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Parametric sensitivity studies of gravel packing

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Abstract

Several factors determine the success of Alpha-Beta gravel packing procedures in deviated wells. Among others gravel concentration, rheology of carrier fluid and injection rates could be mentioned.

Choosing incorrect values for these parameters may end up in an unsuccessful gravel pack that results in part of the sand screen section, or the complete section being exposed directly to sand production. This sand production could lead to various challenges both downhole and top side.

In this thesis, three well known gravel-packing models are reviewed. Using the models, several parametric sensitivity studies were carried out to learn the bed height deposition and settling velocity changes. The analysis is based on single and combined effects of parameters. The fluid systems selected are both Newtonian and near Newtonian fluid behaviors.

Table of content

1 Introduction

This thesis deals with review of gravel packing model and sensitivity analysis. The work analyses the gravel packing fluid and various parameters such as flow rate, gravel and fluid properties. In addition, the fluid rheology is considered in non-Newtonian assumption. For the simulation, three models were considered, namely Gruesbeck et al [1], Penberthy et al [2] and Oroskar & Turian [3]. During simulation the effect of single and combined effect on bed height deposition were analysed.

1.1 Background

Sand production is undesirable during production of hydrocarbon as it can cause many different problems both topside and downhole. Sand production is typically present in formations producing from younger tertiary reservoir such as sands of Miocene and Pliocene ages. These sands are usually weakly consolidated sands and very prone to sand production. As a general rule of thumb, older formations are more consolidated than younger formation. Also unconsolidated sand stone with permeability between 0,5 and 8 Darcies has proven to be very susceptible to sand production.

Due to several mechanism such as lack of enough cementing materials, and inter-granular friction formation sand becomes unconsolidated. Deep-water environments are typically unconsolidated formations. In unconsolidated formation, the fluid or gas flow during production remove the cementations material between grains and cause transport of fine particles to be produced along with the hydrocarbons.

These fines (fine particles) are likely to plug the pore throats at the near wellbore area. This results in decreased permeability of the formation that again leads to higher drawdown with reduced production as a result.

Fig. 1 illustrates a sand arch and loading at the gate of a perforation tunnel. When the loading exceeds the compressive strength of the arch, this leads sand arches unstable.

If the formation around the production well is destabilized, sand starts to flow along with the produced fluid/gas. This costs the industry a lot in terms of sand handling problems, loss of production zones or even the possibility of lost well control, due to eroded surface and/or downhole equipment.

Other causes of sand production are:

- ***Decline in reservoir pressure***, which may increase the overburden stress that is supported by the sand grains. This then could result in weakening the cementation of the sand grains in the reservoir and cause sand production.
- ***Increasing water production*** that dissolved and destroy the inter-granular cementing materials. This also decrease the capillary force that tend to retain the sand particles together.

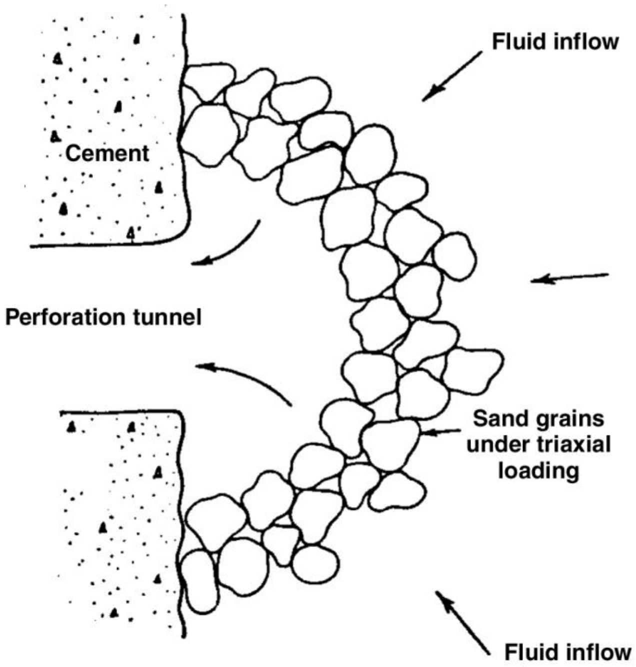


Figure 1 Geometry of stabile arch surrounding a perforation[4]

If these stresses exceed the formation-restraining forces, the sand will start to move and be produced along with the hydrocarbons. Rapid changes in flow rates and fluid properties can also result in increased sand production.

