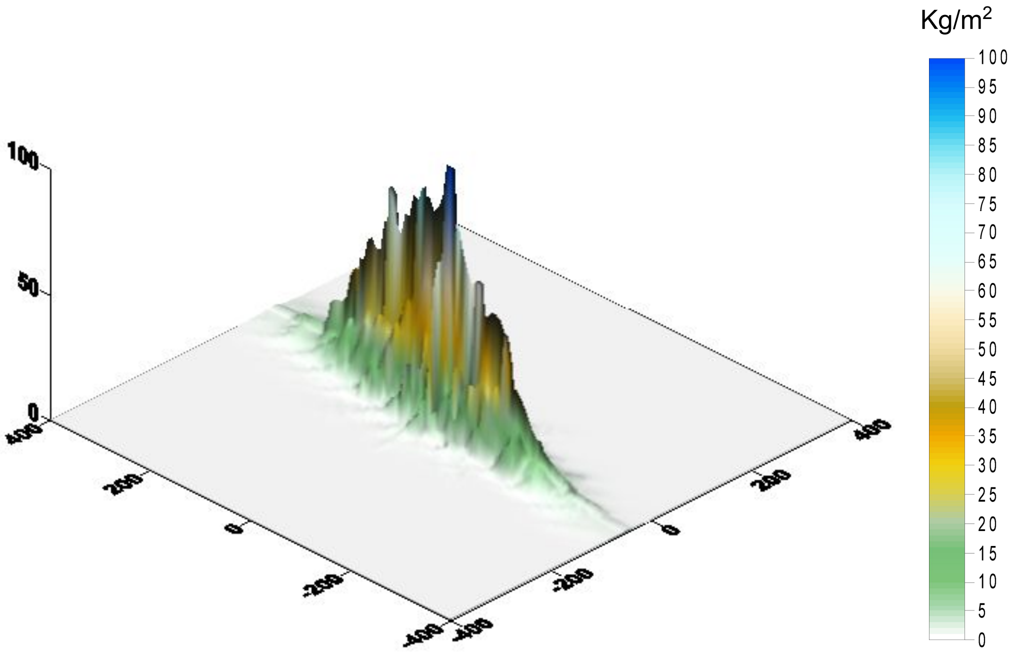
After Tovar J. et al 2010

SAFE DISPOSAL OF THE PRODUCED SAND

Environmental compliance is a major requirements for disposal of the produced sand, various methods are common:

1. Discharge to the sea (Offshore)
2. Skip and ship which involves transportation of the sand to shore
3. Reinjection into geological suitable formations

All methods are heavily regulated and involve complex logistics and increased costs



WHAT A SAND MANAGEMENT PROGRAM MUST DELIVER

Well production/injection under a sand management programs are labour & data/information intensive. In principle a sand management program must safely and successfully deliver the following:

1. A detailed integrated knowledge of the reservoir, well and processes that will lead to a comprehensive reservoir production strategy
2. Estimations of sand volumes, sand and fluid rates to be produced
3. An operating envelop for each of the production and/or injection wells
4. Detailed equipment specifications and procedures for sand producing well designs
5. A data acquisition and information program that will allow management to make the required decisions
6. A fully documented set of procedures for the training of operating personnel
7. A clear and compliant environmental policy and procedures for the management and disposal of the produced sand

MODULE 2 - SUMMARY

The sand management process is a multidisciplinary and complex process requiring a contribution from many disciplines (Technical, operational and managerial).

Management of sand production is an integrated process and requires managers's involvement to deal with the risk and economics imposed by the process

This process is composed of four (4) main steps: a detailed formation characterization, effective transport of the solid's produced, efficient separation and finally safe and environmentally compliant disposal

In addition to typical formation characterization carried out for well design and reservoir development, a rock/soil mechanics element must be added in order to determine the conditions under which sand will be produced.

MODULE 2 – SUMMARY (Continued)

There are various modes under which sand is produced: burst, transient, continuous and catastrophic. A reservoir might start producing sand in any of these modes depending on its intrinsic rock properties and well operating conditions

Transporting produced sand through the completion and surface facilities must comply with the required flow assurance principles to ensure efficient flow of produced fluids and mechanical integrity of the various systems (Valves, restrictions, tubing, tree, chokes..)

Conventional vertical or horizontal separators must be adapted or purpose built to cope with the solids production's requirements. Options to retrofit are also available

Safe environmental compliance during disposal of the produced sand is a key feature of these programs, local/internal regulations must be complied with.

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Module 3

FORMATION CHARACTERIZATION

CONTENT

- *Mineralogy of sandstones*
- *Grain size*
- *Grain shape*
- *Sand quality*

SAND PROPERTIES

Sandstones are arenaceous rocks mainly composed of quartz (up to 95%) but commonly formed by other minerals such as feldspars, carbonates, clays, mica etc. From a sand production perspective the most important properties to be determined are:

- Size
- Detailed mineral composition
- Shape
- "Quality"

MINERAL	QUARTZ	FELDSPARS	MICAS	CLAYS	CARBONATES	SULFATE	OTHER
VARIETY	-	Orthoclase Microcline Albite Plagioclase	Biotite Muscovite Chlorite Glauconite	Kaolinite Illite Smectite Chlorite	Calcite Dolomite Ankerite	Gypsum Anhydrite	Halite Iron Oxides

SAND PROPERTIES (Continued)

There are two (2) main types, mobile and swelling clays

- Mobile clays are : Illite, kaolinite
- Swelling type of clay are : Smectite, Montmorillonite

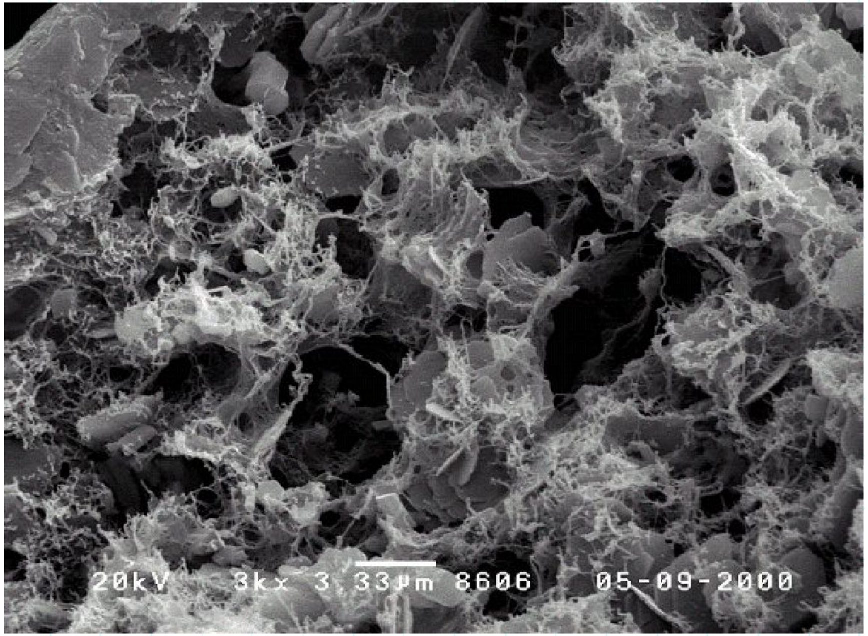
- Both are known to cause severe problems to the wells, equipment and production processes

- Clays tend to have very large surface areas making it ideal plugging material

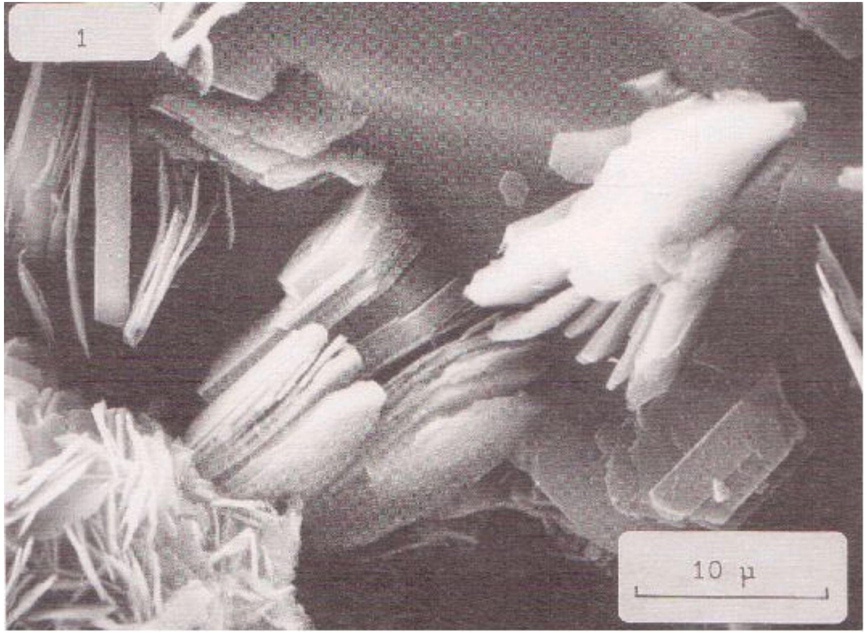
- Pore blocking of the rock matrix or equipment plugging are common in reservoirs/wells with high clay content

SAND PROPERTIES (Continued)

Clays produced along with the production fluids and sand can cause impairment but are not a risk to the mechanical integrity of the wells and surface equipment



Illite clays



After Bertaux J. 1986

Kaolinite clays

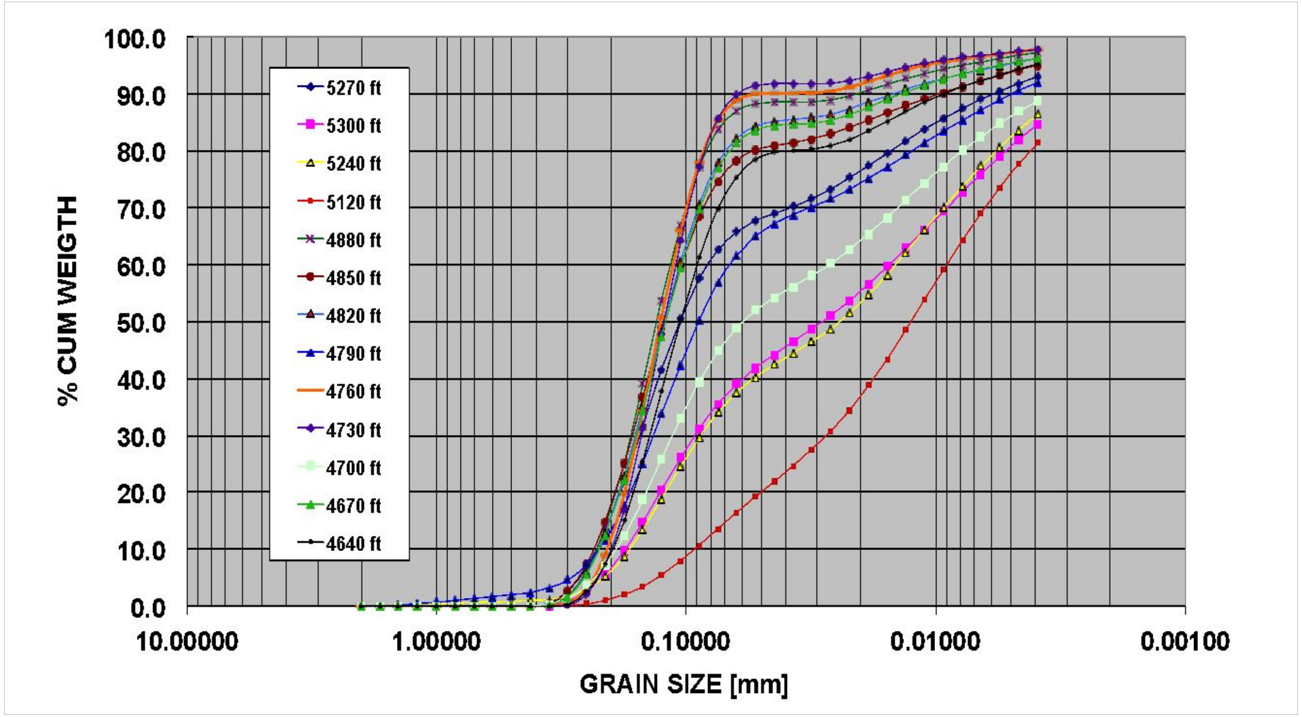
GRAIN SIZE

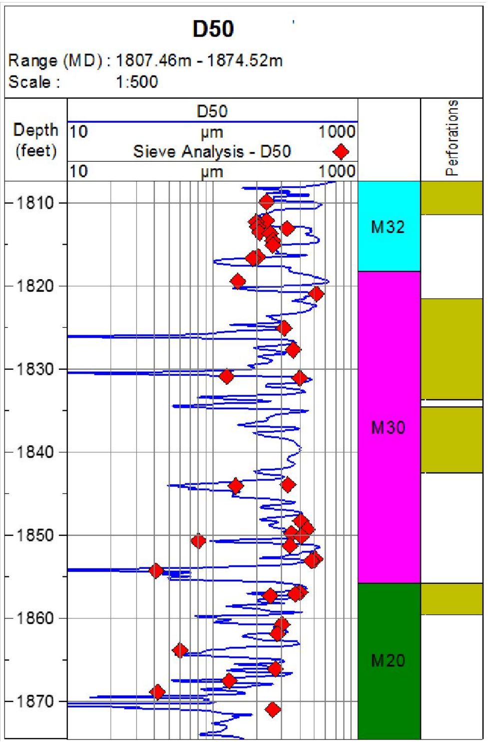
Determination of the variation in grain sizes across the reservoir is critical to the sand management process, size is important because:

- Through the knowledge of grain size, localization of the actual source is possible
- Determination of the erosion potential considers grain size
- Detailed knowledge of the size is required to estimate transport conditions such as flow rate and fluid's rheology for both the wells and the flowlines
- Grain size is the main parameter considered for the selection of sand control methods to be used.
- This information is also required for modelling the various disposal options for a safe and environmental discharge of produced sand

GRAIN SIZE (Continued)

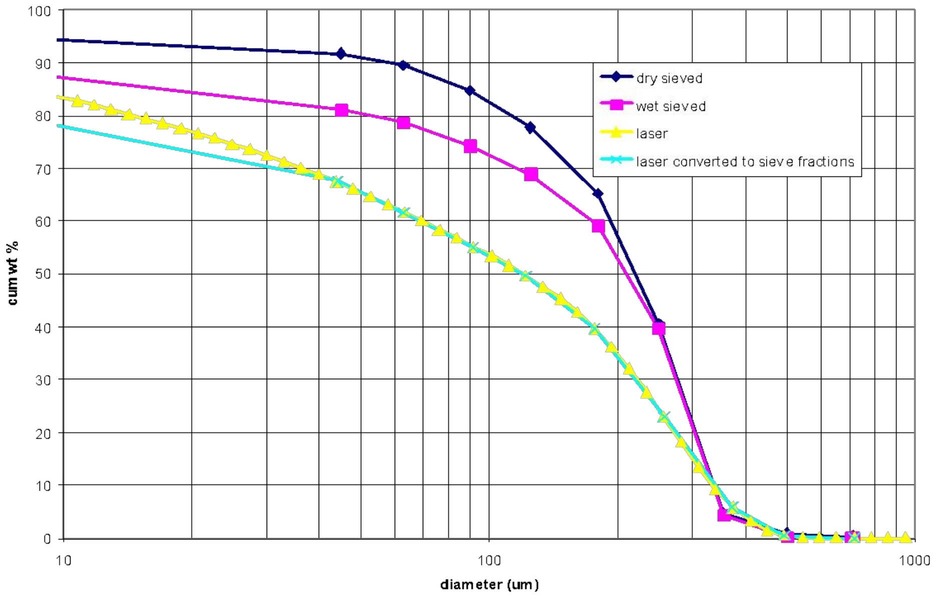
There are two (2) distinctive methodologies for determining grain size: laboratory based (Static) and log-derived (Dynamic) measurements

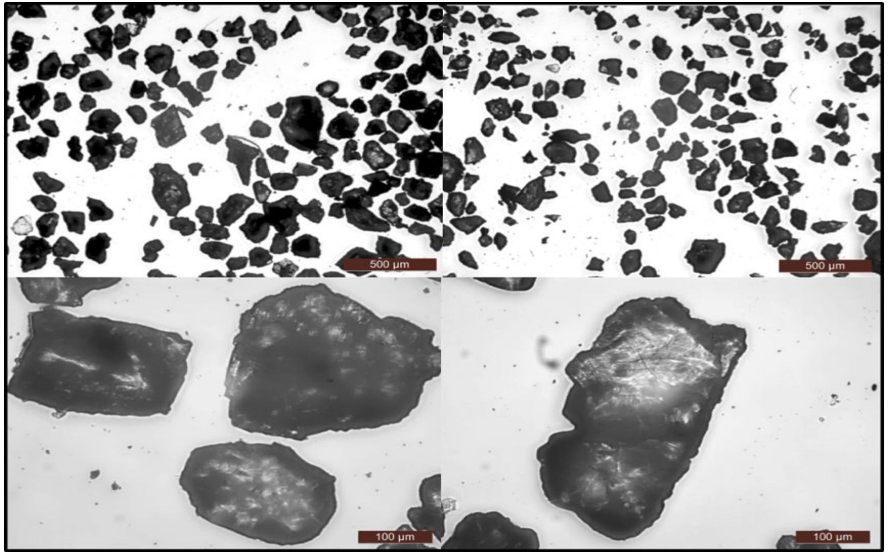




GRAIN SIZE (Continued)

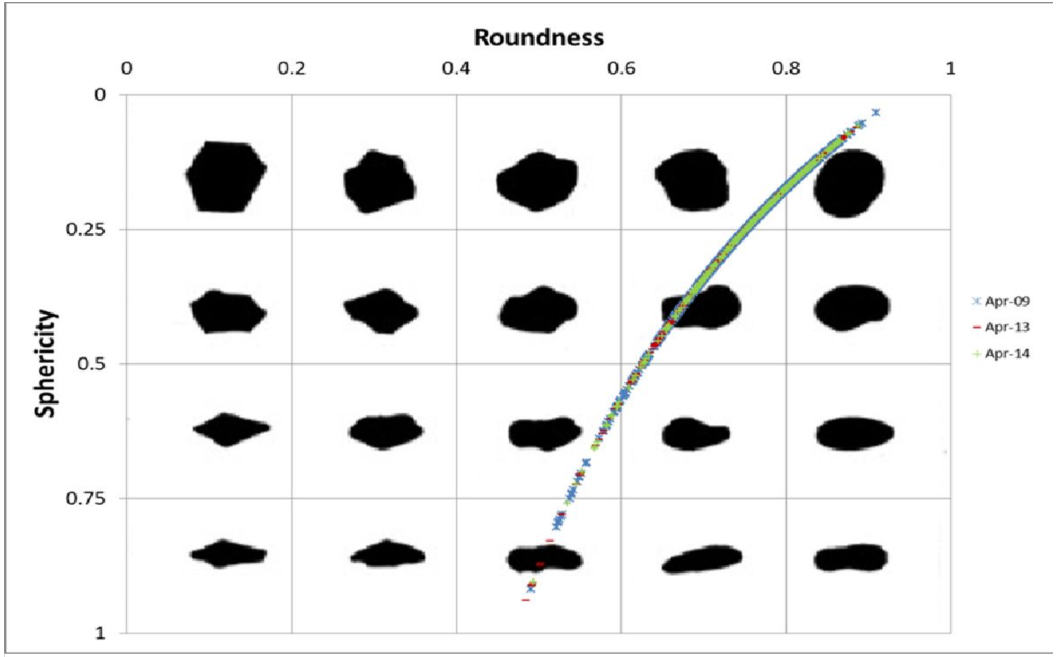
The most common laboratory based (Static) methods include: Sieving, laser diffraction and visual imaging. Results vary between the methods





GRAIN SHAPE

The shape of quartz grains is defined by two (2) parameters: roundness and sphericity

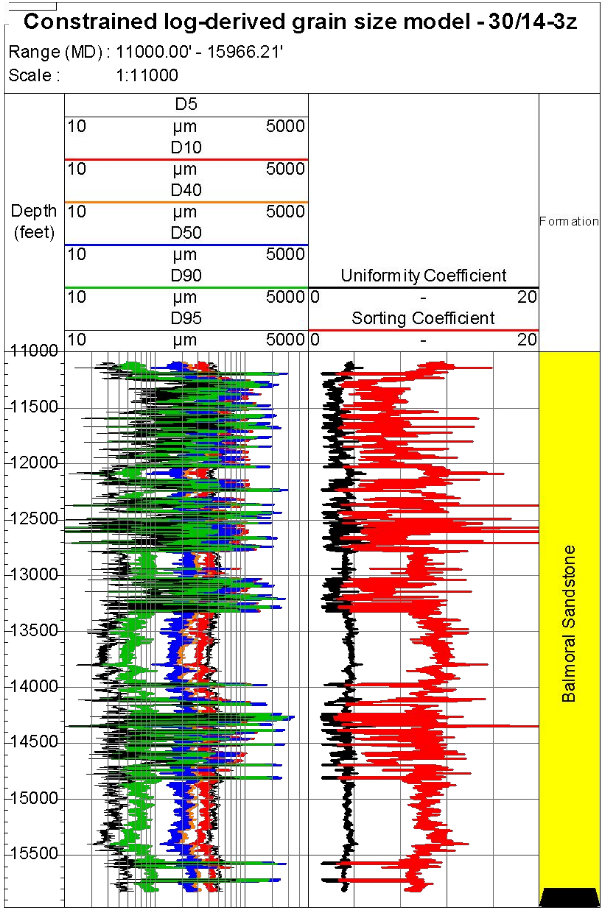


Roundness vs Sphericity plot superposed on modified Krumbein & Sloss chart

SAND QUALITY

Sand quality provides an indication of grain size variation along the reservoir interval. In completion engineering there are three (3) main indicators of sand quality defined as:

Sorting coefficient	D_{40} / D_{90}
Uniformity coefficient	D_{10} / D_{95}
Fines fraction	< 40 microns

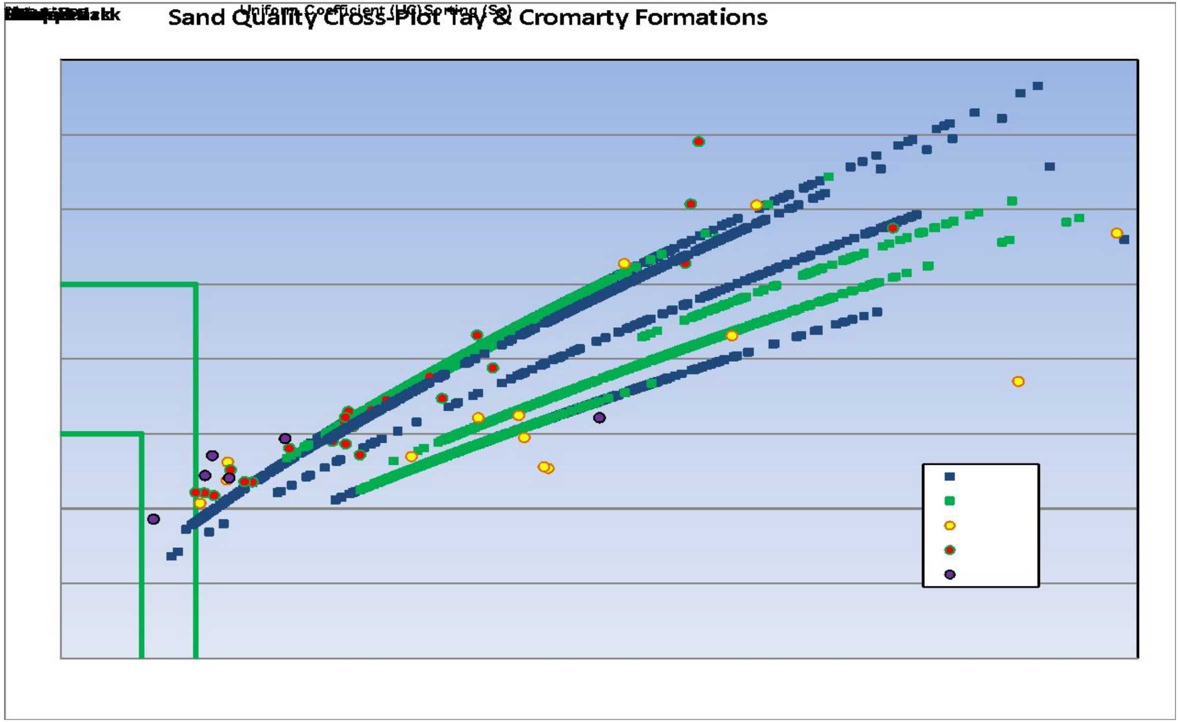


SAND QUALITY (Continued)

Sand quality can be determined for both; static and dynamic grain size measurements.