In order to control sand production, the method of Gravel packing has been used by the oil industry since the 1930's. It is currently the most widely employed sand control measure, accounting for more than 75% of the treatments worldwide.

The term gravel packing means when a slurry of accurately sized gravel in a carrier fluid is placed into the annular space between the sand screens (metal filters) and the open hole or perforated casing. The gravel is also entering the perforations in a cased hole scenario. As pumping continues clean carrier fluid leaks into the formation or through the sand screens and back to surface. The gravel that is placed outside the screens is acting like an additional filter, with very high permeability typically around 120 Darcies, which prevents formation sand from being produced. In this thesis only open hole gravel packing will be discussed.

Produced sand can cause many different problems;

- Damage to downhole equipment like casing and safety valves,
- Damage to topside equipment like chokes, valves, tubulars, separator etc.
- Reduced/lost production due to produced sand filling up wellbore

A successful gravel pack is preventing these problems and extending the lifetime of the well.

Due to the pressure regime during a gravel pack treatment, the reservoir completed must have a sufficient pressure difference between pore pressure and fracture gradient to allow for gravel pack treatment without fracturing the well. In this thesis, methods of reducing the total pressure increase during the gravel pack treatment will be discussed. In order to calculate the very critical alpha wave dune height different particle transfer models will also be presented.

1.2 Problem statement

Several authors have investigated the factors affecting gravel transportation and placement towards achieving an effective gravel pack and modeling the process. The models are derived most from several experimental measurements, which measures pack efficiency as a function of screen parameter, fluid and gravel properties, completion configuration (concentric/eccentric) and angle of inclination of the well bore. In this thesis we will look at issues such as

- How *different single parameters* influence the bed height during gravel packing?
- Which parameter is most sensitive for bed height deposition?
- What would be the *combined effects* of parameters on bed height?

The information obtained from this simulation may give advice for engineers during design phase of gravel packing.

1.3 Scope and objective

The scope and objective of this thesis is limited to the literature study and analysis of gravel packing models. The main activities are:

- ✓ Review rheology models
- ✓ Review three sand pack models
- ✓ Perform the impact of single and combined parametric sensitivity studies on gravel dune height and settling velocities

1.4 Structure of the thesis

Chapter 1. The first part gives a short introduction and background for this thesis.

Chapter 2. This second part consists of the literature study part of this thesis. In this section the reader is introduced to lower completion and an introduction to several different methods of lower completion is presented with main focus on gravel pack.

Chapter 3. This section presents theory related to gravel packing including rheology and settling velocity. Three mathematical gravel pack models are presented.

Chapter 4. This section presents the simulation work done related to this thesis. The results from the simulations are reviewed and analysed. The sensitivity to certain parameters for each model is then evaluated.

Chapter 5 presents summary and discussion of the simulation results

Chapter 6 presents main conclusions learnt from the overall analysis

2 Literature study

2.1 Well completion

The term completion is the process and activities of making a well ready for production. This process comes after drilling reservoir section. During completion, first the drilling equipment will be removed, and a production tubing is installed along with a production packer. The tubing hanger will then be installed in order to set tubing in wellhead or in Christmas tree.

Completion categorized into two parts, namely upper completion and lower completion. Figure 2 illustrate this. In this thesis, the process of lower completion and gravel packing will be studied.

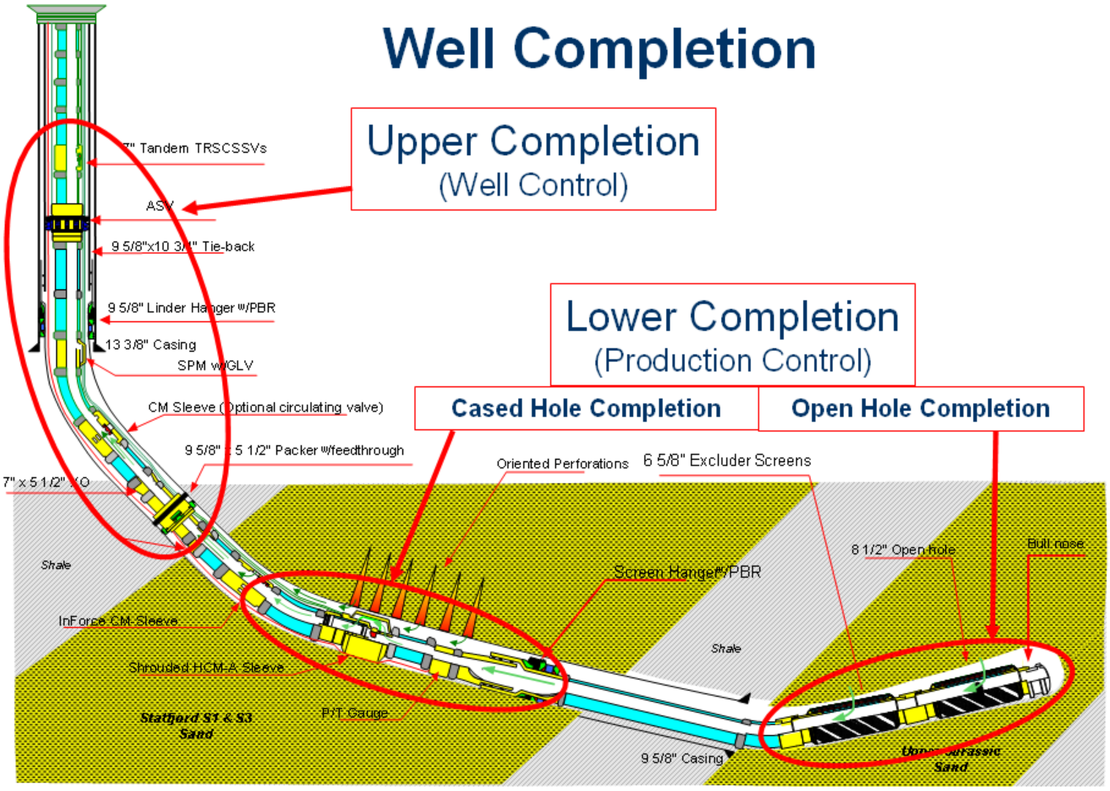


Figure 2 Typical well completion [5]

2.1.1 Upper completion

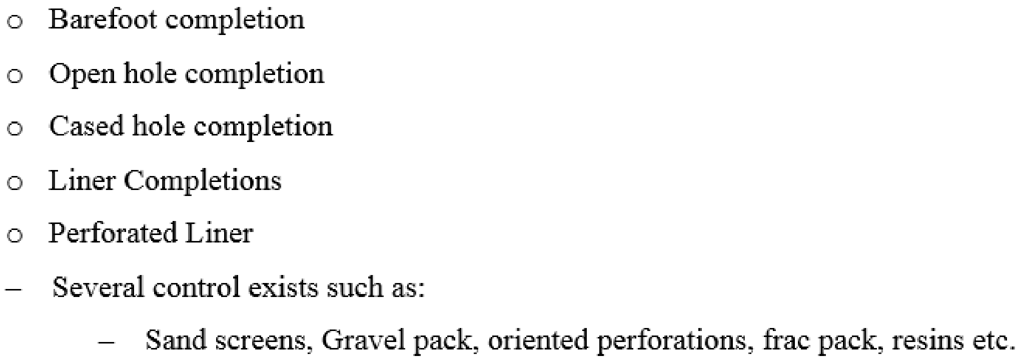
The upper completion controls the flow from reservoir to surface facilities, which is called well control. Figure 2 illustrates a typical upper completion design. The upper completion system includes facilities above the packer, which includes- among others:

- Wellhead, Christmas Tree, Tubing hanger , Production tubing, Downhole safety valve (DHSV), Annular safety valve, Side pocket mandrel, Electrical submersible pump, Sliding sleeve, Production packer,

Upper completion will not be discussed in this thesis.