Continuous (foot-by-foot) sand quality is preferred

It represents the variation in grain size along the whole reservoir interval



MODULE 3 - SUMMARY

Formation characterization allows the determination of the most important parameters required for effective sand management.

Many of these parameters are determined in current well design practices however, its interpretation and application with respect to sand management focus on the mobilisation, transport and separation processes

Sandstones are mostly composed of quartz grains, other minerals are present in the rock matrix such as clays, feldspars and carbonates are commonly found in sandstones

All particles must be mobilised, transported and separated but only quartz presents a risk to the mechanical integrity of the well, plant and flowlines. Minerals such as clays are produced but are not detrimental to the mechanical integrity of the production system

MODULE 3 – SUMMARY (Continued)

Grain size is the most critical parameter required, it can be determined using laboratory based methods (Static) or log-derived methods (Dynamic). Static methods provide discrete values while dynamic methods provide continuous (foot-by-foot) estimations of the variations in grain size

Grain size measurements are required to estimate mobilisation, transport and separation rates, volumes of sand to be produced and modes of failure. grain quality refers to two (2) parameters; roundness and sphericity

From a sand management point of view, sand quality is defined by three (3) parameters; uniformity coefficient, sorting coefficient and fines content

Particles in the rock matrix of sizes lower than 44 microns are considered fines. These type of particles do not compromise the mechanical integrity of the completion.

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Module 4

GRAIN SIZE DETERMINATION EXERCISE

CONTENT

- *Problem to be solved*
- *Graphical description*
- *Data and information*
- *Solution*
- *Interpretation of the results*

PROBLEM TO BE SOLVED

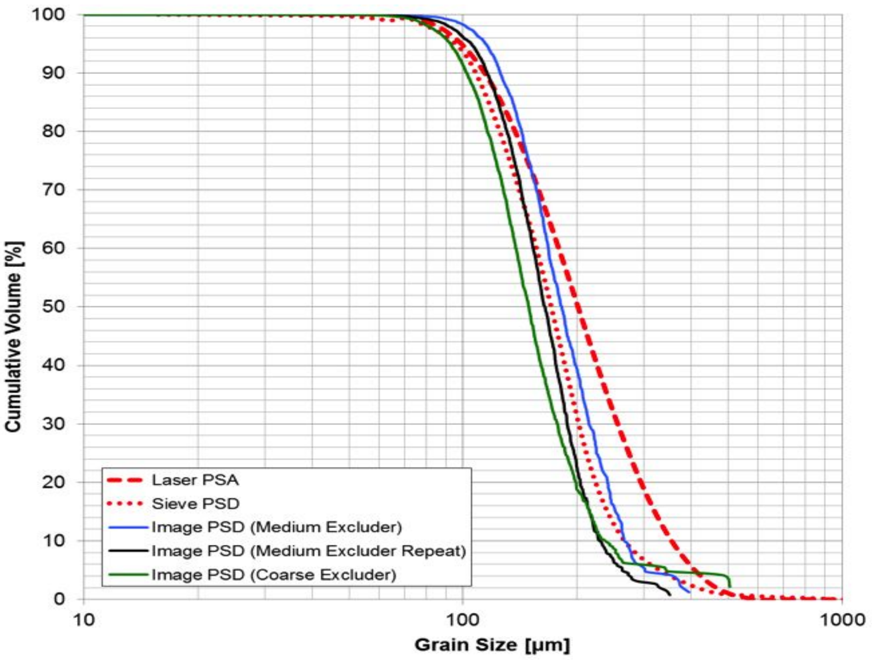
A sand management program is to be implemented due to the failure of a sand control completion in a well. Core samples were taken during drilling and grain size measurements were taken. Your are asked to:

1. Graph the data with the *cumulative* percent of the sample on the Y-axis and grain size in microns on the X-axis (Logarithmic scale)
2. Determine the mean grain size (D_{50}) representing the diameter of the 50% percentile of the sample
3. Determine the fines content (In percent)
4. Determine the quality of the sand sample using the formulas provided

GRAPHICAL DESCRIPTION

There are a number of ways to present the measured data for grain size. You are requested to use a semi-log graph (See sample). Keep in mind the following:

- X-axis is for grain size in microns
- X-axis is in a logarithmic scale
- Cumulative means the addition of each measurement (See table in next page) of the sample
- Y-axis is for the cumulative weight



DATA AND INFORMATION

Sieving was used to take the measurements

- Note that units are in inches and percentage
- Conversion factors from inches to microns are:

1.0 Inch = 25.4 mm
1.0 mm = 1000 microns

US Sieve No	Grain dia. in.		Weight Retained gms	Cumulative Wt %
8	.094		-	
12	.066		-	
16	.047		-	
20	.033		-	
30	.023		-	
40	.017		0	0
50	.012		0.1	0.1
70	.0083		1.9	2.0
100	.0059		1.0	3.0
140	.0041		3.0	6.0
200	.0029		14.0	20.0
270	.0021		50.0	70.0
325	.0017		28.0	98.0
400	.0015		1.0	99.0
PAN (residue)			1.0	100.0
Total			100.00%	100.00%

DATA AND INFORMATION (Continued)

Formulae for determination of sand quality

Sorting coefficient	D_{40} / D_{90}
Uniformity coefficient Uc	D_{10} / D_{95}
Fines fraction	< 40 microns

Guidelines:

- Convert data in the table from inches to microns
- Plot the data in columns 2 and 4
- Quantify the fines fraction in the sample
- Determine the magnitude of the mean grain size D_{50}
- Determine the magnitude of the D_{10} , D_{40} , D_{50} , D_{90} , D_{95}
- Determine sand quality of the sample

SOLUTION

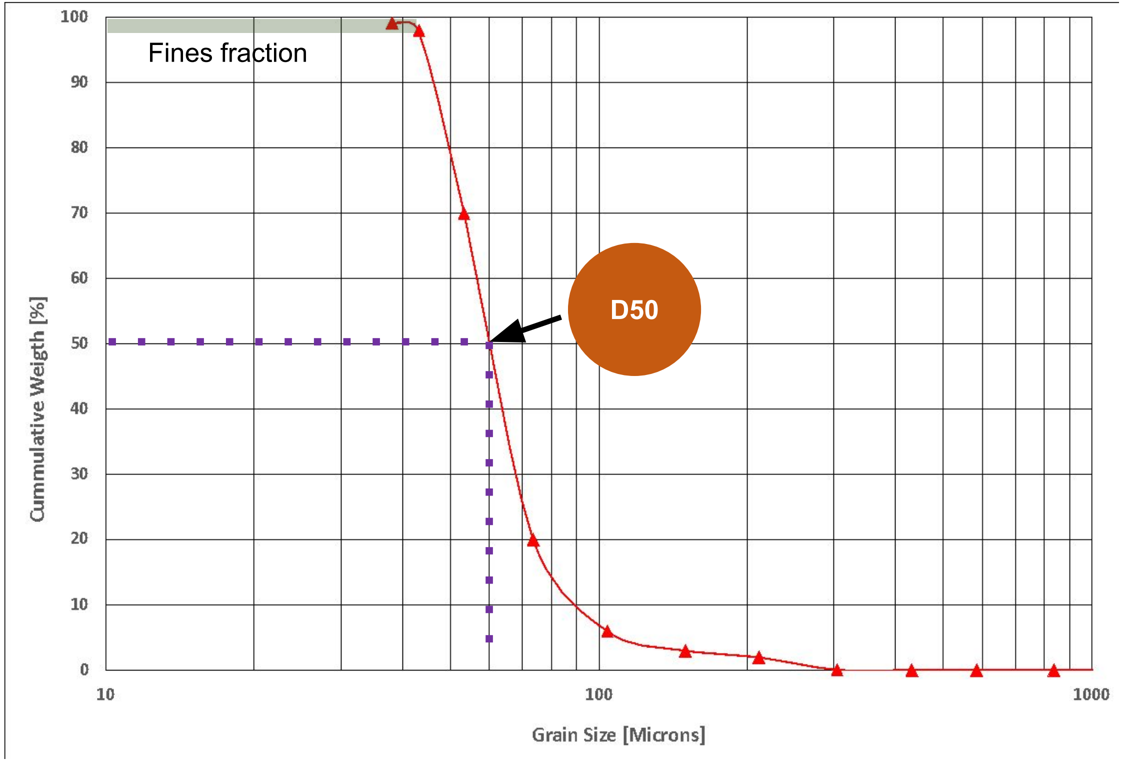
SOLUTION

1. Fines fraction ~ 2%

2. D_{50} ~ 60 microns

3. Sorting = D_{40}/D_{90} ~ 1.44

4. Uc = D_{10}/D_{95} ~ 2.0



INTERPRETATION OF THE RESULTS

The following conclusions can be made from the results in the graph as follows:

- It appears to be a clean sand with a very low fines fraction
- Grain sizes are small probably indicating a well consolidated sand
- Sand quality is good which indicates small variations in grain sizes along the reservoir section. This can also be inferred from the slope of the curve

In sand management terms these conclusions indicate the following:

- Possible burst regime of sand production due to the strength of the rock, this has to be verified with the mechanical tests
- Smaller grains are easier to transport to surface and along the flowlines
- Smaller grains also indicate larger residence times in the separator and possible carry over problems

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Module 5

MECHANICAL CONDITIONS FOR SANDING

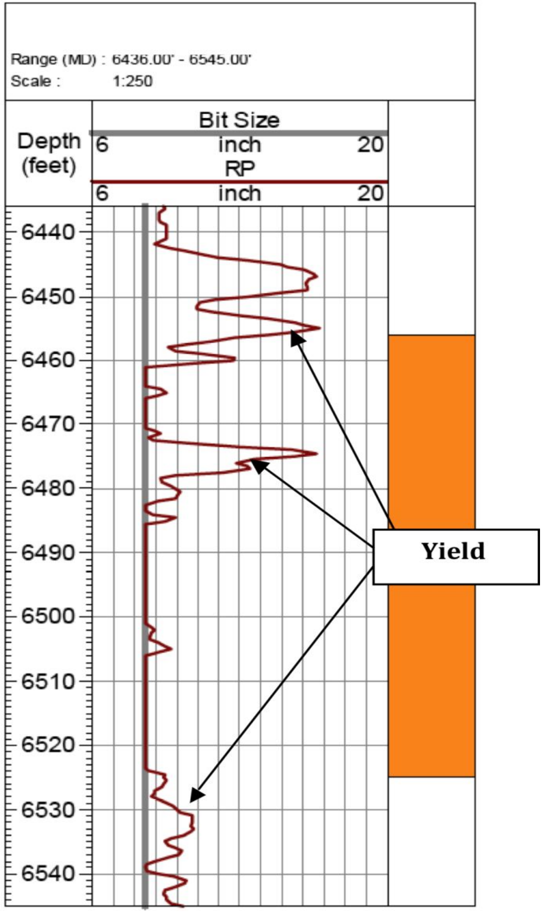
CONTENT

- *Conditions for sanding*
- *In-situ field stresses*
- *Rock deformation and failure*
- *Testing methods*

CONDITIONS FOR SANDING – THE SOURCE

Mechanical failure and mobilisation of the intact rock and granular material are the two (2) main conditions for sanding.

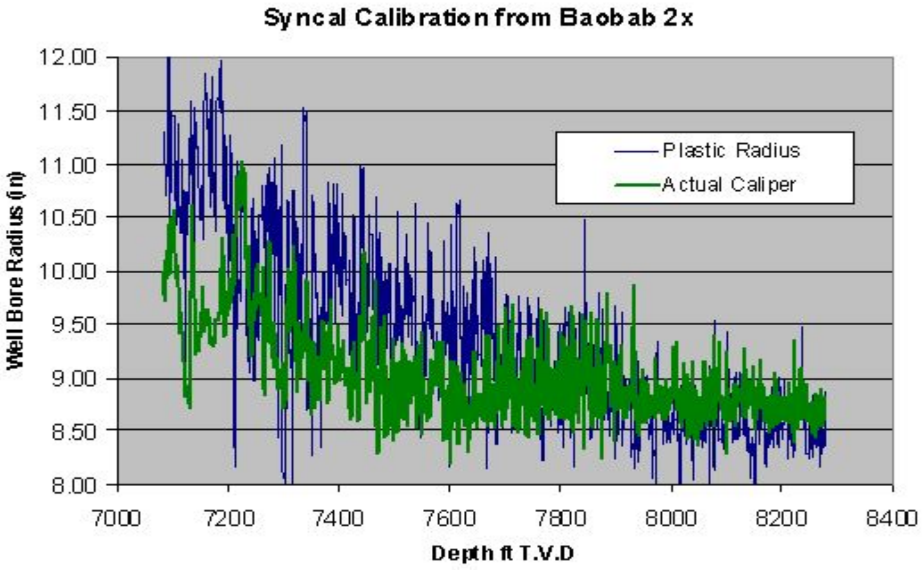
- A source of failed material that can be mobilised must be present for sand production to occur.
- The first failure of intact rock occurs during drilling and completion and is known as the yield zone or radius of plasticity R_p
- R_p is the zone at the near wellbore where such a deformation and eventual failure has occurred



CONDITIONS FOR SANDING – THE SOURCE (Continued)

This zone R_p exists in every well and its radial and axial extension varies depending on the pressure conditions applied during drilling and completion.

- Its mode of failure, location and extension can be determined using deformation principles
- The R_p is a function of the acting stresses, rock mechanical properties
- A good estimation of the location and extension of the R_p can be made using calliper logs
- Rock-fluid interaction can affect the extension of the R_p

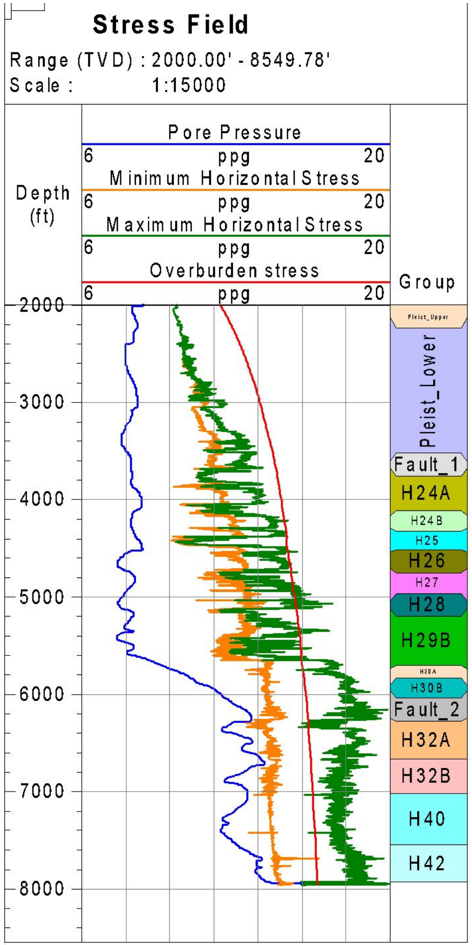


IN-SITU FIELD STRESSES - LOADS

The in-situ field stresses are the loading being applied to the reservoir rock, it varies with pore pressure depletion and the tectonics acting in the area. There are three (3) main principal stresses

- Overburden ($\boldsymbol{\sigma}_v$) – It represents the weight of the sediment deposited above the reservoir
- Maximum horizontal stress ($\boldsymbol{\sigma}_H$) – It represents the larger stress acting on the horizontal plane
- Minimum horizontal stress ($\boldsymbol{\sigma}_h$) – It represents the lower stress acting on the horizontal plane

$\boldsymbol{\sigma}_H$ and $\boldsymbol{\sigma}_h$ depend on the tectonics acting in the area

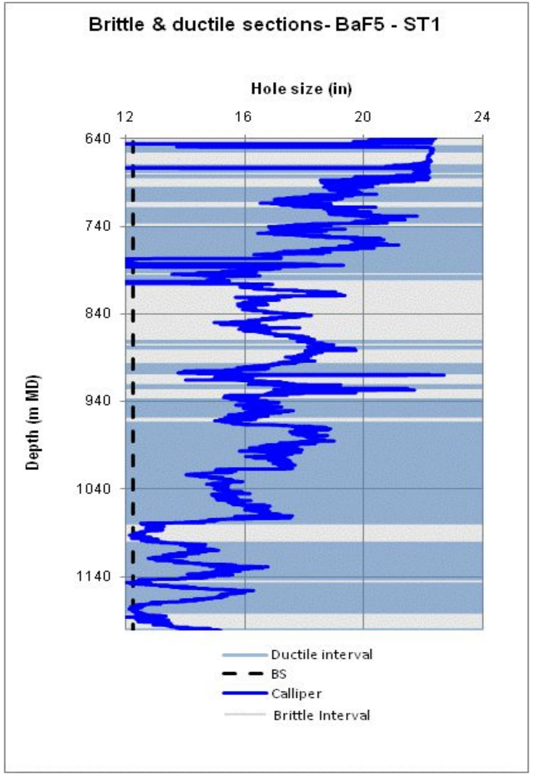


ROCK DEFORMATION AND FAILURE

Rock and soil deformation takes place in two (2) modes : Brittle and ductile

- **Brittle** is the sudden drop in strength as a result of failure, it tends to occur in intermediate and high strength rocks

- **Ductile** is a process in which the rock ”absorbs” a lot of the energy and deforms before failing. It tends to occur in weak, highly porous rocks or rocks with high clay content



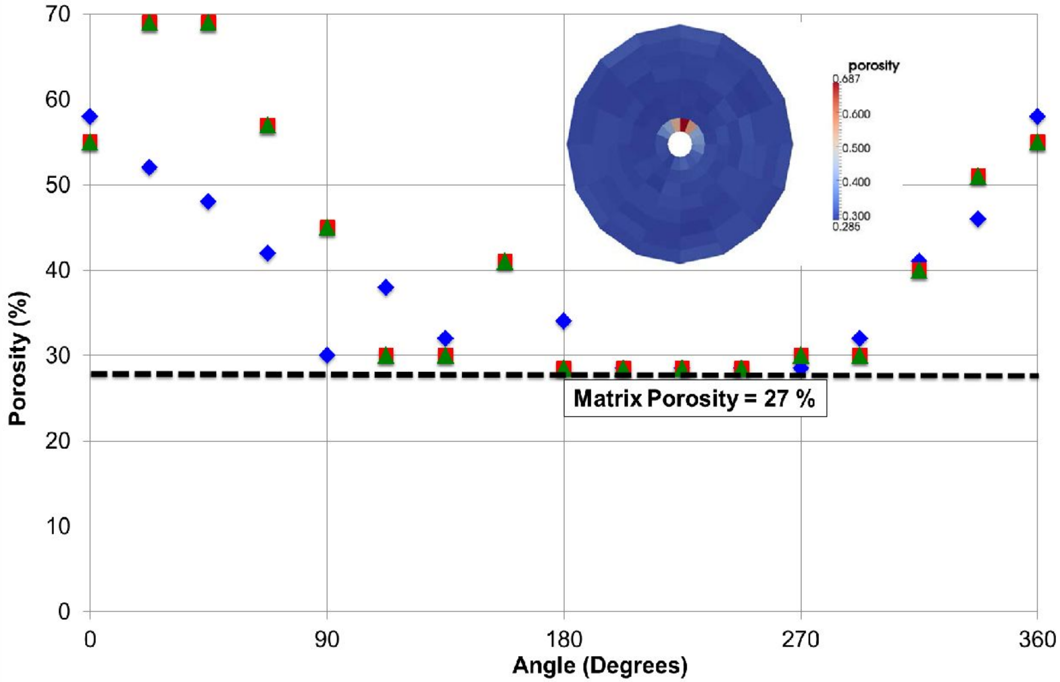
The end of the deformation process means that intact rock under load is broken and passes to a granular condition

Mobilisation of the granular material is required for sand to be produced

ROCK DEFORMATION AND FAILURE (Continued)

DEM simulations illustrate what happens during the transition from intact rock to granular material

- Breaking of the matrix's framework starts to occur due to high loading (drawdown)
- The rock becomes dilatant and its petrophysical properties start to change
- The porosity increases as a result of the granular material being mobilised
- Mobilisation is a localized and oriented phenomena



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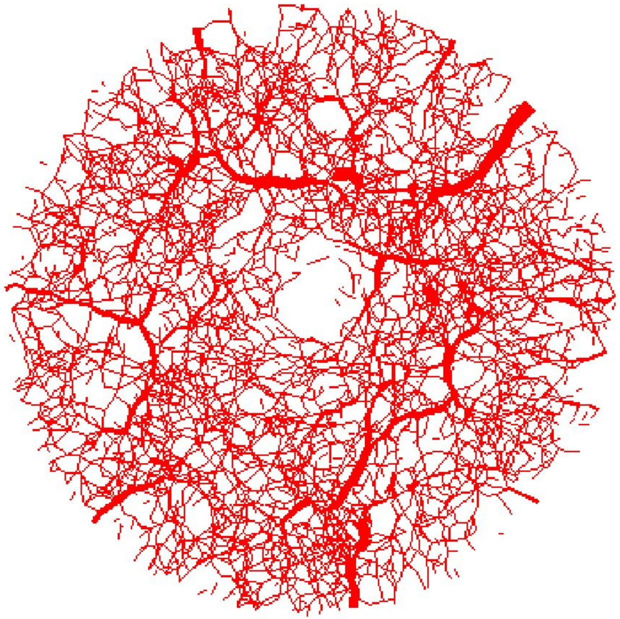
ROCK DEFORMATION AND FAILURE (Continued)

Deformation and failure of granular material are caused by different mechanisms than those on intact rock

Open hole and cased/perforated wellbores are exposed to cyclic loading (Drawdown) as a result of well operations

Granular material is “held” together by two (2) grain contact sub-networks, the strong and the weak sub-network

- Strong sub-network holds the loads
- Weak sub-network act as a load dissipation mechanism



Courtesy of IESL

MECHANICAL TESTING METHODS

Formation characterisation relays on measurements carried out on samples and under conditions that attempt to simulate reservoir conditions. All these are considered static tests (Laboratory test), mechanical testing of samples is critical for sand management.