2.1.2 Lower completion

The lower completion controls flow between reservoir and the well. This part of the completion controls the production. Lower completion is associated with the portion of the well across the production or injection zone. The lower completion is typically systems below the production packer. As illustrated on Figure 3, some of the lower completion methods are listed below.



- Barefoot completion
- Open hole completion
- Cased hole completion
- Liner Completions
- Perforated Liner
- Several control exists such as:
  - Sand screens, Gravel pack, oriented perforations, frac pack, resins etc.

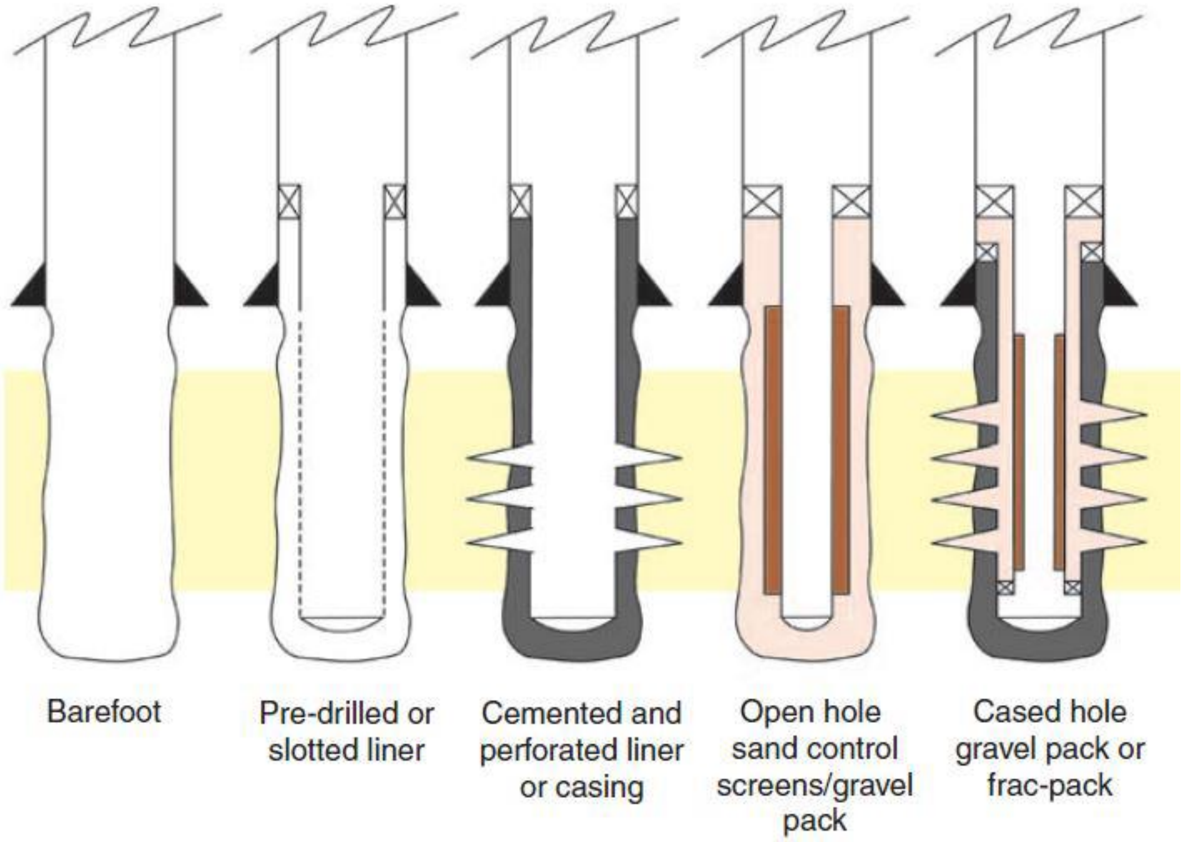


Figure 3 Lower completion methods [6]

The decision on which lower completion method to be used is based on the reservoir conditions and the budget of the well: open hole versus cased hole, sand control requirement and type of sand control, stimulation and single or multi-zone.

2.2 Norsok standards and regulations

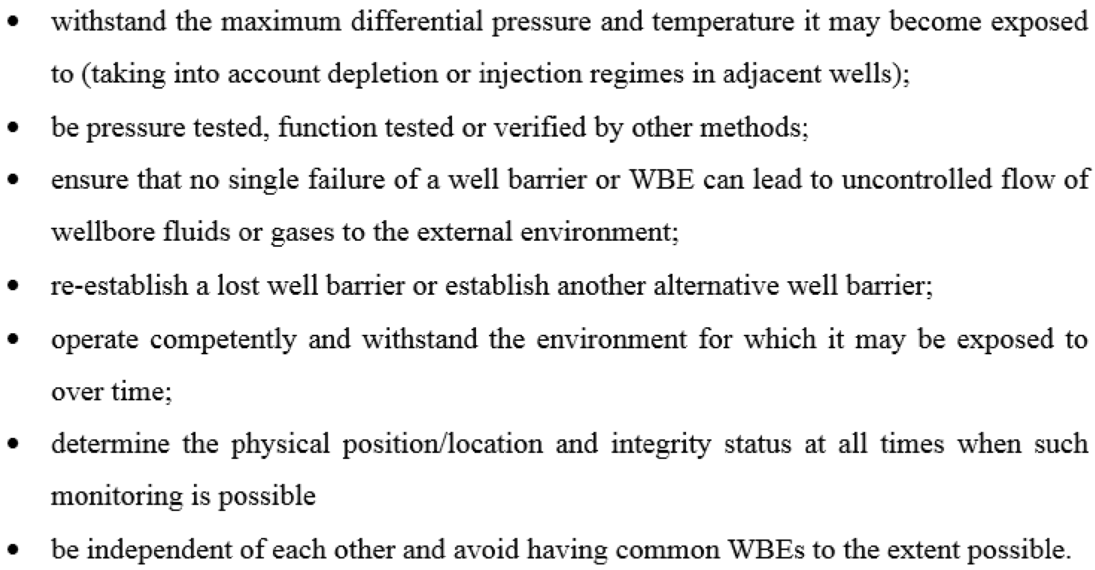
Well integrity

Well Integrity is defined in the standard Norsok D-010 as: “application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well”. Norsok D-010 defines the minimum functional and performance oriented requirements and guidelines for well design, planning and execution of safe well operations

Well barrier

Norsok D-010 is a functional standard and sets the minimum requirements for the equipment/solutions to be used in a well, but it leaves it up to the operating companies to choose the solutions that meet the requirements. All types of well operation during the life time of a well needs to be in appliance to this standard.

Following from this definition, the personnel planning the drilling and completion of wells will have to identify the solutions that give safe well life cycle designs that meet the minimum requirements of the standard. NORSOK D-010 specifies that: “There shall be two well barriers available during all well activities and operations, including suspended or abandoned wells, where a pressure differential exists that may cause uncontrolled outflow from the borehole/well to the external environment”. This sets the foundation for how to operate wells and keep the wells safe in all phases of the development. According to Norsok D-010 the well barriers shall be designed, selected and constructed with capability to:



- withstand the maximum differential pressure and temperature it may become exposed to (taking into account depletion or injection regimes in adjacent wells);
- be pressure tested, function tested or verified by other methods;
- ensure that no single failure of a well barrier or WBE can lead to uncontrolled flow of wellbore fluids or gases to the external environment;
- re-establish a lost well barrier or establish another alternative well barrier;
- operate competently and withstand the environment for which it may be exposed to over time;
- determine the physical position/location and integrity status at all times when such monitoring is possible
- be independent of each other and avoid having common WBEs to the extent possible.