- Test such as EDAX/SEM, PSDs are typical for characterising grain size, mineral content and quality of the reservoir rock
- Mechanical testing is carried out to determine both strength and deformation parameters that are used as input parameters for sand production prediction
- Field tests are also carried out in many cases as the means to validate some of the simulations carried out using laboratory results.
- Step-rate tests, FITs and LOT/XLOT tests are some of the most common test carried out during drilling and completion operations

MECHANICAL TESTING METHODS (Continued)

Mechanical testing relays on measurements carried out on samples sometimes extracted from cores

There are four (4) main types of formation sampling, these are:

- Full size and Sidewall coring obtained during the reservoir evaluation process
- Bailing (During well intervention or workovers)
- Surface sampling (Separator or flowline)

TESTING METHODS (Continued)

Rock mechanical tests are required to be used for the prediction of sand production, typical types of tests include:

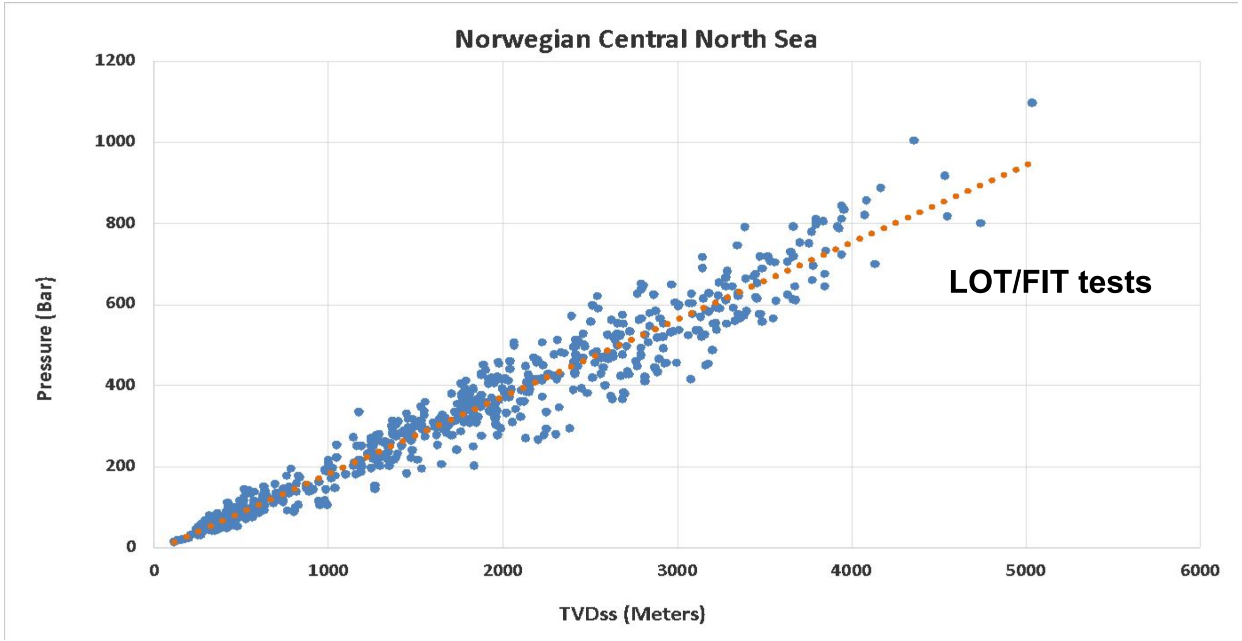
- Unconfined compressive strength UCS
- Thick-walled cylinder test or TWC
- Tri-axial stress tests

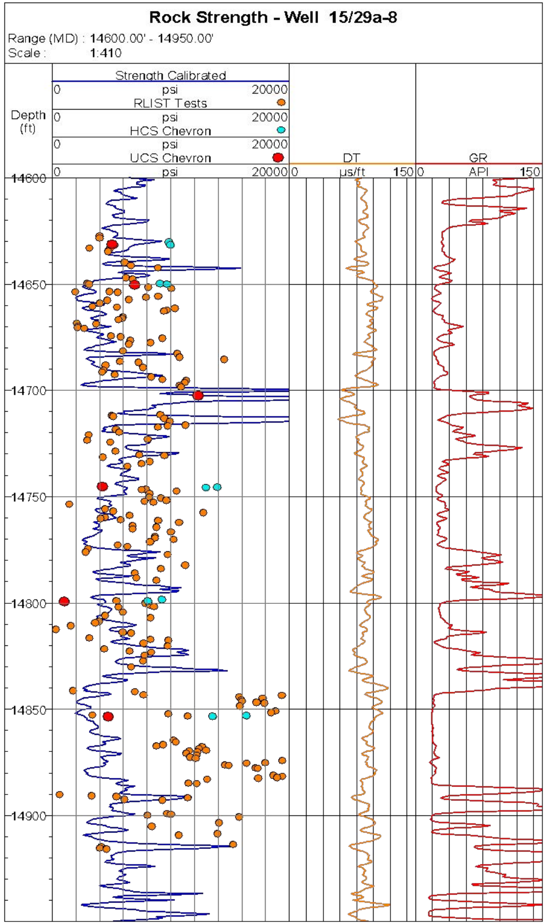
Different methods can be utilised and depend on the service provider

Most tests involve stress and strain measurements to determine parameters such as Poisson’s ratio, Young modulus, Biot constant and strength

MECHANICAL TESTING METHODS (Continued)

Results of the static tests and log-derived computations are then integrated and calibrated





After www.strata-mecanica.co

MODULE 5 - SUMMARY

The mechanical conditions that will result in sand production must be determined for any sand management program. These conditions require determination of the rock mechanical properties and the in-situ stress conditions.

In terms of rock properties, strength and deformation are critical and specific to the various computational models that will predict the likelihood of sand production

Two (2) separate routes are commonly used to quantify these properties; laboratory based tests and log-derived properties

Typical laboratory tests include UCS, TWC and tri-axial test and these will allow properties such as strength, Poisson’s ratio, Young modulus, Biot constant to be determined

MODULE 5 – SUMMARY (Continued)

Laboratory test results are carried out under simulated reservoir and well conditions however, the sampling and testing process introduce uncertainties that requires calibration of the results

Log-derived properties (Dynamic) properties are generated based on physical laws and measurements, their main advantage is that they are taken on a continuous basis (i.e. foot-by-foot).

Calibration is required for both the laboratory testing and the computations to be able to be used during the sand management program.

Calibration of stresses can be carried using drilling (LOT/FITs) tests, coring and well testing.

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Module 6

SAND PRODUCTION PREDICTION

CONTENT

- *Brief history*
- *Prediction methods*
- *Impact of pore pressure depletion*

BRIEF HISTORY

Prediction of sand influx in oil and gas wells is a relative new discipline, empirical methods were the first to be used based on field observations and measurements

- Engineering approaches commenced in the 70s starting with the combined modulus of elasticity (Stein & Hilchie) which related a number of rock properties and log measurements (Density & Sonic).
- Schlumberger introduced the first commercial service based on log-derived measurements, MechPRO™* (1974) and it was the first software to predict sand production based on density and sonic log measurements
- Now days there are many different algorithms developed to predict sanding. Most are based on the prediction of the first condition for sanding; *Intact rock failure*

* Trademark of Schlumberger

PREDICTIVE METHODS

There are two (2) distinctive methodologies used for the prediction of sand production: the first one is operationally based. The second is based on engineering methods that can simulate the loading and mechanical properties around an open hole or perforated tunnel.

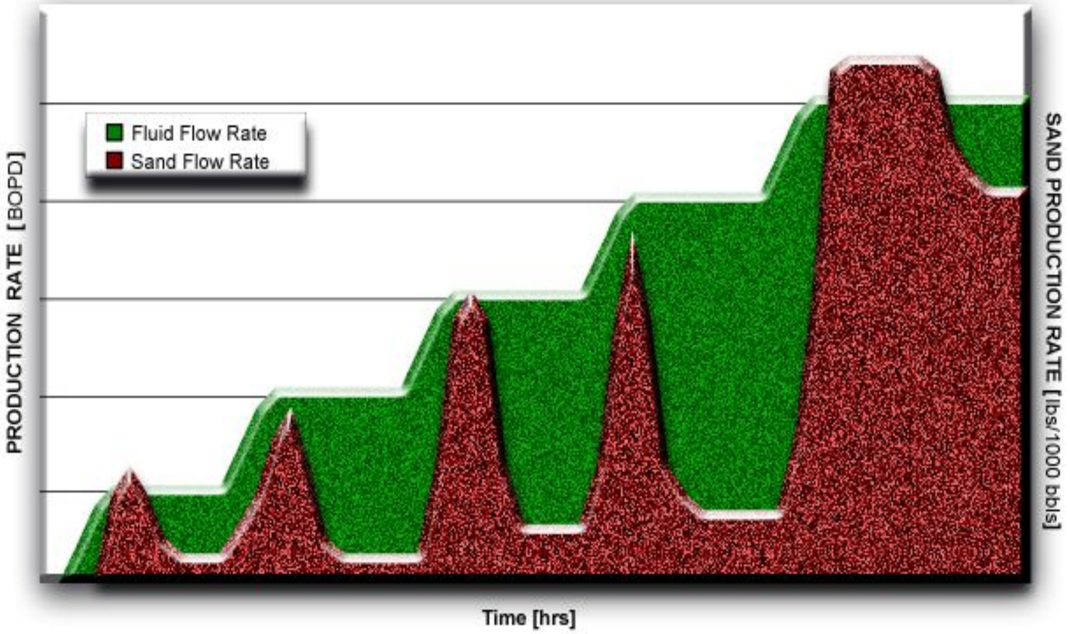
Failure of the rock is then predicted using rock and soil mechanics principles

- ***Operationally*** based methods include the step-rate flow tests SRFT, core testing and sampling. One of the main advantages of the SRFT is that exposes the reservoir to actual production conditions
- ***Engineering*** based methods relay on simulating/validating the loading, deformation and failure of the rock under expected conditions. Simulations take into account depletion, near wellbore damage and rock deformation

PREDICTIVE METHODS (Continued)

Operational type of methods such as the SRFT can be used, in many cases carried out during well test operations. Its aim and sequence is as follows:

- Aims to produce the well at a rate at which sanding can be induced
- Well is produced through a various flow rates and pressures until each is stabilised
- Sand production is measured (if any) at each rate

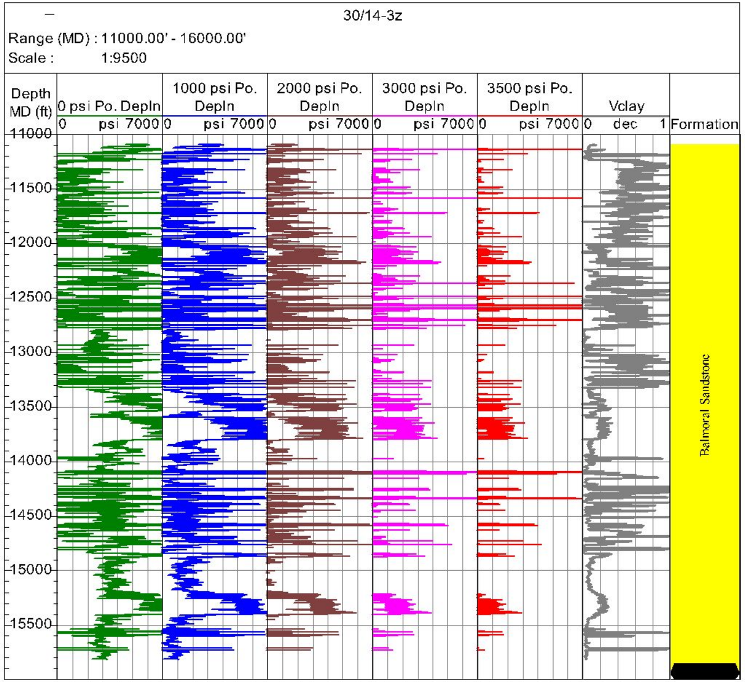


A sand free and maximum sand production rate can be established from the SRFT

PREDICTIVE METHODS (Continued)

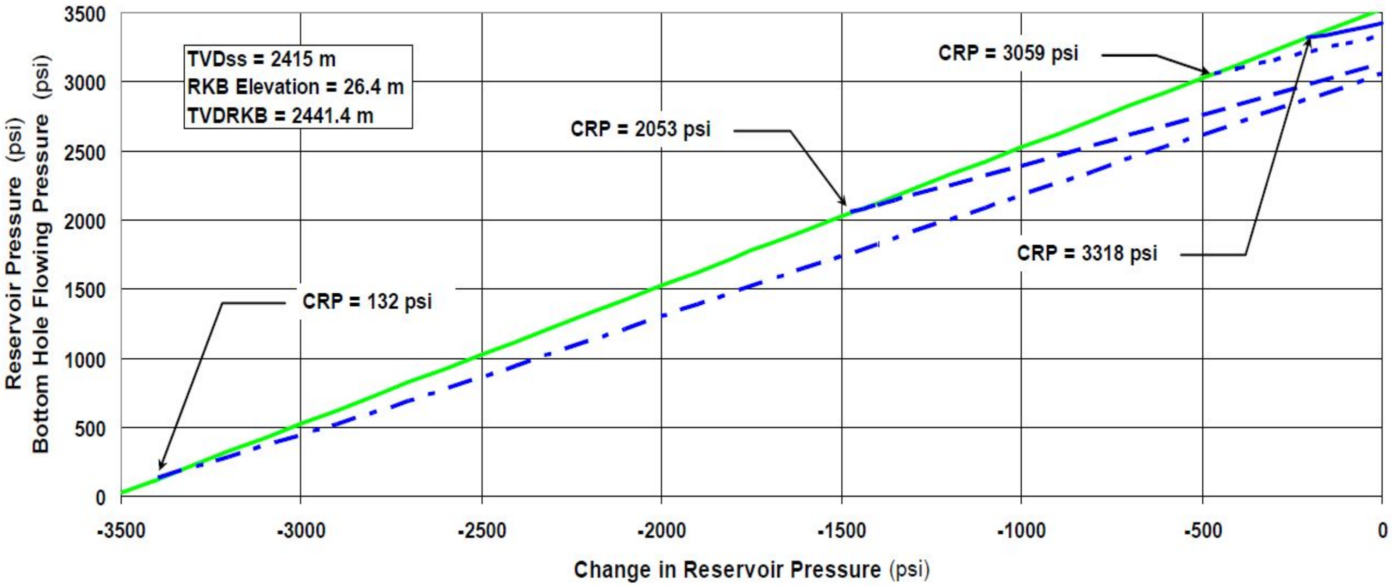
The engineering type of methods are based on the physics of rock/soil mechanics. The prediction in this case refers to under what loading (Pressure conditions) will the rock fail and sand might start to be mobilised.

- The results of the methods is represented by the critical drawdown pressure CDP
- The CDP is the mechanical limit of the rock and a reference for the production drawdown
- Exceeding the CDP during production is not necessary an indication of immediate sanding, mobilisation of the failed material still has to occur



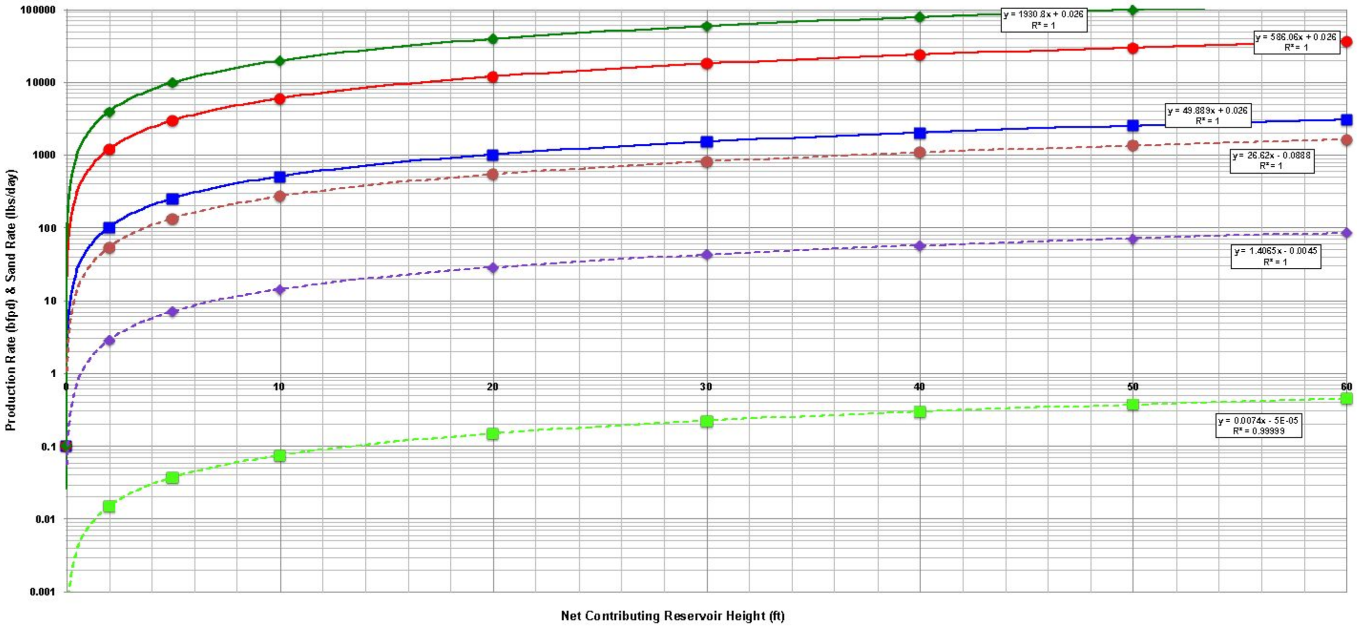
PREDICTIVE METHODS (Continued)

Presentation of the results will depend on whether the CDP is calculated for a discrete data set (See figure below) or for a continuous (foot-by-foot) log-derived data set (On the previous slide)



PREDICTIVE METHODS (Continued)

The CDP complies with the first condition for sanding however, mobilisation also must take place for sand production to occur. A number of empirical and computational models have been developed to predict grain mobilisation and sand production rate



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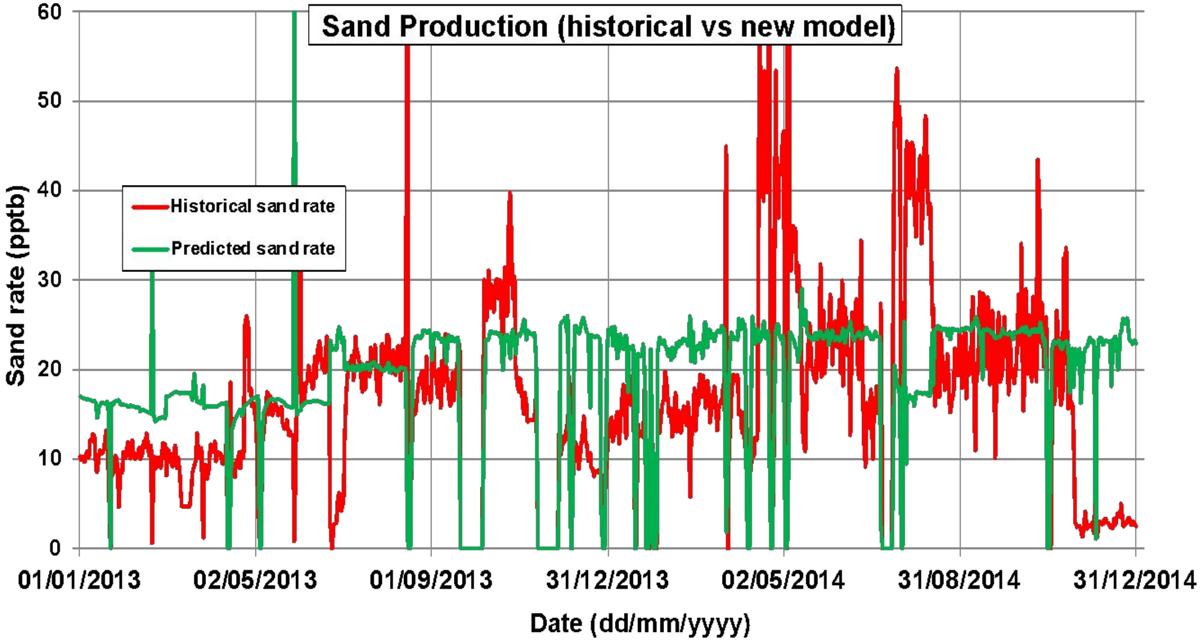
PREDICTIVE METHODS (Continued)

Engineering modelling results for sand production require verification therefore, these results must be compared and adjusted with actual measurements in order to have a representative model that can be use for sand management purposes



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PREDICTIVE METHODS (Continued)

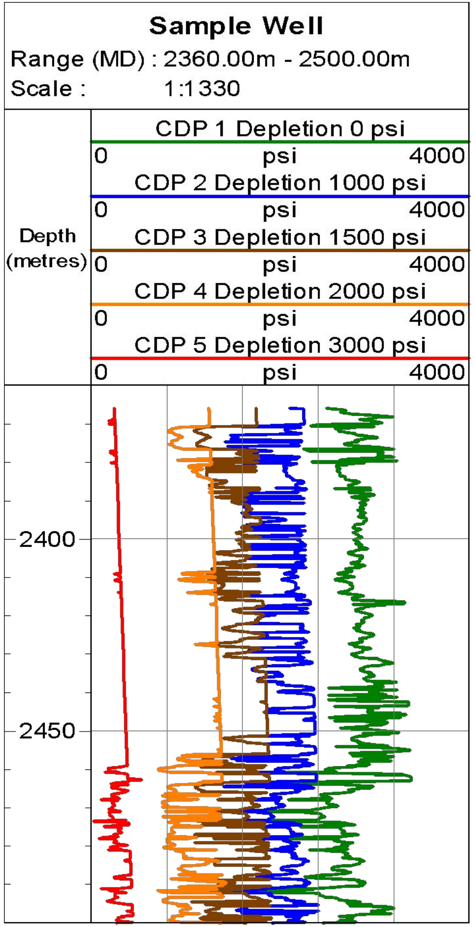
Regardless of the type of modelling carried out to predict the onset of sanding, the results must contribute to:

- Estimate the actual maximum production rates either sand free rate or with sand production
- These results also facilitate the estimation of the volumes of sand to be produced
- Additionally, from these simulations the source (Depth) and orientation from where the sand will come from can be identified
- Mobilisation continues to be difficult to estimate therefore, predictions of sand rate need to be calibrated.
- Current engineering modelling can be as complex as required, computational tools such as DEM can contribute significantly to the understanding of the physics of mobilisation of granular material.

IMPACT OF PORE PRESSURE DEPLETIOIN

The loading applied to the wellbore that results in sanding is composed of the existing in-situ stresses and drawdown. In the long term these loads are increased due to the loss of pore pressure because:

- Loss of pore pressure increases the intergranular forces within the framework and gets closer to failure
- As a result, the CDP decreases as depletion increases
- Such a decrease in the CDP forces the drawdown pressure and production rates to be lowered in order to manage the production of sand
- The impact of depletion reduce reserves recovery, well rates and affects field life and project’s economics



MODULE 6 - SUMMARY

Sand production prediction is a relative new discipline, early empirical efforts started in the 70s with the combined modulus of elasticity and MechPRO™*.

- Currently two (2) methodologies are used for the prediction of sand production: an operational based on field operations and engineering methods based on rock/soil mechanics principles.

- Operational methods include the step-rate flow test SRFT in which a well is placed in production and the flow rate is increased in steps up to when sand production is induced

- The importance of the SRFT is that it exposes the wellbore to actual production conditions and up to the point where rock failure and sand mobilisation occurs

* Trademark of Schlumberger

MODULE 6 – SUMMARY (Continued)

Engineering methods for the prediction of sand production relay on rock/soil mechanics principles that allow determination of the loading and mechanical properties of the rock at the near wellbore.

- This method determines the mechanical limit of the formation also known as critical drawdown pressure CDP, at which point failure of the intact rock will occur. This is the first condition for sanding.
- There are many models based on an engineering approach to predict sanding
- Mobilisation of the failed material is a very different matter and it is quite difficult to simulate, progress still to be made in this area.
- The impact of depletion reduces the magnitude of the CDP leading to a decrease in flow rate and increase in rock failure

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Module 7

SAND CONTROL METHODS

CONTENT

- *Reservoirs with sanding problems*
- *Sand control methods*
- *The economics of sand control*

RESERVOIRS WITH SANDING PROBLEMS

Oil and gas reservoirs producing from sandstones will at some time in the field life produce sand. A number of conditions can cause these reservoirs to produce sand, the main ones are:

1. Reservoir is composed of weak or unconsolidated rocks leading to sand production from the early stages
2. Highly depleted reservoirs will tend to produce sand towards the late stages of field life
3. High near wellbore damage that will impose excessive drawdown pressures

Rock failure and mobilisation are required for sand to be produced, in oil bearing reservoirs the stresses generated by flow(Viscosity) induce mobilisation. In gas bearing reservoirs velocity plays the major role in mobilisation.

RESERVOIR WITH SANDING PROBLEMS (Continued)

There are two (2) basic options to deal with the issue of sand production:

1. *Active sand control* installed at the reservoir interval, 90% of the times this is the preferred solution as it ***"resolves"*** the problem at the source. Active sand control does indeed resolves the problem but it introduces other important issues such as production impairment
2. *Passive sand control* or sand management in which the sand is transported to surface to be separated/disposed. This option introduces higher risks but if properly designed and managed will result in higher productivity wells and reserves recovery

Each of these basic options include a number of different methods suitable for many of the conditions found in these type of reservoirs.

SAND CONTROL METHODS

Active and passive sand control methods and technologies vary significantly, there are over 12 different methods used in the industry such as

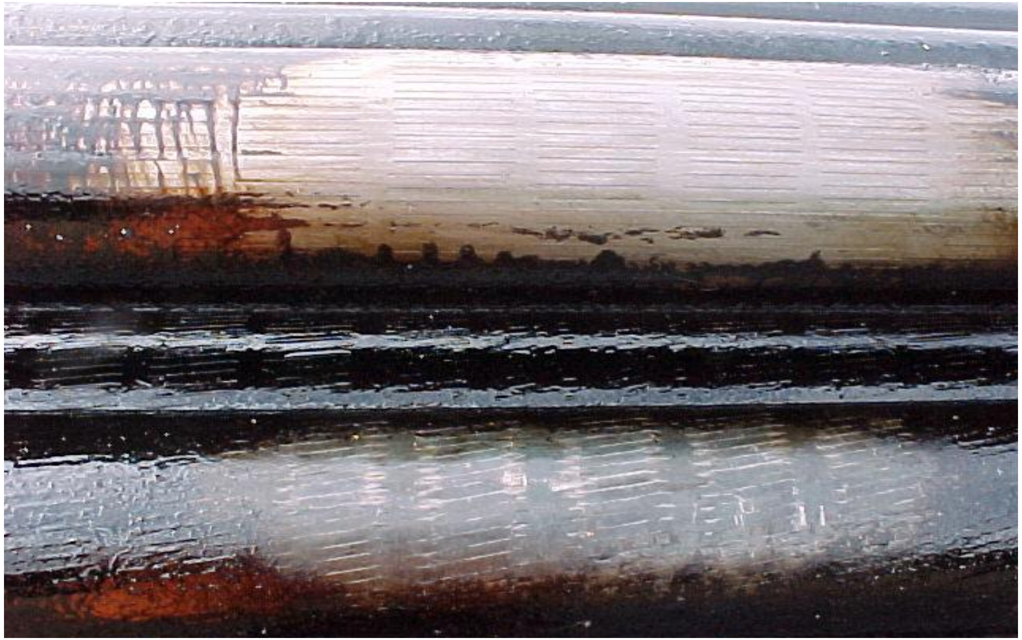
- Slotted liners
- Sand screens (4 types)
- Gravel packs (2 types)
- Sand consolidation
- Frack & Pack
- Swelling filters
- Oriented and selective perforating
- Sand management

COMPLETION OPTION	LIMITATIONS
Sand Management	• Requires high quality reservoir data • Strict monitoring of well & field performance • Facilities and surface equipment
Selective & Orientated perforation	• Requires good quality reservoir data • Difficult to implement in the field, due to depth and orientation problems.
Slotted liner & Screens	• Mechanical damage • Plugging and erosion • No flow conformance control
Gravel pack (Internal & External)	• PI reduction • Expensive • Operationally difficult, limited length in horizontal wells • Under-reaming might be required (EGP)
Hydraulic fracturing & Frac pack	• Impaired productivity of the propped fracture • Vertical containment of the fracture • Expensive • Operational risk • Proppant flow back
Expandable Screen Technology	• Reservoir compactation • Severe hole stability problems • Expensive

SAND CONTROL METHODS – Slotted liners

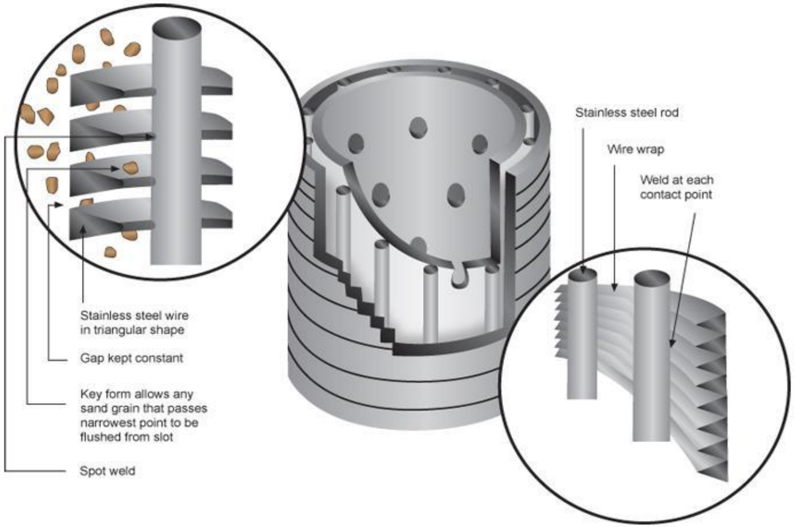
Slotted liners are an active sand control method, it is composed of:

- Base pipe and filter media
- Slots are the sand retention mechanism
- These slots are cut along the axis of the base pipe
- Utilised in reservoirs with very homogeneous sands
- Flow area does not exceeds 6%
- Mechanically very weak



SAND CONTROL METHODS - Screens

There are at least four (4) main types of sand screens:



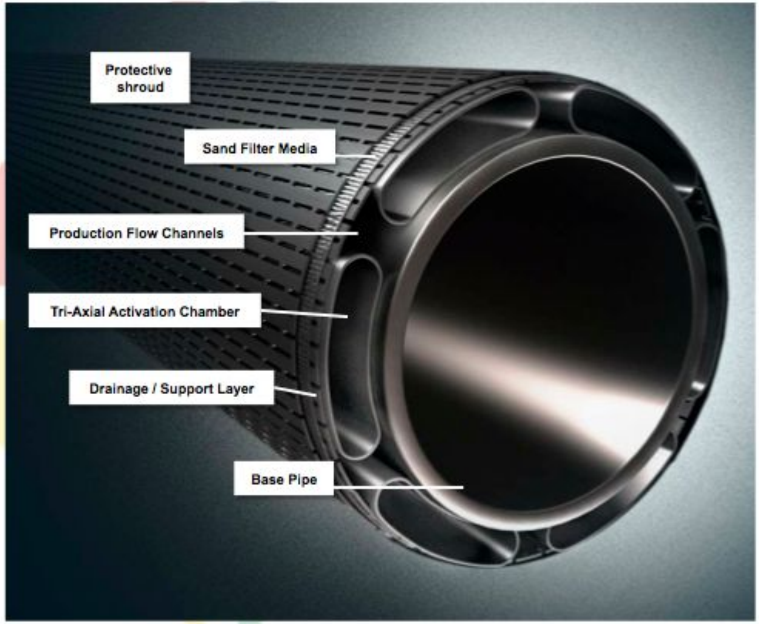
Wire-wrapped screens

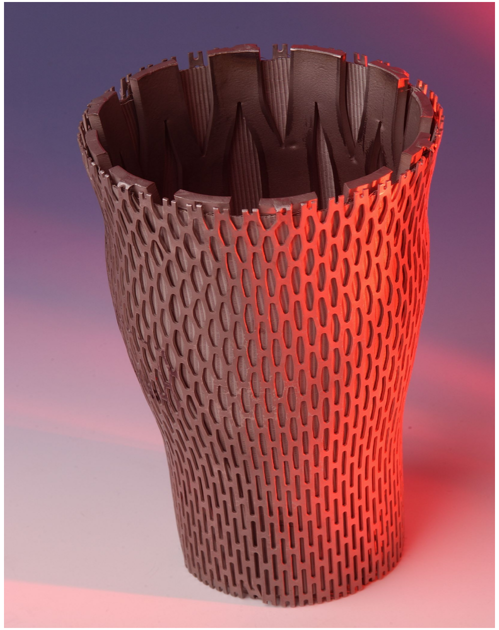
Pre-packed screens

Premium screens

SAND CONTROL METHODS – Screens (Continued)

Expandable type of screens are relative new technology, it involves the expansion of one or various of its components until it reaches the wellbore wall.

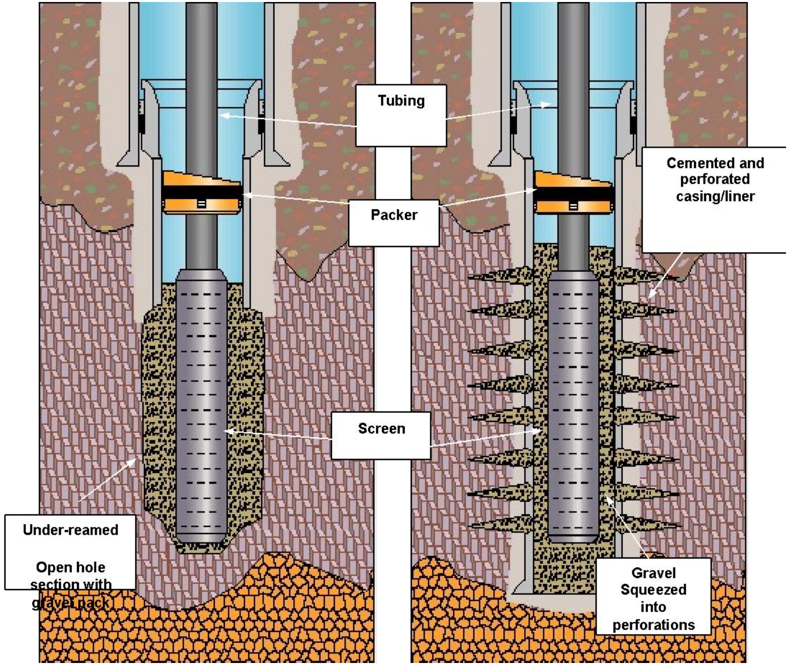




SAND CONTROL METHODS – Gravel packs

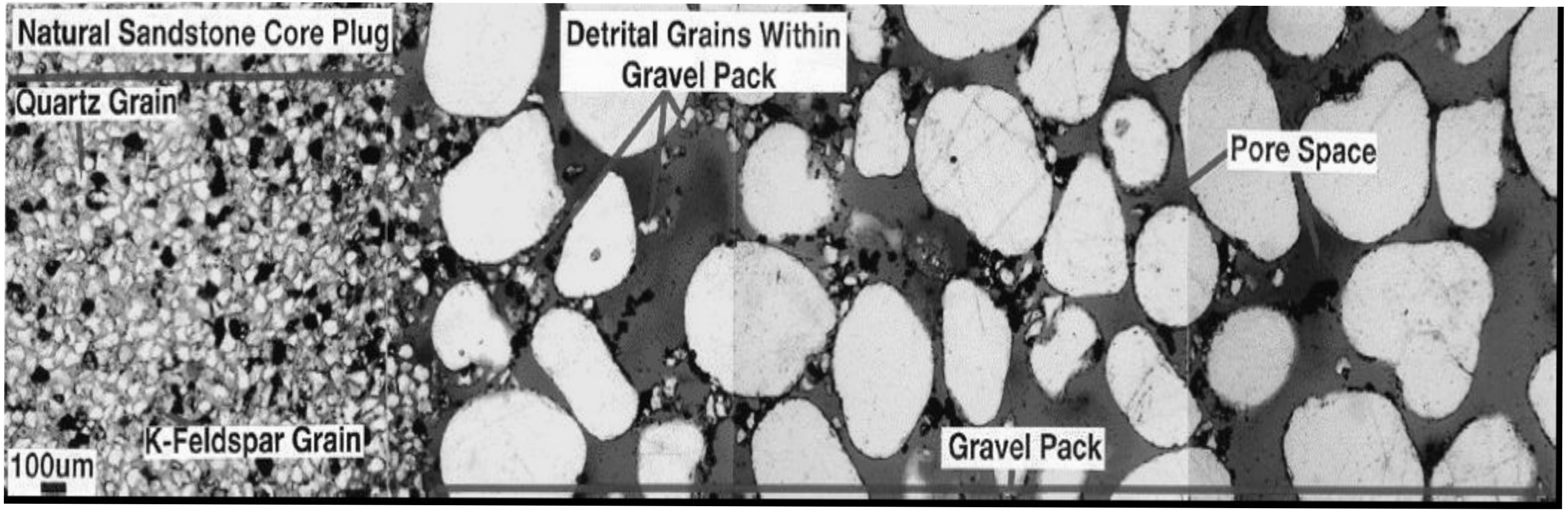
Gravel packs are common active methods of sand control, it involves the placement of gravel in between a screen and the wellbore wall, the gravel is the retention mechanism

- Offers larger flow area
- Gravel is the filter media
- Suitable for very heterogeneous formations
- Two (2) different types depending on well configuration (External & Internal)
- External GP for open hole and internal GP for cased/perforated completions
- Can have an impact on productivity, prone to plugging



SAND CONTROL METHODS – Gravel packs (Continued)

Internal and external gravel packs can be operationally complex particularly in long horizontal wells. Gravel placement is critical to maximum productivity



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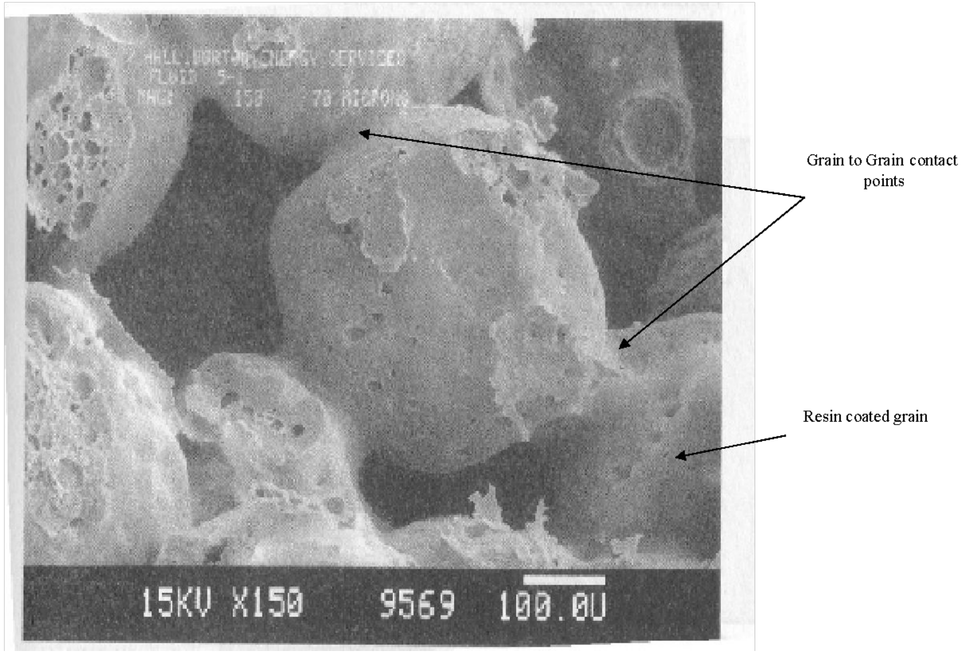
SAND CONTROL METHODS – Sand consolidation

It is an active method of sand control that involves the strengthening of the near wellbore.

- The method is based on the injection of chemicals into the matrix that add strength to the formation
- It is sensitive to fluid contamination and temperature
- Used in very clean sands
- Designed for reservoirs with porosities higher than 30%
- Carried out in short intervals < 30 feet

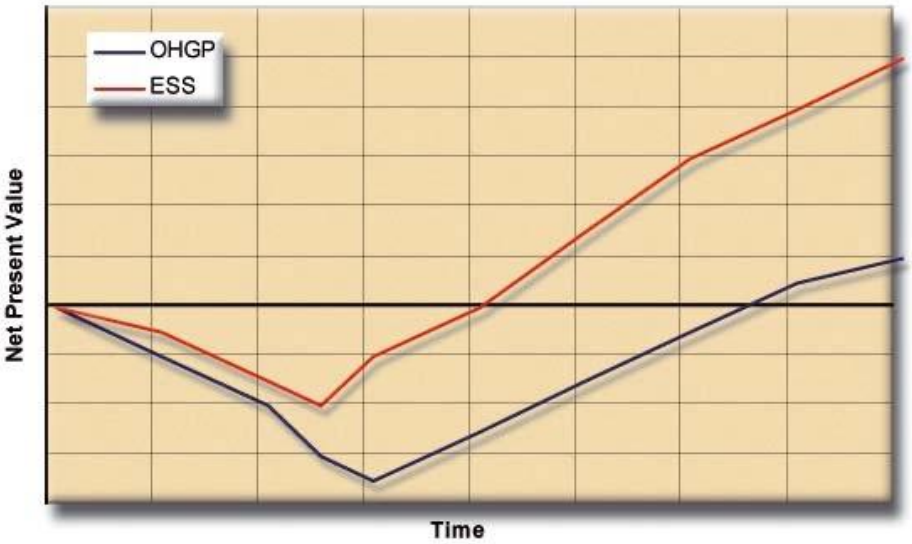


After Bertraux

THE ECONOMICS OF SAND CONTROL

Sand control completions require higher investment than sand management due to the cost of additional rig time and equipment. Two (2) cost factors impact the overall economics of a well

- Open hole sand control completions tend to deliver better productivity than cased/perforated
- This results in better ROI and NPV
- Rig time tend to be the higher cost for sand control completions
- Positive cashflow then results earlier



Courtesy of Weatherford

EFFECT OF NET PRESENT VALUE

MODULE 7 - SUMMARY

There are two (2) fundamental choices for completions in sandstone reservoirs, sand management and downhole sand control

- Sand management involves free production of acceptable levels of solids that can be cost effectively managed and disposed off at surface
- Downhole sand control involves placement of a filter at the sand face that will avoid sand being produced to surface.
- The main methods of downhole sand control include slotted liners, screens, gravel pack, sand consolidation, frac & pack and expandable screens
- Each sand control method requires detailed understanding of the rock properties and well operating philosophy.

MODULE 7 – SUMMARY (Continued)

- The choice between sand management and downhole sand control is a complex one that requires detailed assessment.
- Failure of the sand control method at some point in the life of a well leads to consideration for implementing a sand management program before a workover or recompletion is attempted.
- Sand control is CAPEX intensive and sand management is OPEX intensive.