All well barriers needs to be leak tested before

- They can be exposed to pressure differential.
- After replacement of pressure confining components of a well barrier element
- When there is a suspicion of a leak
- When an element will become exposed to different pressure/load higher than original well design values
- Periodically

Static leak test pressure shall be observed and recorded for minimum 10 min.

Acceptance leak rate shall be zero, unless specified.

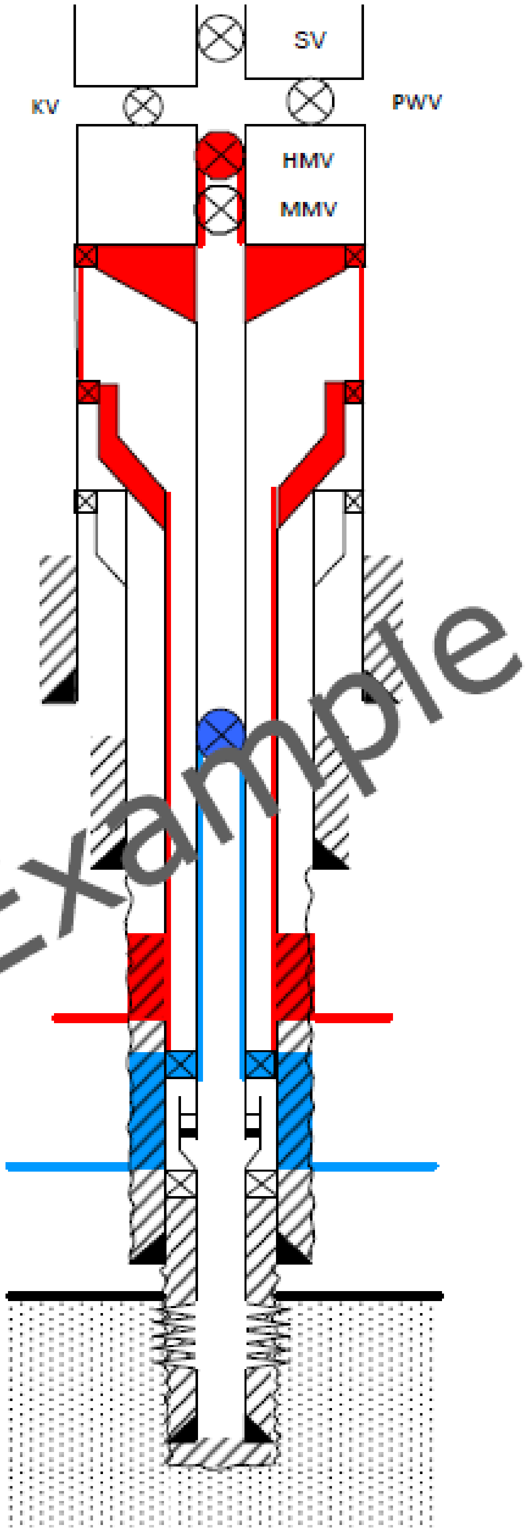


Figure 4 Well barrier illustration, primary and secondary well barriers [7]

2.3 Numerical gravel pack models

Several experimental and numerical modelling studies has been published on gravel packing in vertical, inclined and horizontal wells. In this thesis only three models were selected for the simulation to be presented in Chapter 4. This section only highlights some of research-documented papers related to gravel pack models.

Gruesbeck et al. [1] have experimentally investigated the influence of several parameters on the packing efficiency. These are the properties of gravel and fluid, screen and well inclinations. The investigators also developed a correlation equation to determine the height of equilibrium dune height during packing of an inclined well. Their investigation shows that the lower gravel concentration, lower gravel density, higher flow rate increases the packing efficiency. The authors recommended that the ratio of wash pipe diameter to the inside diameter of screen higher than 0.6 is good for efficient packing.

Elson, et al. [8] also conducted an experiment to determine an optimum gravel pack procedures for high angle wells. Their results indicated that carrier fluid with higher viscosity and high gravel concentration are good for gravel transport, but not suitable in high angle well such as 80 deg. They have also observed good transport and improved packing with lower carrier fluid viscosity and gravel concentrations. The authors verified the wash pipe design requirements proposed by Gruesbeck et al.