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Module 8

SAND TRANSPORT

CONTENT

- *Sand transport in wells*
- *Flow regimes and multiphase flow*
- *The importance of well configuration*
- *Sand transport in flowlines*

SAND TRANSPORT IN WELLS

For a single phase fluid, stokes law can be used

$$V = \frac{2}{9}\frac{(\rho_p - \rho_f)}{\mu} g R^2$$

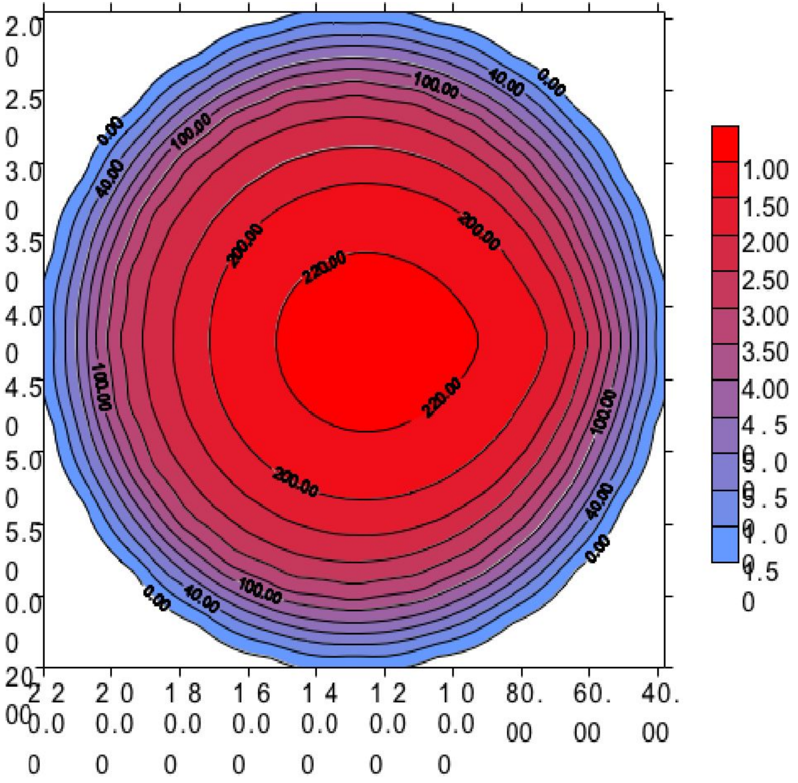
Where

V	Critical (Settling) velocity (ft/sec)
μ	Fluid viscosity (cP)
ρ_p	Particle density (gr/cc), 2.65 for sand particles
ρ_f	Fluid density (gr/cc)
R	Mean grain size radius
g	Gravity

SAND TRANSPORT IN WELLS (Continued)

CFD flow sample (5 ½” tubing)

- Fluid velocity distribution in a vertical well configuration
- Fluid friction at the boundary defines lower velocities
- Centre of the pipe shows the higher velocities with the best solid’s carrying capacity

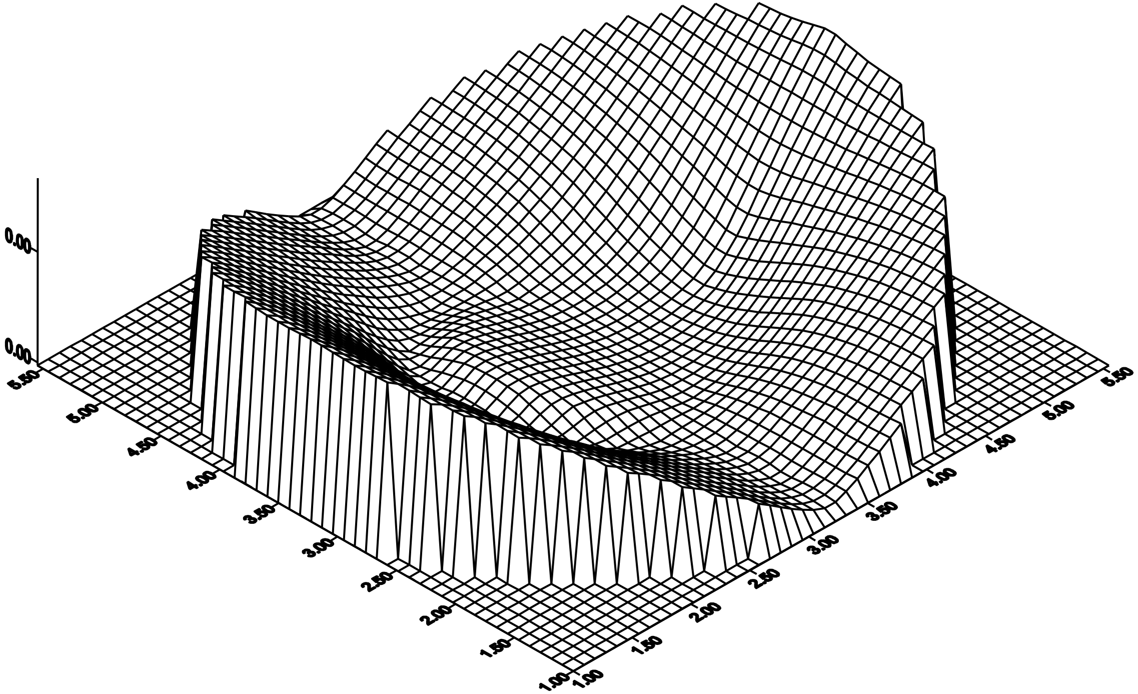


SAND TRANSPORT IN WELLS (Continued)

CFD flow sample (5 ½” tubing)

- Fluid stress profile indicates opposite trend to the velocity profile

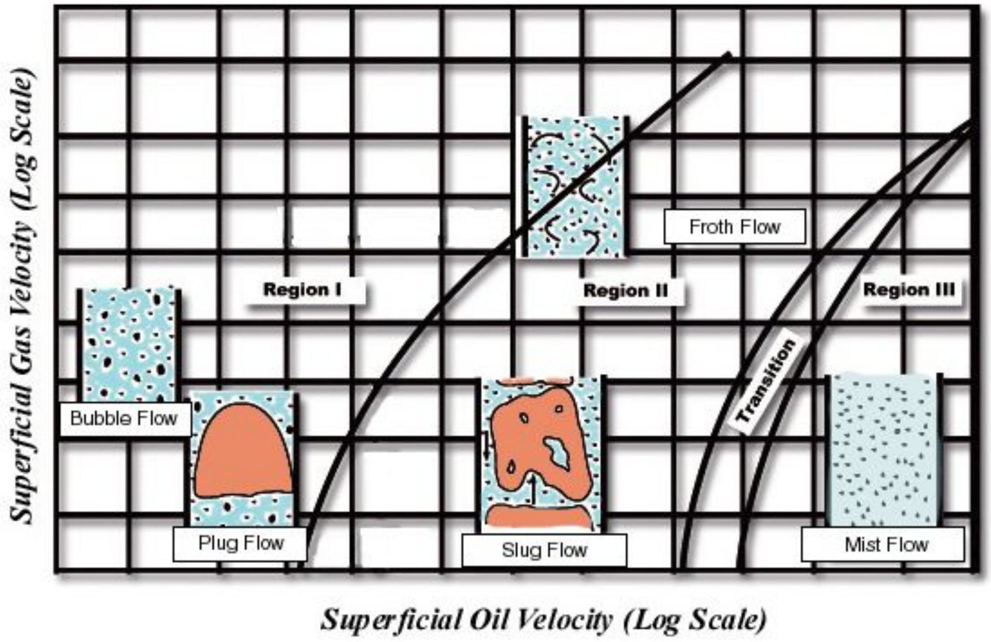
- Higher stresses at the boundary



FLOW REGIMES AND MULTIPHASE FLOW

Knowledge of flow regimes is critical to understand solid's transport

- Some flow regimes are more efficient at transporting solids
- The carrying capacity of a fluid can improve removal of sand from the wellbore
- Fluids with high GOR increase the velocity resulting in a higher risk of erosion



THE IMPORTANCE OF WELL CONFIGURATION

Example of a sand producer that utilizes PCPs for lifting fluids

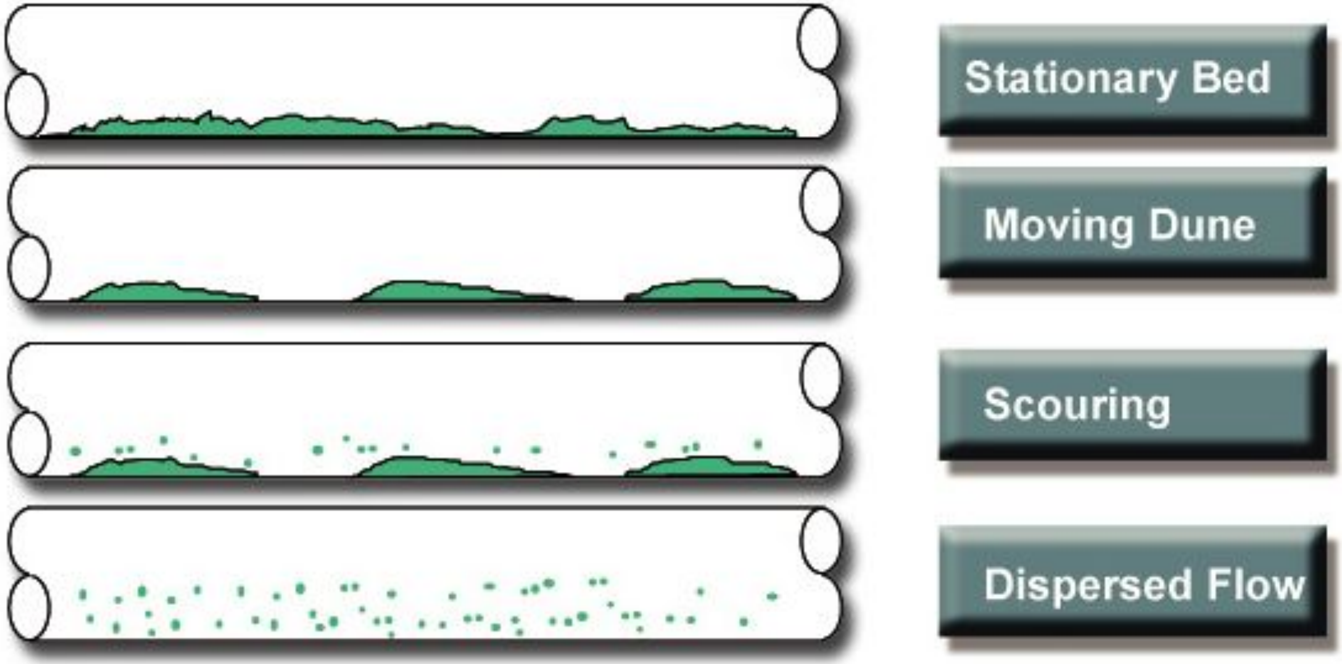
- Based on Stokes law
- Flow through larger cross-section areas exhibit lower velocities
- Require higher flow rates to lift the solids
- Larger particles can be lifted with fluid rheology or velocity can be used to optimise solid's lifting

FLOW RATE [bopd]	WELL CONFIGURATION	PARTICLE SIZES					
		40 •m	150 •m	300 •m	600 •m	1000 •m	2000 •m
50.0	7" Casing only	🟢	🔴	🔴	🔴	🔴	🔴
	7" Casing w/PCP	🟢	🟡	🔴	🔴	🔴	🔴
	2 7/8 " Tubing	🟢	🟢	🟢	🟢	🔴	🔴
	2 7/8" Tbg w/PCP	🟢	🟢	🟢	🟡	🔴	🔴
70.0	7" Casing only	🟢	🟢	🔴	🔴	🔴	🔴
	7" Casing w/PCP	🟢	🟢	🔴	🔴	🔴	🔴
	2 7/8 " Tubing	🟢	🟢	🟢	🟢	🟢	🔴
	2 7/8" Tbg w/PCP	🟢	🟢	🟢	🟢	🟢	🟡
100.0	7" Casing only	🟢	🟢	🟢	🔴	🔴	🔴
	7" Casing w/PCP	🟢	🟢	🟢	🔴	🔴	🔴
	2 7/8 " Tubing	🟢	🟢	🟢	🟢	🟢	🟢
	2 7/8" Tbg w/PCP	🟢	🟢	🟢	🟢	🟢	🟢

Note: 🟢 No problems 🟡 Some problems to lift particularly in deviated section 🔴 Insufficient velocity to transport

SAND TRANSPORT IN FLOWLINES

Solid's movement and regimes in horizontal pipes



SAND TRANSPORT IN FLOWLINES (Continued)

- ***Stationary bed*** results from very low fluid velocities where particles can settle and a stable solid’s bed is formed
- ***Moving dunes*** are the result of fluid flow that mobilises the top of the beds formed inducing dune shaped piles of solids that are in continuous movement
- ***Scouring*** is an erosion driven environment where the grains can move independently(in direction) of the fluid flow
- Mobilisation of the dunes and scouring leads to ***dispersion*** of the solid’s as the fluid rate is increased.

Sand beds can lead to the generation of bacteria that can induce corrosion

SAND TRANSPORT IN FLOWLINES (Continued)

Modelling solids and fluid flow - DNV model

- This model assumes that a sand particle will be transported only if the fluid generates sufficient forces capable of removing it from the "pack"

$$F_{bouy} + F_{lift} + S \cdot F_{drag} \geq F_{grav}$$

Shell Model

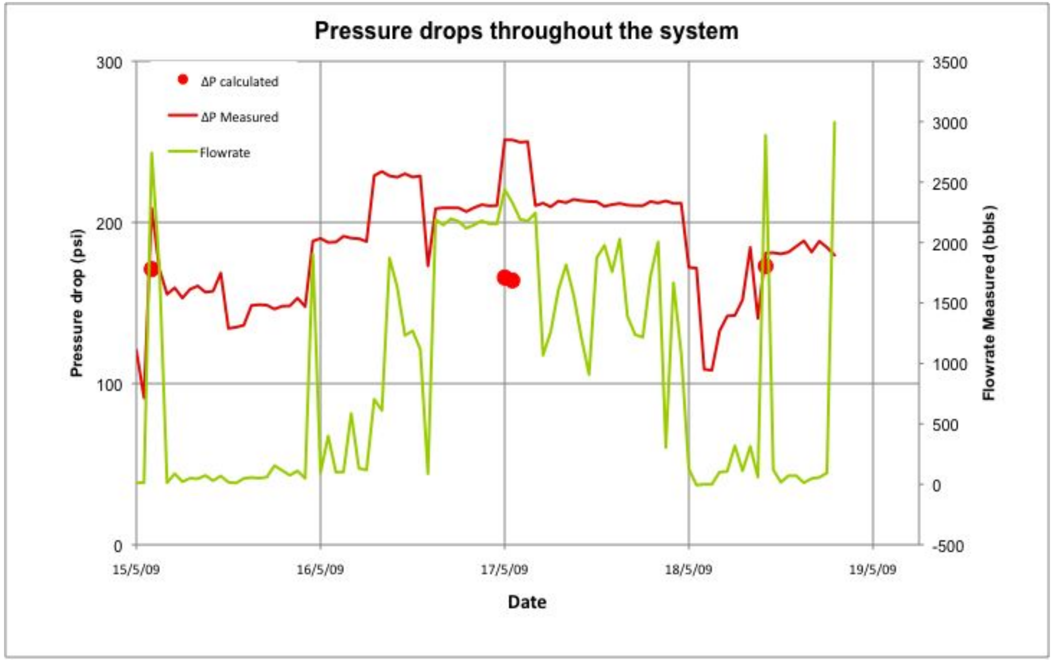
- Formed by dimensionless correlations between the sand transport rate and liquid flow rate based on experiments carried out using air/water systems. Limited to gas phase of up to 20% and fluids of up to 7 cP viscosity.

$$S = \frac{1}{8}\left(F_{drag} + F_{lift}\right) \cdot \phi^2 \qquad \Psi = \frac{\rho_l^2 \cdot d \cdot U_s^4}{\left(\rho_p - \rho_l\right) \cdot g \cdot \mu_1^2}$$

SAND TRANSPORT IN FLOWLINES (Continued)

Sand beds reduces the cross-section area of the flowline which can lead to:

- Increase in pressure drop along the flowline can be an indication of sand beds forming
- Higher ΔPs result in higher horse power requirements
- Reduction in flow rates and higher risk of pipe integrity issues are the result of sand beds



MODULE 8 - SUMMARY

Sand transport in wells, vessels and flowlines is critical to the success of a sand management program

- The main factors for effective sand transport in vertical or near vertical wells are the cross sectional area, particle and fluid density.

- For horizontal wells, producing below the bubble point sand transport is affected by the viscous stress rather than fluid velocity or flow rate

- There are a number of empirical models used to determine the minimum flow rates for effective fluid transport. The multiphase nature of the fluids makes its use complicated and extensive validation is required

- Determination of optimum flow rates and conditions must be balanced with other important issues such as the risk of erosion and pressure losses.

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Module 9

EROSION MANAGEMENT

CONTENT

- *Parameters influencing erosion*
- *Types of erosion*
- *Material's resistance to erosion*
- *Monitoring and surveillance of surface equipment for erosion*
- *Modelling metal loss*
- *Erosion management*

FACTORS CONTRIBUTING TO EROSION

Erosion is one of the main issues in Sand Management programs, the main parameters influencing the magnitude, location and severity of erosion are:

- Particle size, shape, hardness and concentration
- Type and properties of the surface
- Flow rate and fluid/gas properties (velocity, temperature..)
- Angle of impingement

TYPES OF EROSION

1. "Hydraulic" erosion is that caused by fluids only due to the turbulence generated (Eddie currents) along the fluid path, and it occurs mainly in:

    - Water injectors
    - Gas injectors

2. Solid's laden fluid erosion is caused by the impact of the particle being carried by the fluid onto a pipe or vessel, can occur in wells that are:

    - Used for cuttings re-injection
    - Producing sand

MATERIAL RESISTANCE TO EROSION

Quartz is one of the hardest natural minerals available

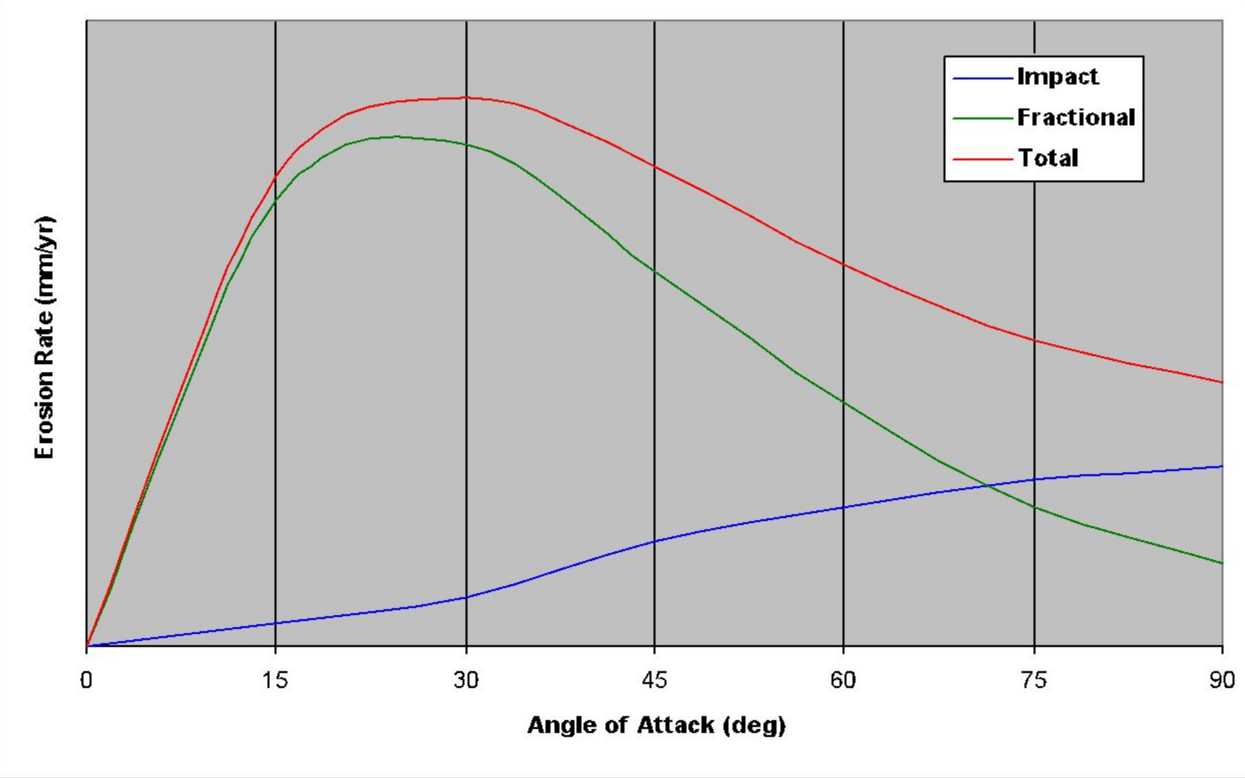
MATERIAL	HARDNESS [kg/mm^2]	REMARKS
Stainless steel	[175 – 290]	316
Carbon steel	[145 – 190]	AISI
Duplex	260	Annealed
Cast iron	240	All values are Vickers hardness
Glass	530	
Alumina	[960 – 1800]	
Quartz	1200	
Silica sand	800	

ANGLE OF IMPINGEMENT

Angle at which quartz grains impact the surface of a pipe determines:

- Force of impact
- Amount of material removed

Grains that impact perpendicularly the surface do not cause the larger damage



MODELLING METAL LOSS

The critical velocity for oil wells (API) $V_{crit} = C / \rho^{0.5}$

The critical velocity for gas wells (API) $V_{crit} = C / [29\ p\gamma g / ZRT]^{0.5}$

Where (Oil)

- C Material constant
- ρ Fluid density

Where (Gas)

- C Material constant
- g Gravity
- ρ Fluid density
- P Internal pressure
- T Temperature
- Z Gas factor

MATERIAL	MATERIAL COEFFICIENT " C "	REMARKS
Carbon steel	80 to 150	J-55, L-80, N-80……..
Duplex steel	280	13% Chrome
Super Duplex	350	25% Chrome
Monel	400	-

MODELLING METAL LOSS (Continued)

A number of analytical, empirical and computational models are available:

- API is the most conservative
- Most models are specific to a set of conditions
- Some are easily available, most require validation

CRITERIA	MODEL	CONDITIONS & USE
API	$E = 22.4\ M \times V^2 / d^2$	Single phase fluids, used for preliminary assessment
Salama & Venkatesh	$E = 604\ M \times V^2 / d^2$	Mainly used for downhole completions and > 5D bends
University of Tulsa	$E = 4280\ M \times V^{1.73} / d^2$	Single phase fluid flow, allows for variable sand particles sized. Not commercially available
RCS	$E = 4.1\ M \times V^{2.5} / d^2$	Used for preliminary assessment, works well for 1.5D bends, reductions and tees, not commercially available

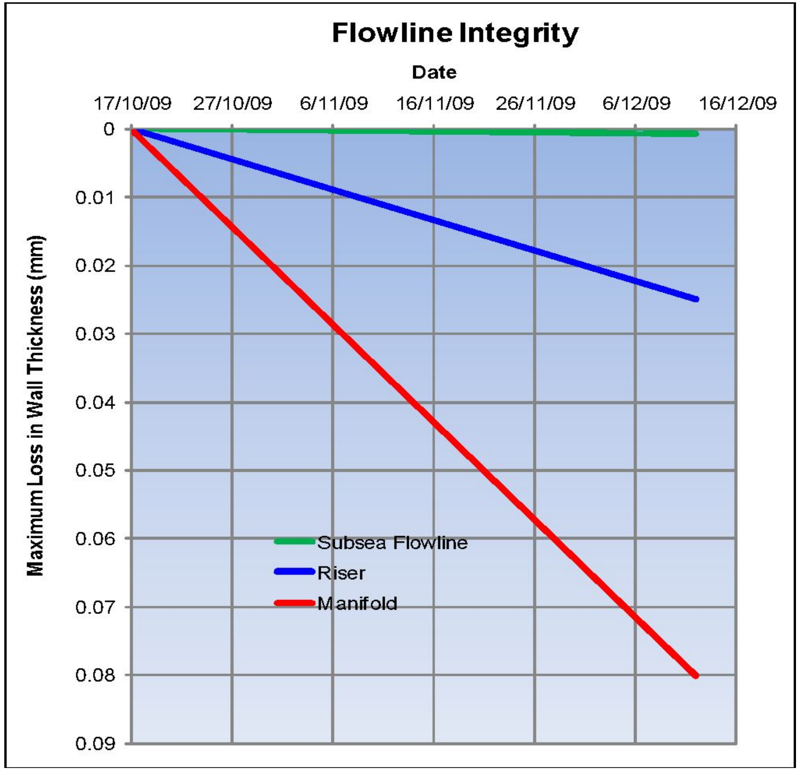
Where:

E	Erosion rate (mm/yr)
M	Sand flow rate (grs/sec)
V	Mixture velocity (m/sec)
d	I.D. of the pipe (mm)

MODELLING METAL LOSS (Continued)

Simulation tools can be used particularly for offshore locations, flowlines and risers

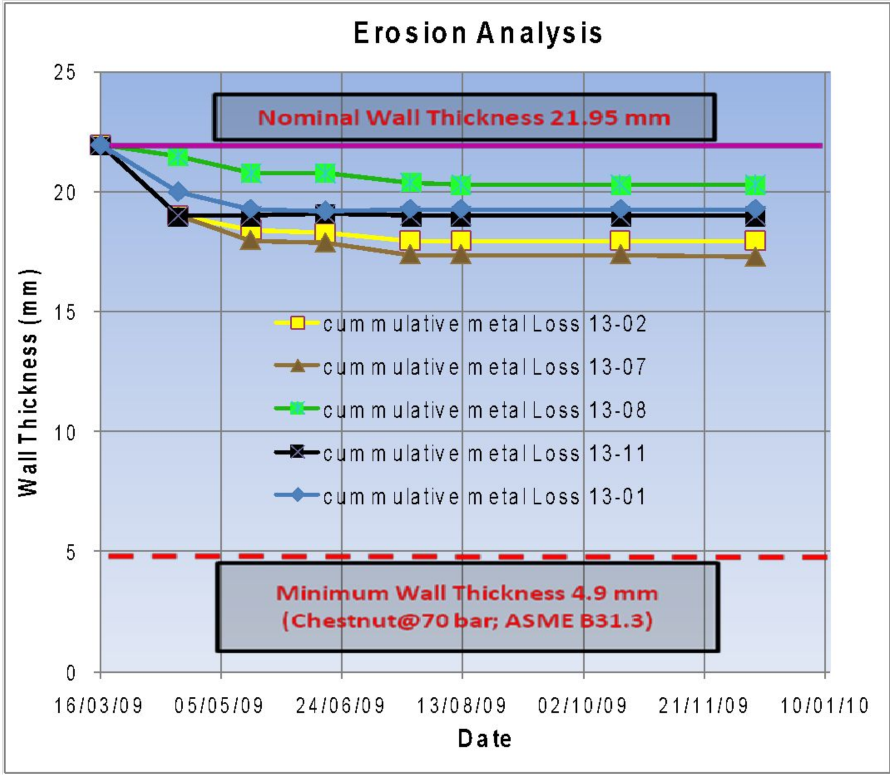
- Both hydraulic erosion and that caused by solid's laden fluids can be estimated
- Validation and verification is complex and sometimes not possible in a cost effective manner (i.e. buried flowlines)
- Subsea measurements and equipment is available for some applications



MONITORING EROSION

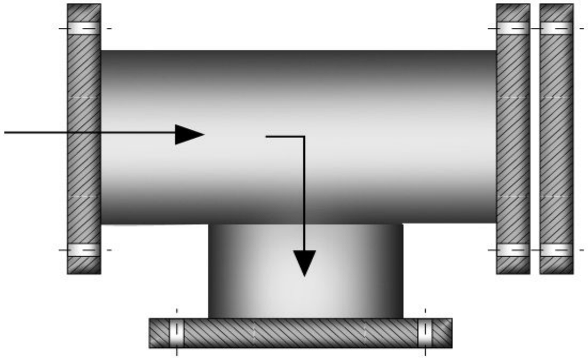
Monitoring/Managing erosion is an integral part of any sand management program

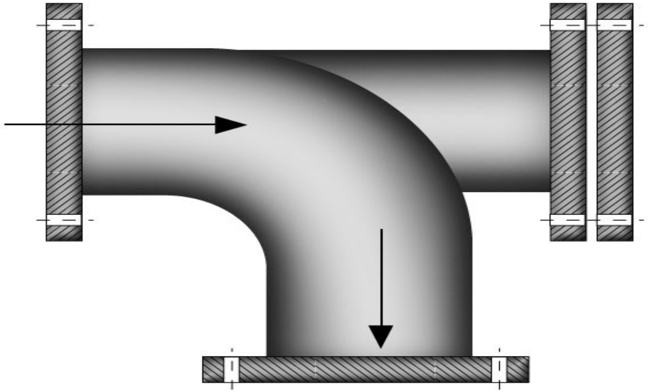
- Discrete measurements along flowlines, wells and plant are common
- Real time monitoring is an alternative, new data transmission technology make the sensors mobile and wireless
- Both type of programs are effective, choice will depend on the risk level, field location (Onshore/Offshore) and cost



EROSION MITIGATION GUIDELINES

- Avoid the use of short radius elbows in piping design
- For all flowline systems and components, blanking should be used by utilising welded caps, blind flanges and/or impact blind flanges
- Depending on space availability, long radius bends should be at least five times the pipe diameter.
- Piping layout design to minimize bends and curves where sand production is expected
- Components in a piping/flowline system where wear is expected should be designed to be fully replaceable.





MODULE 9 - SUMMARY

There are two (2) erosion mechanisms encountered in oil and gas production, one caused by the impact of solids and the other by a hydraulic effect.

- Particle's impingement angle is critical between 30 to 40 degrees. A number of recommendations mainly for plant design are presented in API RP 14 E
- Four(4) current empirical methodologies for the determination of erosion problems were presented
- For larger size particles an increase on the particle momentum contributes to remove more material from the pipe's surface.
- Erosion management is an integral part of a sand management program, it can be done by either regular inspection and measurements or by the use of real-time surveillance and monitoring programs.

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Module 10

EROSION EXERCISE

CONTENT

- *Information and data*
- *Formulae*
- *Results*
- *Interpretations*

INFORMATION AND DATA

Pipes of three(3) different diameters have been identified as having a risk of erosion for the rate and volumes of sand being produced from the field(See table below). Fluid mixture velocity has also been estimated.

- You are requested to investigate the rate of erosion for these conditions using the four(4) criteria provided in the following page.
- Using the API formulae determine the V_{crit} for a crude API 30 degrees, carbon steel and super duplex pipes
- Compare results between the four(4) criteria provided

Sand Rate (grs/sec)	Mixture Velocity (m/sec)	Pipe Diameter (mm)
100	1	50
200	1	50
300	1	50
400	1	50
400	1.5	50
400	2	50
500	2	50
500	2	75
500	2	100

FORMULAE

CRITERIA	MODEL	CONDITIONS & USE
API	$E = 22.4\ M \times V^2 / d^2$	Single phase fluids, used for preliminary assessment
Salama & Venkatesh	$E = 604\ M \times V^2 / d^2$	Mainly used for downhole completions and > 5D bends
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Where:

E	Erosion rate (mm/yr)
M	Sand flow rate (grs/sec)
V	Mixture velocity (m/sec)
d	I.D. of the pipe (mm)

FORMULAE (Continued)

The critical velocity for oil wells (API) $V_{crit} = C / \rho^{0.5}$

Where (Oil)

C   Material constant

ρ Fluid density

MATERIAL	MATERIAL COEFFICIENT " C "	REMARKS
Carbon steel	80 to 150	J-55, L-80, N-80……..
Duplex steel	280	13% Chrome
Super Duplex	350	25% Chrome
Monel	400	-

RESULTS

CRITERIA	EROSION RATE [mm/year]	EROSION RATE [mm/year]	EROSION RATE [mm/year]	OBSERVATIONS
API	0.896	1.792	2.68	Results for sand rates of 100, 200 and 300 grs/sec in 50 mm pipe diameter
Salama & Venkatesh	24.16	48.32	72.48	
University of Tulsa	171.2	342.4	513.16	
RCS	0.16	0.328	0.48	

Note: Result presented in the table are only for the first 3 sand rates and at constant pipe diameter

RESULTS (Continued)

Density for a crude API 30° degrees	55.35 Lb/ft^3
Value of material constant C for carbon steel	150
Value of material constant C for super duplex steel	350

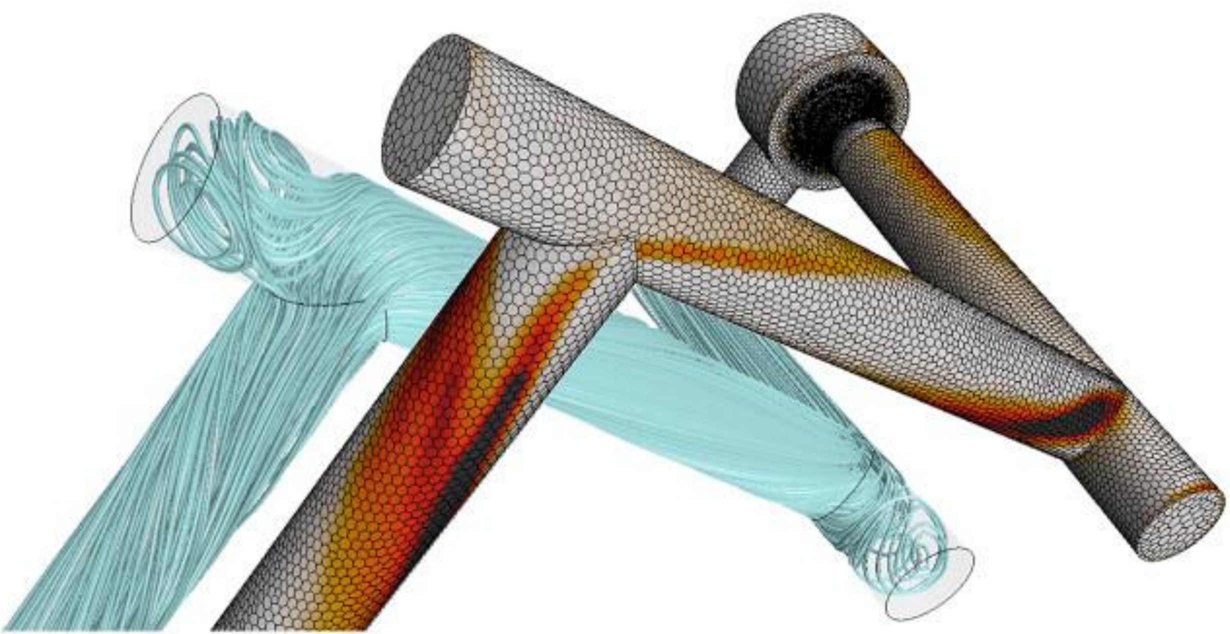
Following the API criteria then we have:

V_{crit} for Carbon Steel	20.16 ft/sec
V_{crit} for Super Duplex	47.04 ft/sec

INTERPRETATION

- The four (4) correlations used for the estimation of the erosion rate give very different results. The API correlation and the RCS results differ by one order of magnitude
- This is common with empirical correlations as they have been obtained for specific sets of conditions
- The only solution is to take actual measurements either in the lab or in the field in order to calibrate the correlation
- The critical velocities to avoid erosion estimated using the API formulae give both reasonable values despite its limitations.
- These results also indicate that resistance to erosion can be mitigated by changing the metallurgy of the pipe as in this case.

FLOW & EROSION SIMULATION RESULTS USING CFD



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Module 11

SAND DETECTION

CONTENT

- *Type of sand detection systems*
- *Intrusive and non-intrusive measurements*
- *Factors influencing sand detection*
- *Ultrasonic sensors*
- *Typical responses*
- *North Sea acoustic detector sample*
- *Selection of sensor's location*

TYPES OF DETECTION DEVICES

1. Intrusive systems require a location in the process, plant or flow line where the sensor is in contact with the fluid stream

2. Non-intrusive methods employ ultrasonic sensors to measure the noise made by solid's particles as they hit the metal surface during production.

Other methods include:

Sand Shake-outs
Leutert sampling
Monitoring sand build up in the separator
Sand traps

TYPES OF DETECTION DEVICES – ADVANTAGES & LIMITATIONS

- All sensors required calibration, this is a severe limitation
- Non-accurate measurements are not uncommon but the qualitative side of the data can still be used successfully for sand management

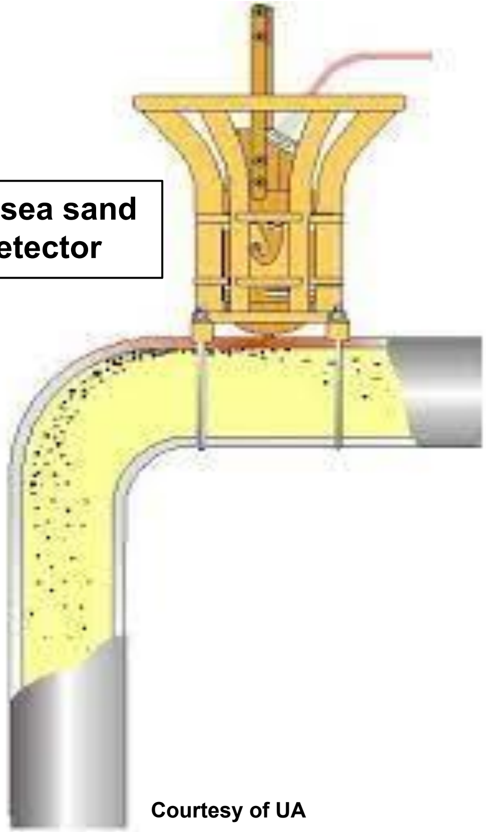
	INTRUSIVE	NON-INTRUSIVE
INSTALLATION COST (Surf)	High	Low
INSTALLATION/ REPLACEMENT	Complex, requires breaking containment	Simple, fitted on the outside piping
REAL TIME MEASUREMENT	No	Yes
LIFE EXPECTANCY	Depends on solid production	Sensor up to 15 years

FACTORS INFLUENCING SAND DETECTION

FAVOURABLE CONDITIONS	NON-FAVOURABLE CONDITIONS
Gas wells	Wells producing high viscosity fluids
Wells producing low viscosity fluids	Low rate wells
Wells with high GORs	Very small size sand particles produced
Fluids being produced at high velocities	Wells where hydrates or wax are a problem
Larger sand particles are produced	High level of background noise
Small size (ID) flowlines	Larger size (ID) flowlines

ACOUSTIC SAND DETECTORS

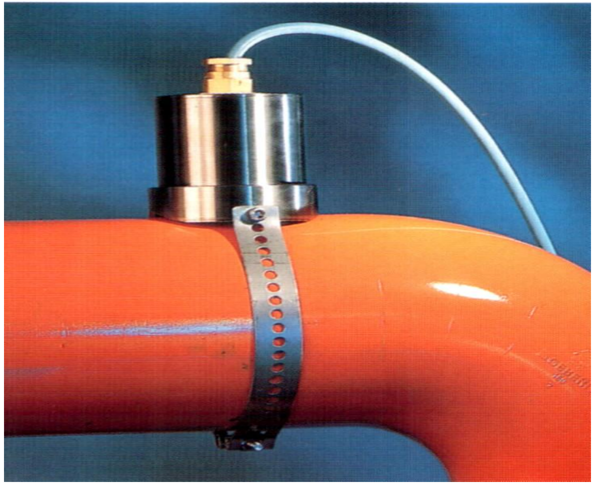
Subsea sand detector



Courtesy of UA

Courtesy of Emerson

Courtesy of Roxar



Courtesy of ClampOn

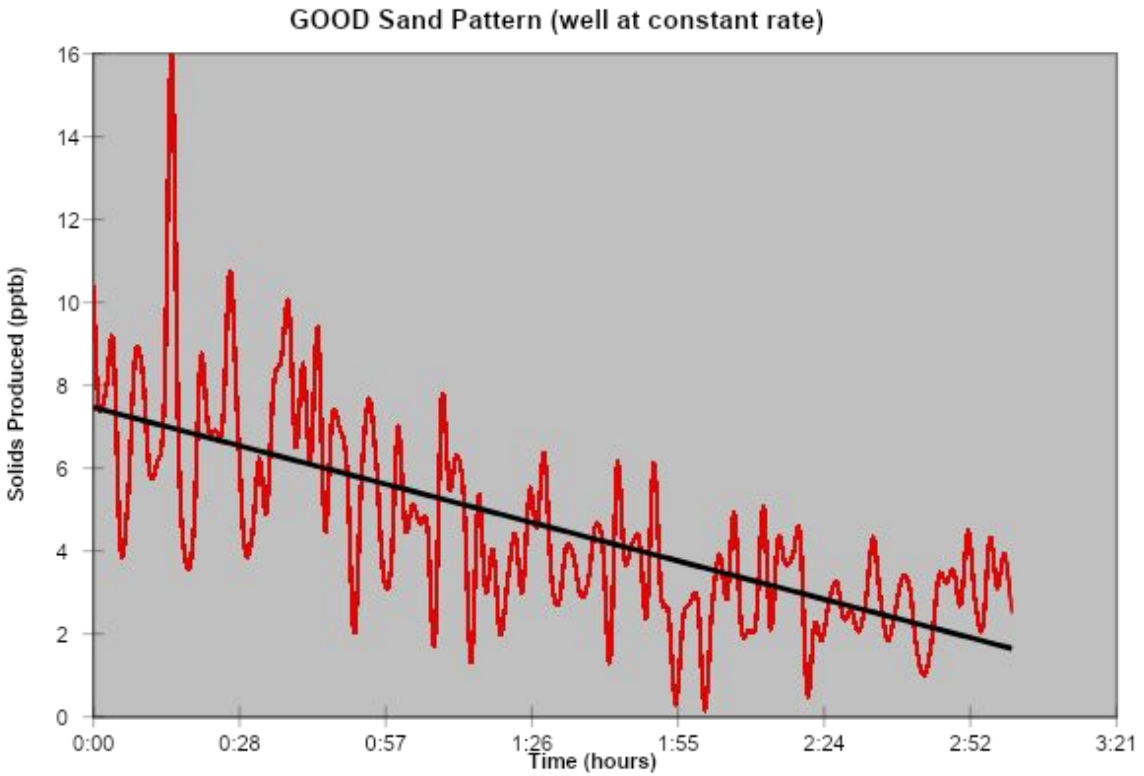
INTRUSIVE SAND DETECTORS

Courtesy of SLB

TYPICAL SENSORS RESPONSE

Noise is converted to sand rate through calibration. A "Good" response can be:

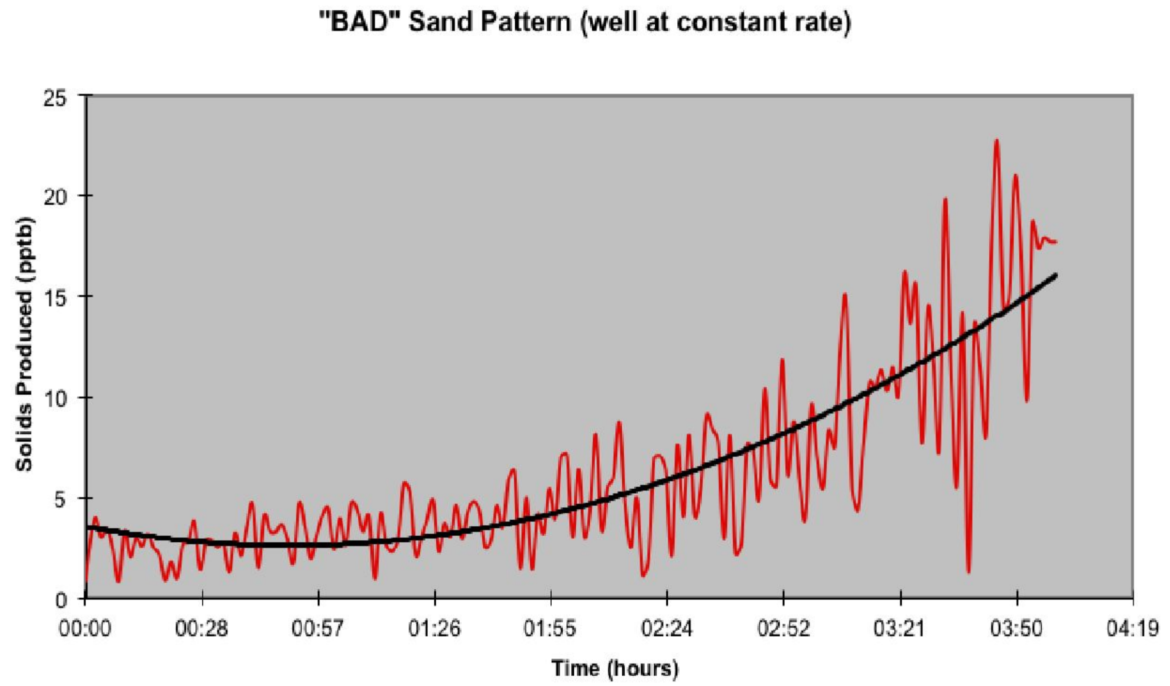
- Response for a burst or transient sand production model
- Shows higher initial rates that then decline in time
- Sand production rates can decline to zero pptb



TYPICAL SENSORS RESPONSE (Continued)

A “Bad” response can:

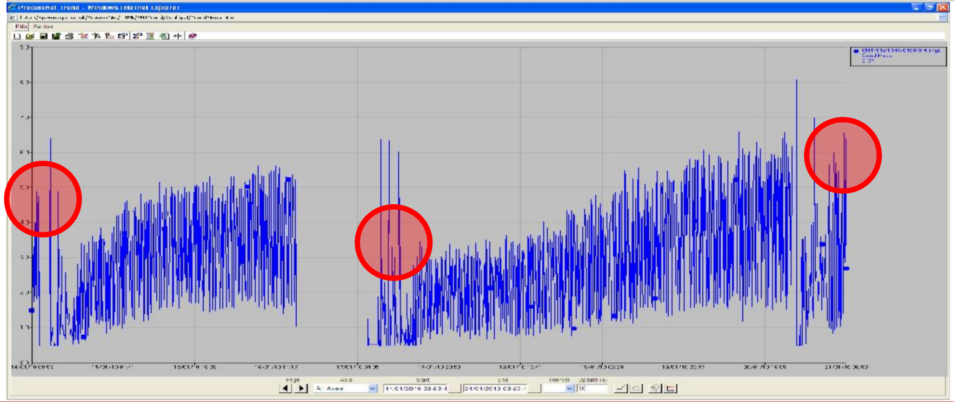
- Show a continuously increasing sand rate response, an indication of continuous sand production
- Show no decreasing trends
- Be typical of weak, unconsolidated or highly depleted reservoirs



NORTH SEA EXAMPLE – Ultrasonic sensor

Acoustic sensor response for a sand management program

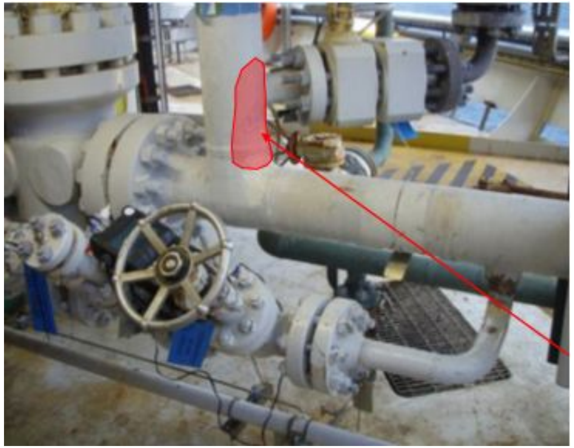
- High sand rates (Blue curve) at the start up are a function of choke opening
- Three(3) start up conditions, in the first two(2) the sand rate tends to stabilise in time
- During a sand management program, operators tends to characterise the well's sand production signature signature



LOCATION OF THE MEASUREMENT

Selecting sensor/measurement locations for surface facilities

- Critical for real-time sand management
- Chokes and piping (Elbows) are the ones more affected



COMPONENT	EROSION PRONE LOCATION	INTENSITY
Piping	Any obstacle such as a crossover, welds	Low
	Typical in the outer curvature of elbows	Medium
	"T" junctions where turbulence is created	Low
Valves	Valve seat in needle valves	High
	Cage and outlet pipe in sleeve type valves	
Chokes	Choke's cone body	

MODULE 11 - SUMMARY

- Sand detection is one of the most critical step in reservoirs being produced using a sand management strategy.

- Two (2) different methods are used, intrusive and non-intrusive

- The intrusive methodology uses probes inserted into the production streams that measure impact noise and metal loss of the probe. Both measurements can be correlated to sand volumes

- The non-intrusive methodology utilises the noise (sonic) made by the sand particles impacting the metal surface.

- Solids production in wells can be characterised by measuring and monitoring the production trends in order to determine what mode of solids production should be expected.

MODULE 11 – SUMMARY (Continued)

- The most common erosion prone locations are the chokes and piping therefore, detection should be concentrated in these areas.
- There are some limitations for each of the measuring methods, particularly in heavy crudes and in complex well locations such as subsea
- Other type of basic measurements such as sand traps and manual sampling are also used however, their accuracy and representativeness is difficult to asses and require constant monitoring and interpretation to be useful
- Calibration of sand detection instruments is critical and must be carried regularly
- An important use of data is the determination of patterns and trends of solids production that will help the successful management of the wells

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Module 12

SAND SEPARATION

CONTENT

- *Separation principles*
- *Gravity separation*
- *Centrifugal separation*
- *Design and selection guidelines*
- *Cleaning of separators*
- *Cleaning flowlines, pigging*

SEPARATION PRINCIPLES

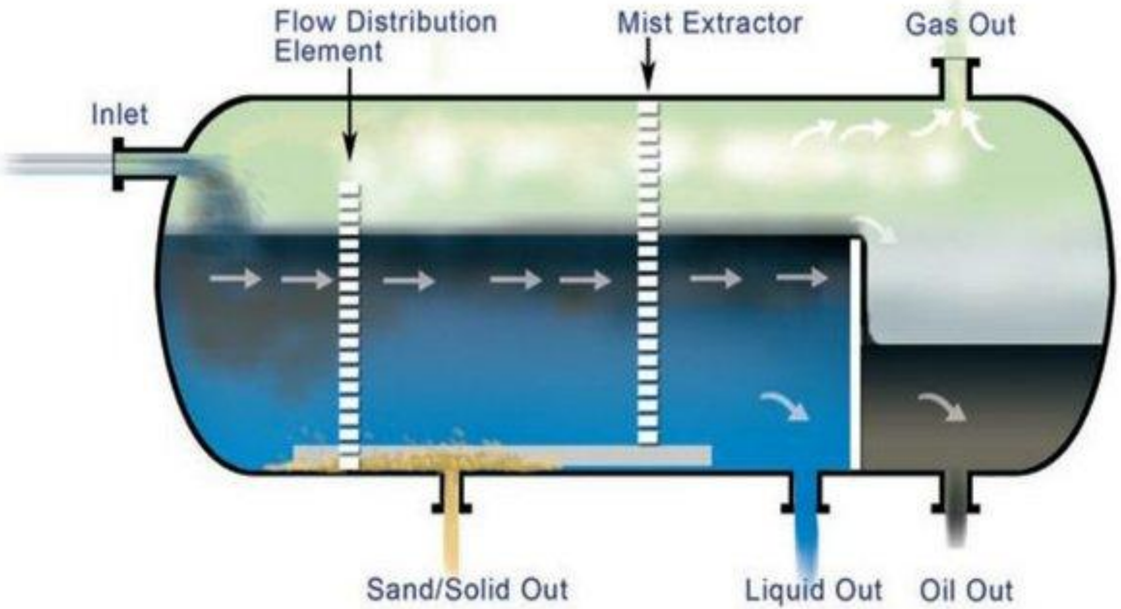
In sand management programs, sand separation at the existing plant is the desired option however, in gas wells (Onshore) were the erosion risk is higher then some type of separation devices can be installed at the production line off the tree.

- Gravity is used in large separation vessels where surface area and time ensures efficient gas, fluids and solid's separation. Regular cleaning and maintenance of the vessels is required.

- Centrifugal forces direct three(3) phase fluids through a helical path were density differences ensure separation of the phases. Hydro cyclones are typical examples of this type of separation

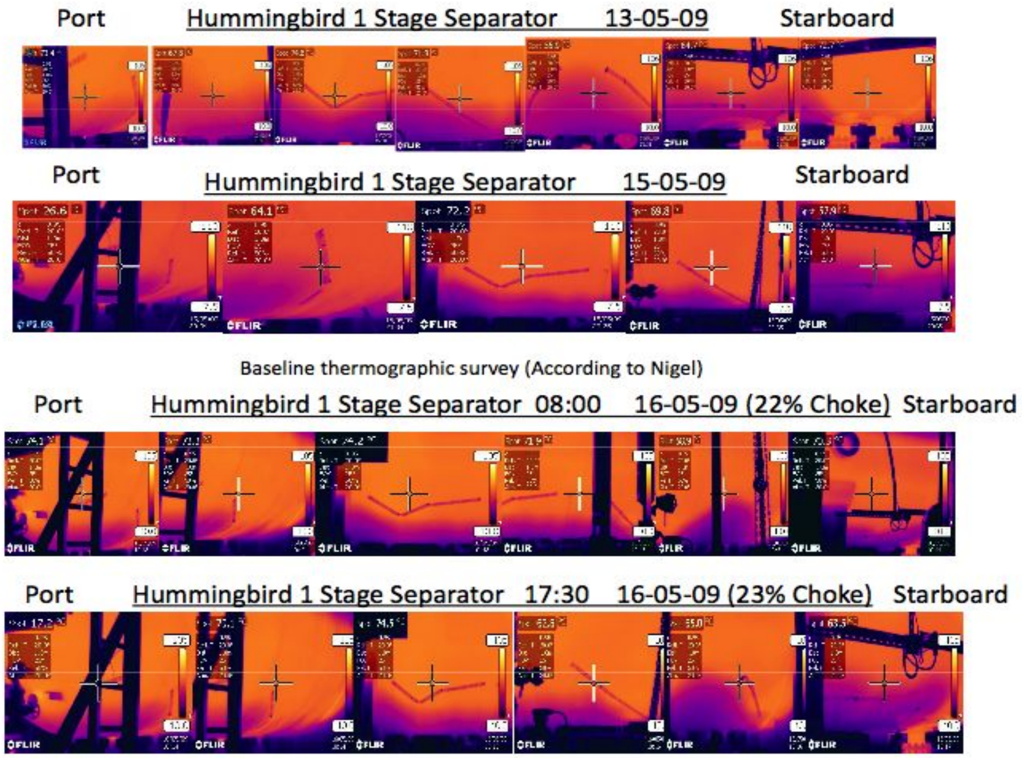
GRAVITY SEPARATION

- Fluid's residence time is critical to efficient sand separation
- Sand settling leads to a reduction in area that can reduce residence time
- This results in impaired separation efficiency and solids carry over



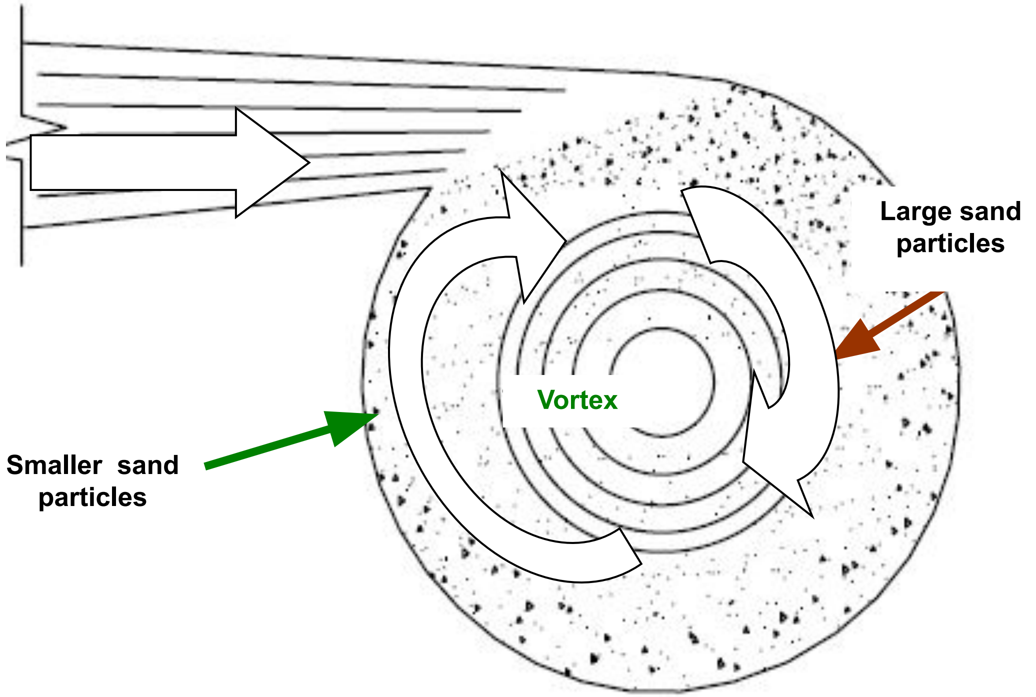
GRAVITY SEPARATION (Continued)

- Large vessels
- Capable of storing large amount of solids (Tones)
- Need to be cleaned regularly
- Potential alteration of the process
- Monitoring is labour intensive



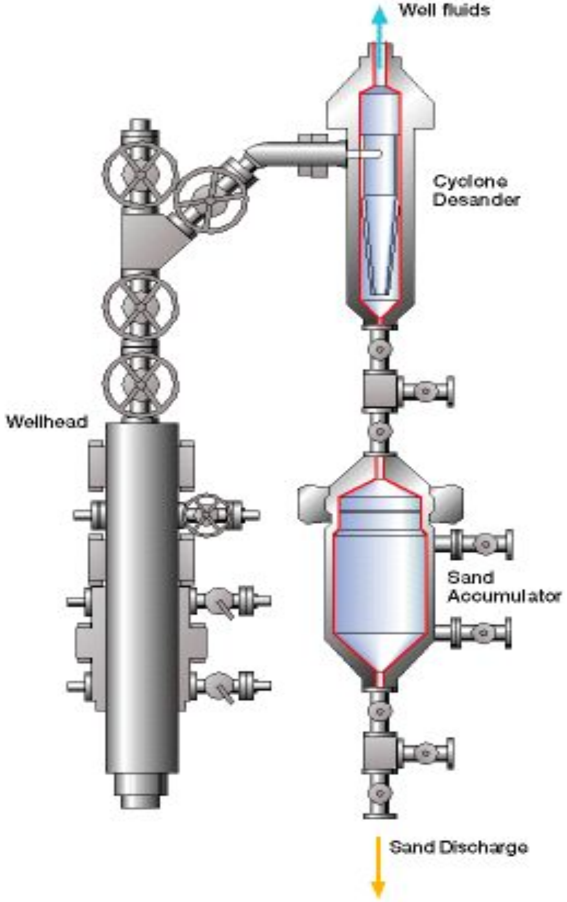
CENTRIFUGAL SEPARATION

- Fluid is forced into a helical path generating centrifugal forces
- Sand grains are heavier than the fluid therefore, will move towards the walls of the vessel
- Fluid and gas are collected via different flow paths



CENETRIFUGAL SEPARATION (Continued)

- Common in gas wells
- Located at the tree
- Small volumes can be accumulated & drained
- Typical of land and platform based wells
- Also common for well’s flowback after fracturing operations



CENTRIGUGAL SEPARATION (Continued)

Courtesy of Enercorp

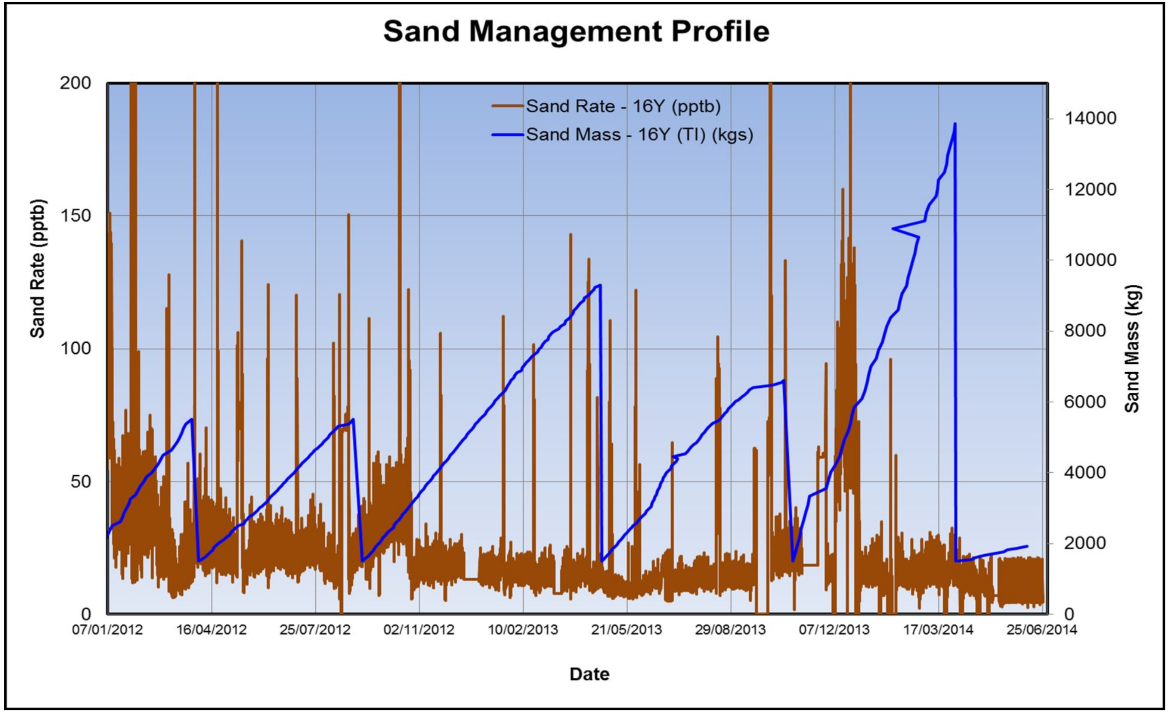
DESIGN AND SELECTION GUIDELINES

PARAMETER	DESIGN RULE	REFERENCE	REMARKS
Vessel height	Dictated by sand storage required	6 months of produced sand	Southern North Sea based criteria at maximum sand production
Separation efficiency	100 %	Depending on the design	Cyclones can separate close to 100% for particles larger than 10 microns
Maximum sand production	Regionally based	9 lbs/MMSCF	UKCS Southern gas fields
Pressure drop	0.5 % of Pi	-	Maximum value
THP	< Operating pressure	-	Might limit productivity

SOLIDS CARRY OVER EFFECT

- Poor separation can lead to sand carry over from the separators to the flowline and storage facility
- Typically smaller sand grains can be carried over due to insufficient transit time in the separator
- The results are high pumping pressures required to transport the crude
- Regular maintenance might be required
- Flow assurance issues like corrosion are common

CLEANINING OF SEPARATORS



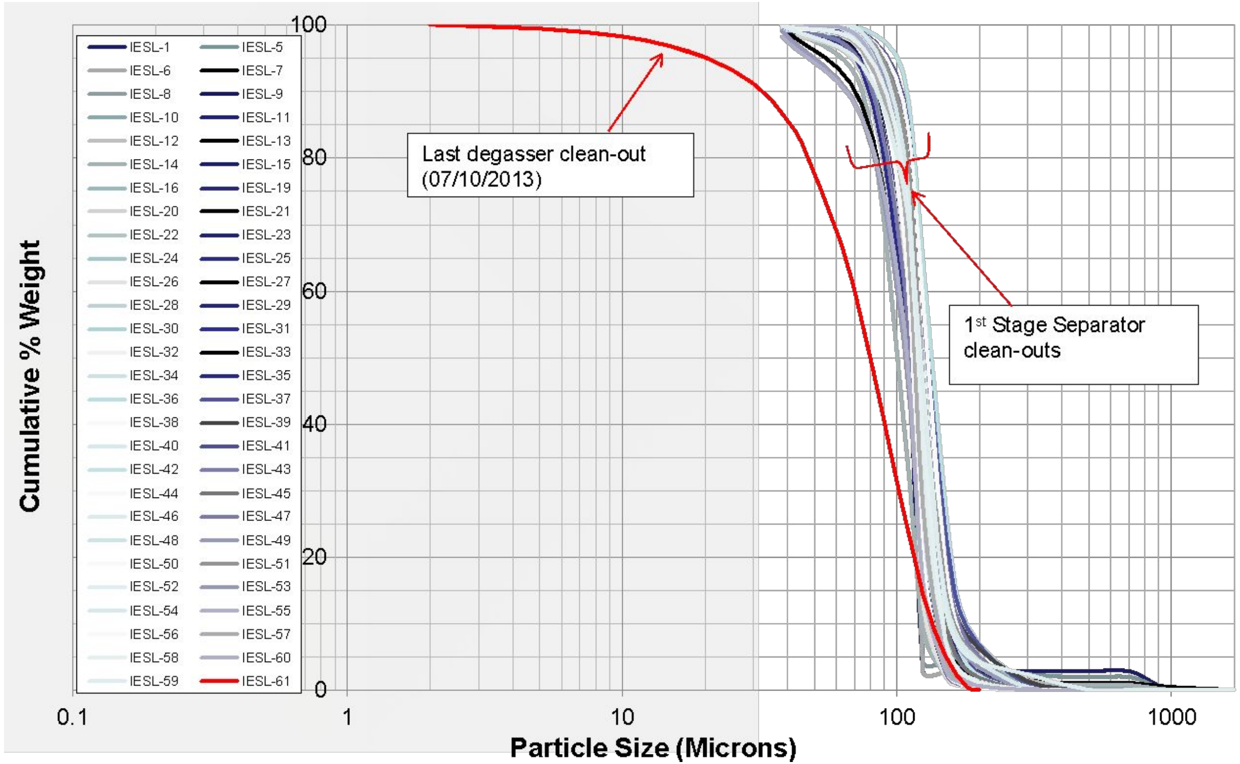
Date	Cycle number	Tonnes
15/05/2009	1st cycle	16.00
19/06/2009	2nd cycle	12.30
10/09/2009	3rd cycle	4.40
06/06/2010	4th cycle	12.10
08/10/2010	5th cycle	9.10
27/03/2011	6th cycle	7.50
07/09/2011	7th cycle	9.00
03/11/2011	Shutdown Cleanout	8.50
27/03/2012	8th cycle	4.00
05/09/2012	9th cycle	5.50
24/04/2013	10th cycle	9.30
28/10/2013	11th cycle	12.00
14/04/2014	12th cycle	8.80
Total		**118.50**

SEPARATOR SAMPLING AND TESTING

- Samples of cleaned sand are regularly taken during a sand management program

- Changes in PSDs can indicate variation in the source, carry over trends

- Over 69 samples taken over 8 years of sampling for this case (Graph)



MODULE 12 - SUMMARY

Efficient separation is mostly a surface activity that utilises existing plant equipment and allows sand to be removed from the production fluids and prepared for disposal

- Two different methods are used, centrifugal and gravity type of separation
- Centrifugal separators are sometimes installed at the production side of the tree for wells with high GOR or in gas producers
- Integrating sand separation capabilities in plant design is a desired step in the design of production facilities but it is not always carried out due to cost issues
- Poor separation of sand particles lead to reduced transient times and particles carry over, this result in additional flow assurance problems in flowlines and storage facilities

MODULE 12 – SUMMARY (Continued)

- A large amount of data can be obtained from the separated solids including volumes, sizes and mineral content, this can be used for determining/inferring source location, separation efficiency and condition of the wellbore

- A detailed program of how sand separation will be integrated in the overall plant and fluid's management is a component of any sand management program

- Additional surveying and monitoring steps and equipment are required to ensure that sand separation is achieved

- This type of programs also requires operational training for the personnel that might be mostly used to traditional fluid/gas/water separation, the addition of the solid's separation phase will add major changes to the conventional practices and procedures.