Peden et al [9] developed a mathematical models based on several experimental studies, which investigated the effect of parameters that affect packing efficiency.

The model used to predict an optimum combination of parameter required during design. These parameters are slurry flow rates, gravel concentration and tailpipe diameter

Shryock [10] performed experimental study on a full scale deviated well. The observation of the work was similar with earlier workers documented in literature. His investigates shows that water carrier fluids completely gravel pack well bore inclined at 60 deg .

Penberthy et al. [2] analyzed field treatment pressure data in order to evaluate the dynamics of gravel pack placement. The authors observed that the development of pressure as alpha wave propagation as the annular spacing reduction results in a higher-pressure loss.

Table 1 review and summarize various gravel pack models

#	MODEL	TYPE	**Features**
1	*Gruesbeck et al.*	0-D	0-Dimensional
			Empirical model
			Derived by dimensional analysis on laboratory experimental data
			Estimates equilibrium velocity and height of dune
			Does not determine location of bridge
			Mostly for deviated and vertical wellbores
			Does not account for settling effect
2	*Penden et al.*	0-D	0-Dimensional
			Empirical model
			Derived by dimensional analysis on laboratory experimental data
			Estimates equilibrium velocity and height of dune
			Determine packing efficiency of perforation and annulus of deviated wells
			Evaluates effects of perforation parameter, deviation angle and carrier fluid on perforation packing efficiency
			Does not determine location of bridge
			Mostly for deviated and vertical wellbores
			Does not account for settling effect
3	*Wahlmeier and Andrews*	Preudo 3-D	Pseudo 3 Dimensional
			Numerical simulator
			Solved conservation of mass, and momentum equations
			For vertical and deviated wells
			Suitable fof multiple zones, perforation intervals and fluid types
			Determine packing efficiency of perforation and annulus of deviated wells
			Does not account for settling effect
4	*Winterfeld and Schroeder*	2-D	2-Dimensional
			Uses empirical relationships
			For vertical, deviated and horizontal wellbores
			Allows for variable wellbore configuration
			Suitable for multiple fluids
			Determine packing efficiency of perforation and annulus
			Can determine location of bridge
			Does not account for settling effect
5	*Nguyen et al.*	3-D	3 Dimensional
			Numerical simulator
			Uses empirical relationships
			For vertical, deviated and horizontal wellbores
			Can determine location of bridge
			Determine packing efficiency in 3 dimensions
			Suitable for multiple fluids
			Does not account for settling effect

Table 1 Gravel pack models [11]

2.4 Sand control methods

There are several methods available in the industry today to control sand production. In general, sand control methods can be categorized as either mechanical or chemical.

The mechanical means hinders formation sand using down-hole filters such as liners, screens or gravel packs. The chemical method is using chemical injection such as resins in order to consolidating materials or resin coated gravel. This section presents the most commonly sand control methods used today.

2.4.1 Chemical means

Chemical control methods involve in injecting consolidating materials like resins into the formation to cement the sand grains while leaving pore spaces open. This process will increase the formation unconfined compressive strength (UCS).

Resin-coated gravel treatments can be pumped in two different ways. The first is a dry, partially catalyzed phenolic resin-coated gravel. Thin resin coating is about 5% of the total weight of the sand. When exposed to heat, the resin cures, resulting in a consolidated sand mass. The use of resin-coated gravel as a sand-control technique involves pumping the gravel into the well to completely fill the perforations and casing. The bottomhole temperature of the well, or injection of steam, causes the resin to complete the cure into a consolidated pack. After curing, the consolidated gravel-pack sand can be drilled out of the casing, leaving the resin-coated gravel in the perforations. The remaining consolidated gravel in the perforations acts as a permeable filter to prevent the production of formation sand.