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Module 13

SAND REMOVAL FROM VESSELS AND FLOWLINES

CONTENT

- *Solids removal principles*
- *Cleaning of separation vessels*
- *Cleaning of flowlines*
- *Pigging*

SOLIDS REMOVAL PRINCIPLES

Once solid's separation is completed, their removal from flowlines and vessels can then be attempted. There are a number of techniques currently used in the oil and gas industry

- In flow lines or pipes (Including tubing) chemical and mechanical methods are utilized. Milling and jetting are common for well cleanouts or scale removal

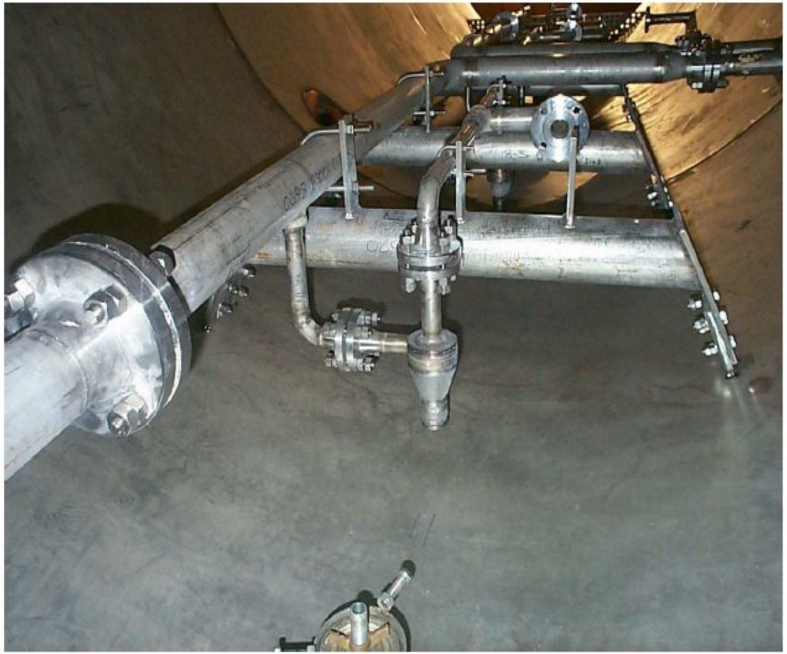
- In separators and vessels extraction is carried out using mechanical methods, chemicals and additives are utilised as an aid in the mechanical process

Dissolution, crushing and mobilisation are the most common mechanisms utilised

CLEANING OF SEPARATORS AND VESSELS

In the early days cleaning of a separation vessel involved physical access to the internals, this implied

- Complete stop of the process and ventilation of the vessel
- Additional protective gear for the personnel involved depending on the type of solids present in the vessel (Radioactive minerals)
- NPT and cost in terms of services and lost production



CLEANING OF SEPARATORS AND VESSELS (Continued)

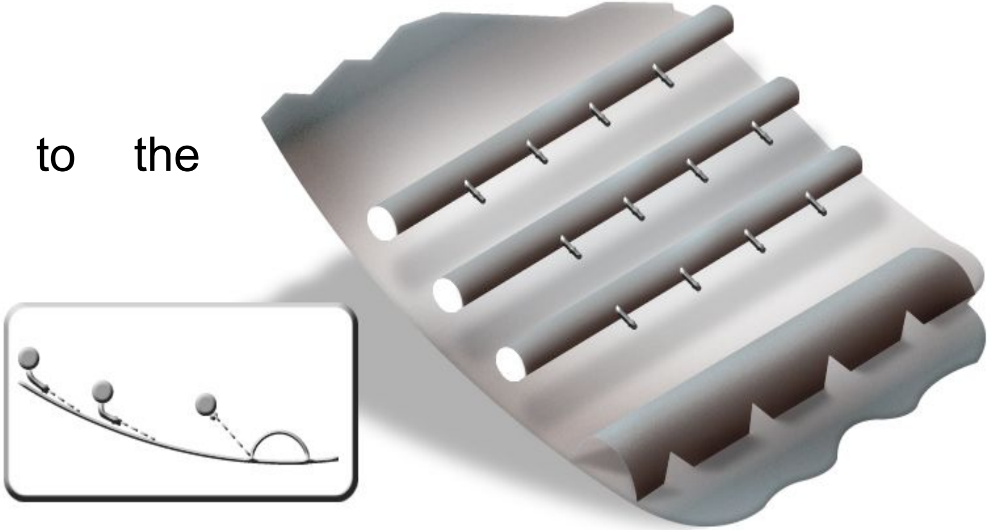
Typical separator's design included a solid's "flushing" capability using high pressure water

- Jet bays located at the bottom of the vessel were used for this purpose

- Nozzle design varied according to the requirements

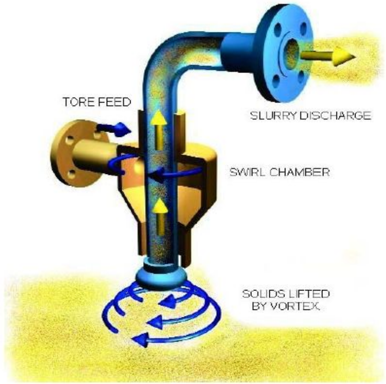
- Sand beds deposited could reach a certain hight making the jet bays ineffective

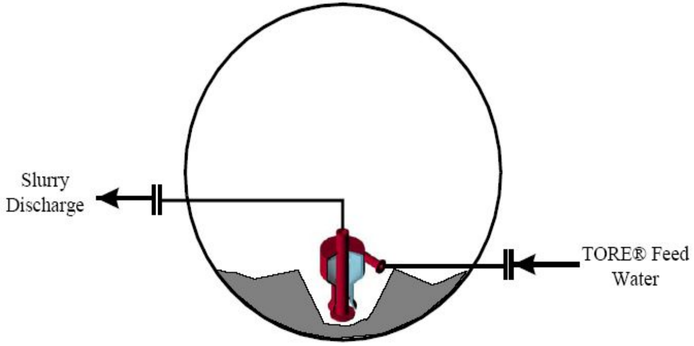
- HP jetting could induce erosion of the vessel's wall



CLEANING OF SEPARATORS AND VESSELS (Continued)

- Other methods such as online centrifugal devices are also common
- High water rates creates a vacuum that induces mobilisation of the deposited sand that is then transported outside the vessel
- Can be used without stopping the process and plant
- Permanent and mobile systems are commonly utilized effectively





CLEANING OF SEPARATORS AND VESSELS (Continued)

Courtesy of Merpro Limited

CLEANING OF FLOWLINES AND PIPES

- Sand can deposit along with many other type of minerals that form scale
- Calcium Carbonate and Barium Sulphate scale is commonly found in completion strings and pipes
- Mechanical intervention (Milling/Jetting) can be use to remove the scale from the pipe walls
- Chemical treatments are effective were the material is soluble (Salts, carbonates)

Courtesy of Marais A. et al 2016

CLEANING OF FLOWLINES AND PIPES (Continued)

Guidelines

- Assess volume of solids settled in the pipeline
- Validate hydraulic simulations for pressure drop and flow
- Identify potential solids settling locations
- Recover samples & test for mineral identification
- Identify treatment and operational practices

Courtesy of Saltworks

CLEANING OF FLOWLINES AND PIPES – PIGGING (Continued)

Pigs are mechanical and fluids used for removal of solids from pipes

- Fluid type of pigs are fluids with special rheological and chemical compositions
- Regularly used for dissolution and transport of solids
- Mechanical pigs are devices used for removal and displacement of solid's and fluid mixtures generated from the cleaning operations

TYPE	GUIDELINES	PHOTOGRAPH
Foam	Used in first stage as the First pig Also used in the second stage w/ closer tolerances Good for complex geometries (restrictions & bends) Also used for fluids removal in pipelines Used individually	
Cup	Good sealing properties Do not use on complex geometries It tends to by-pass some of the settled solids Can be used as a wiping devices Used individually	
Disk	Much more rigid structure particularly the core Very high solids removal efficiency Can be found with brushes and cups as well Used individually	

CLEANING OF FLOWLINES AND PIPES – PIGGING (Continued)

Courtesy of CEPS

EQUIPMENT / CONDITION	GUIDELINE	REMARKS
Fluid flushing	Velocity > 3 m/sec	Higher possible rate is recommended
Type of pig	Foam w/ρ < [2 – 3] lb/cuft	
Pig diameter	[0.5 – 0.3] x D_{Pipe}	Run with bypass open
Contingency	Backflow	Design must include ability to backflow

MODULE 13 - SUMMARY

Removal of solids from pipes, separators and flowlines is carried out using chemical and/or mechanical methods. Sand particles often settle in mixtures of minerals becoming solid “scale” attached to the vessel or pipe surfaces

- In horizontal separation vessels, sand washing using water jets is the common removal method used, efficient fluidization of the settled sand particles is critical
- Sand mobilisation devices based on high water rates are very effective in sand removal from separators, they can be permanently installed or used when and as required
- Removal of solids from pipelines commonly utilise individual or set of mechanical and fluid systems known as pigs
- These pigs are assembled as a “train” of fluid and mechanical devices

MODULE 13 – SUMMARY (Continued)

- Most production systems tend to have facilities for the use of pigs: injection points, launch manifolds and collection systems are common
- Successful removal of sand from vessels and flowlines required that a process of sampling, testing and characterization of the sand and solids be carried out
- Most plant designs include such a process and the resulting designs accommodate measures to deal with the expected solid’s production
- Very few plant designs include facilities, equipment and processes to deal with significant sand production.

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Annex Module

SAND DISPOSAL

CONTENT

- *Introduction*
- *Disposal methods*
- *Dumping*
- *Skip & Ship*
- *Re-injection*
- *Conversion*

INTRODUCTION

Sand disposal is the last stage in a sand management program

Environmental regulations require that prior to its disposal sand particles must be cleaned to remove any potential contaminants (mainly oil) that might have remained attached to the particles.

For instance, there are two particular requirements enforced today particularly for offshore environments, these are:

- Ensure that sand particles are free of LSA (Radioactive) minerals, scale
- Oil remaining in the sand particles does not exceed 1% by volume

DISPOSAL METHODS

There are four (4) common methods of disposing of produced sand, these are:

1. ***Dumping***(Offshore) the produced sand into the sea

2. ***Skip & Ship*** involves ”packing” and shipping the produced sand

3. ***Re-injection*** of the produced sand into suitable geological strata

4. ***Conversion*** of the produced sand into material that can be used for other applications

All have advantages and limitations, cost is a very important issue for all of them

DUMPING (Offshore)

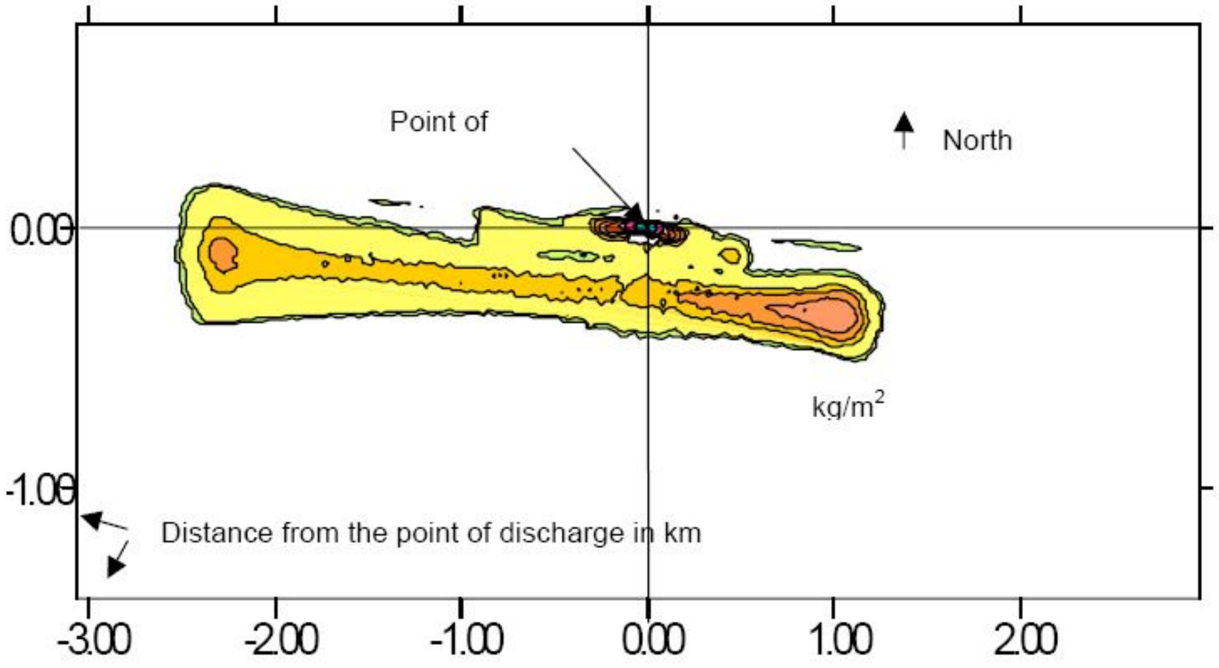
Dropping the produced and separated sand into the ocean or sea. As the sand grains fall into the sea the initial momentum depends upon the discharge rate or concentration. Initially, the relative buoyancy and/or the relative speed of the sand particles discharged will be responsible for the initial mixing and dilution. The behaviour of such a discharge is controlled by a series of parameters, the most important in this case being:

- Buoyancy
- Density of the fluid where particles are discharged
- Sand particle shape and density
- Distance from where the solids are discharged to the sea surface

Sand particles travel through at least three (3) zones: the splash zone, surface currents and the zone of deep currents.

DUMPING (Continued)

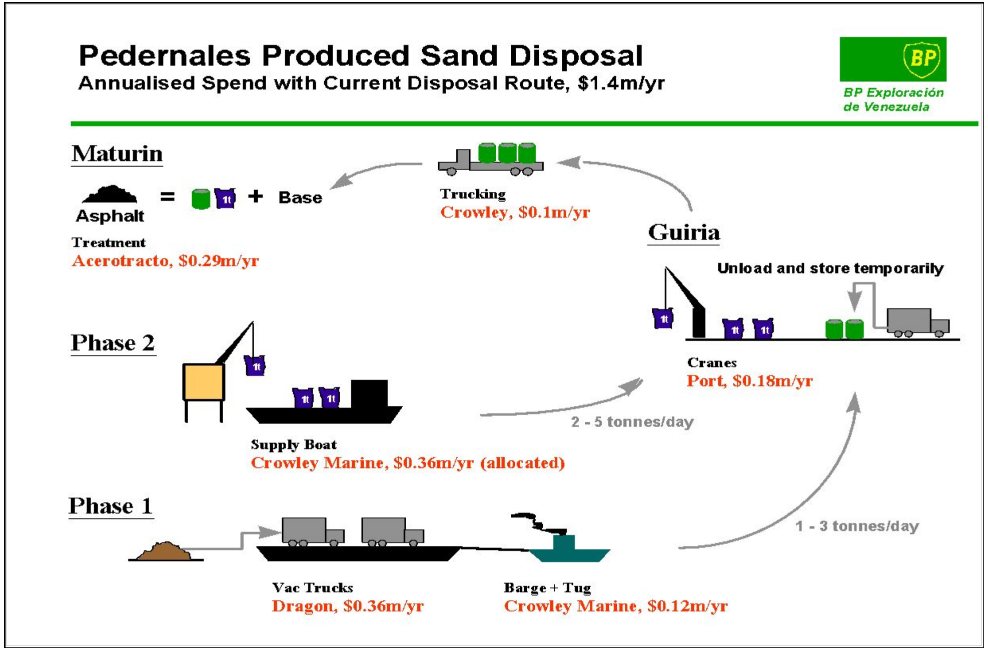
- Graph illustrates a solid's "plume" at the sea bed
- Particle shape and concentrations will vary according to the currents and point of discharge
- Example is from Block 47 in the SNS



SKIP & SHIP

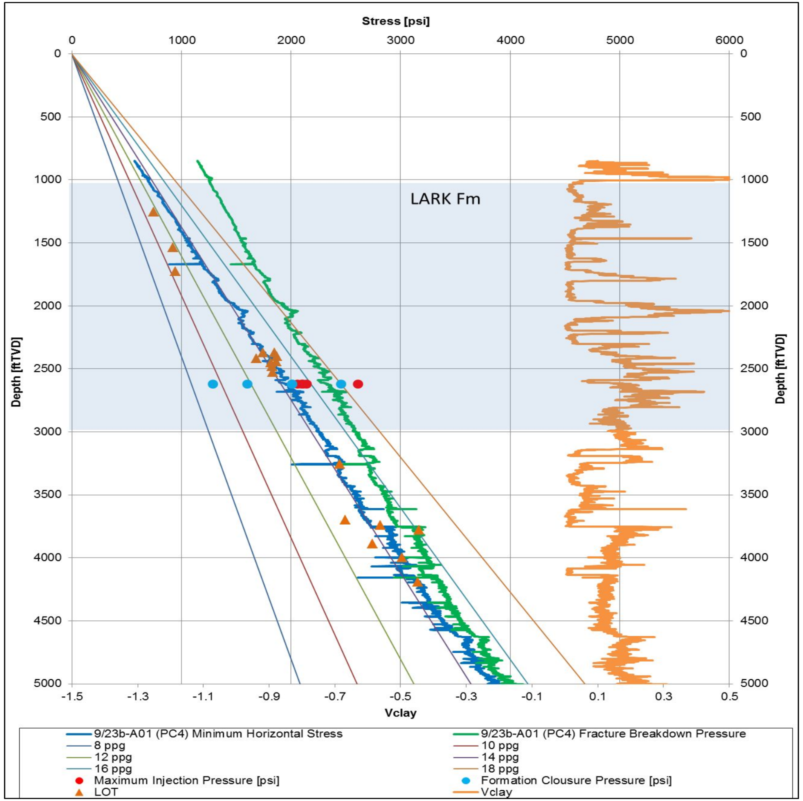
The Skip & Ship method involves the collection of the separated sand and "packaged" to be shipped to a processing location (Onshore, service company base…) where cleaning and further use will take place

- Example of process utilized by BP when it operated the Pedernales field in Eastern Venezuela.
- Field located in the Orinoco delta, swamp and shallow water depth
- Expensive and logistically complex disposal alternatives



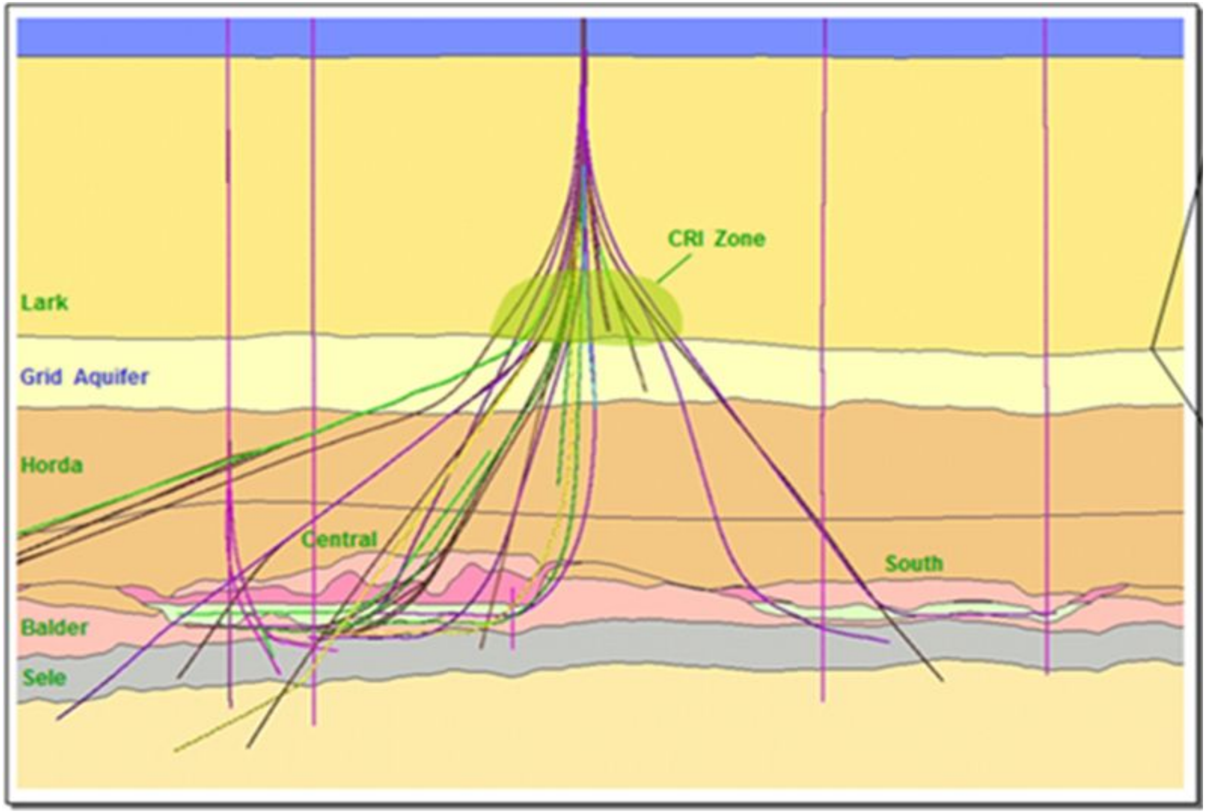
RE-INJECTION

- A suitable (Isolated, non-permeable) strata must be found
- Injection takes place using pressures above fracturing pressures
- Requires HP equipment/services on location a number of times a year
- A combination of cuttings, produced sand and sometimes slops are disposed off using this option
- Requires robust design & planning



RE-INJECTION (Continued)

- Lark formation in the Central North Sea in the UKCS
- CRI and produced sand is re-injected
- Process required carrier fluids for efficient transport
- Fracture propagation is required every time a new batch is injected



RE-INJECTION (Continued)

General guidelines focus on the selection of the geological strata, pressures and fluid's path for re-injection

CONSIDERATION	GUIDELINE	REMARKS
Type of rock	Non-porous	Porous/permeable rocks also suitable
Zonal isolation	Upper and lower barriers for zones to be fractured	Preferably shales or intervals with sufficient strength contrast
	Casing / cement / rock bond	Preferably higher density cement > 14 PPG.
	Minimise risk of contamination	Proximity becomes a critical issue to avoid possible contamination of other reservoirs/rocks
Injection path	Annular side preferred	Perforated casing also used
Injection pressures	Limited by casing rating for casing/casing option	Specific wells (disposal ones) are used
	Limited by fracture gradient for matrix injection	Can be affected by plugging

CONVERSION

Conversion of produced sand into materials or components for other applications included

- Road and building construction
- Filling material
- Filtration material

Process is complex and expensive, sometimes it is the last step in the skip & ship disposal option. Chemical cleaning and conditioning needs to be completed according to the local/country regulations

CONVERSION (Continued)

Conversion while ideal in terms of further use for the produced sand it has not been economically viable so far. Also

- Very large volumes of sand are produced and need to be stored
- It has a large environmental impact
- It can be used with the skip & ship method
- The cleaning of the produced sand requires high energy type of process

Source iStock

SUMMARY

Disposal of the produced sand in an environmentally and efficient manner is critical in any sand management program. Local, internal and/or government regulations must be met continuously

- The oil and gas industry utilises a number of disposal options
- These options tend to vary depending on the environment (Field/wells location), type of crude and local/regional regulations
- All options involve costly services and equipment that require complex logistics and planning
- Four (4) methods are currently utilized: dumping, re-injection, skip & ship and conversion

SUMMARY (Continued)

- Dumping is carried out mostly offshore and requires processing and cleaning of the produced sand prior to offloading the material overboard.
- Skip & Ship involves the collection and transporting of the produced sand to a facility where cleaning and preparation for further disposal can be carried out
- For re-injection the produced sand is converted into a slurry and pumped into a suitable geological strata. This requires the creation of hydraulic fractures
- Conversion of produced sand into a material that can be used for other applications such as road building and in the construction industry
- Sand disposal must comply with all the environmental and legal regulations of the area/company/country

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