Wet resins (epoxies or furans) can also be used. To pump these systems, the well is usually prepacked with gravel; then, the resin is pumped and catalyzed to harden the plastic. After curing, the consolidated plastic-sand mixture is drilled out of the well, leaving the resin-coated sand in the perforations.

Although simple in concept, using resin-coated gravel can be complex. First, and most important, a successful job in a cased hole scenario requires that all perforations must be completely filled with the resin-coated gravel, and the gravel must cure.

Complete filling of the perforations becomes increasingly difficult, as zone length and deviation from vertical increase. Second, the resin-coated gravel must cure with sufficient compressive strength. While resin-coated systems were used extensively after their development, their use today is limited. Experience with them has shown good initial success but poor longevity, as most wells do not produce sand-free for extended periods.

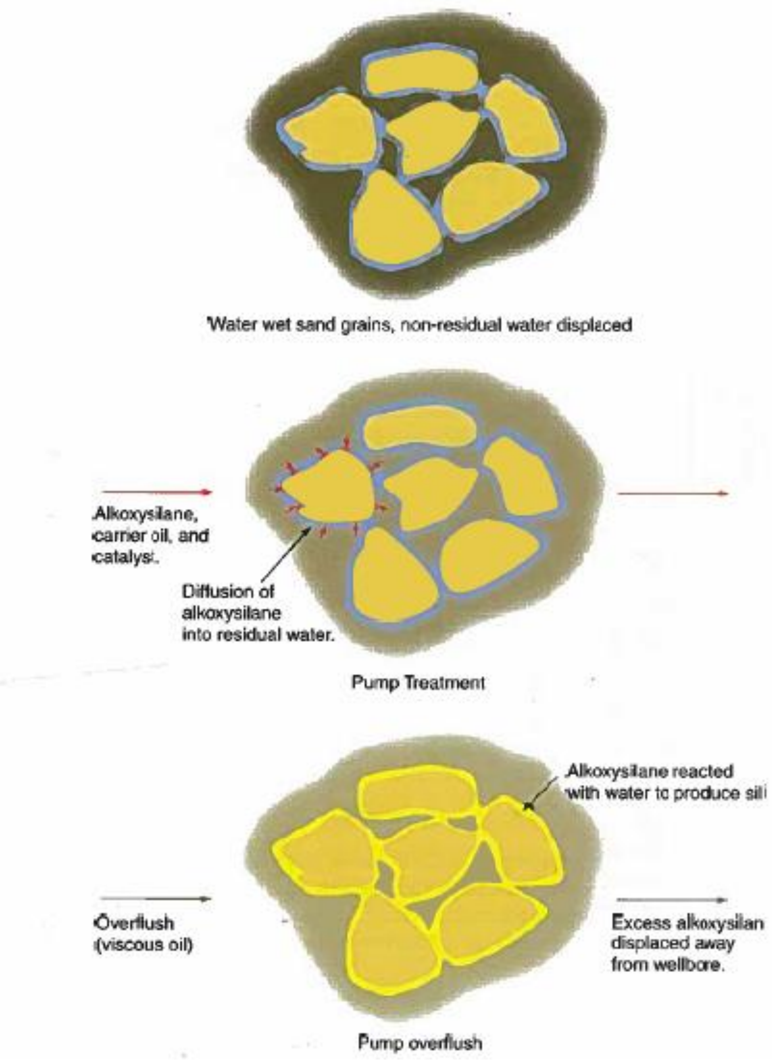


Figure 5 Illustration of the mechanism of chemical sand control [6]

Chemicals consolidate the formation sand near the wellbore using resinous material. If successful, the resin should not impair the permeability by more than 10% although considerable damage may result if the resin is incompatible with clays and mineral

Due to strict environmental regulations, the chemical consolidation method is not very commonly used in the North sea.

2.4.2 Mechanical methods

2.4.2.1 Slotted liners

Figure 6 illustrates different types of slotted liners. These are made of tubular with slot milled along the pipe. Slotted liners provides mechanical support to the borehole. As a result, this prevents wellbore from collapse. In terms of sand control, very fine particles can pass through the slots. This as a result allows unwanted sand production.

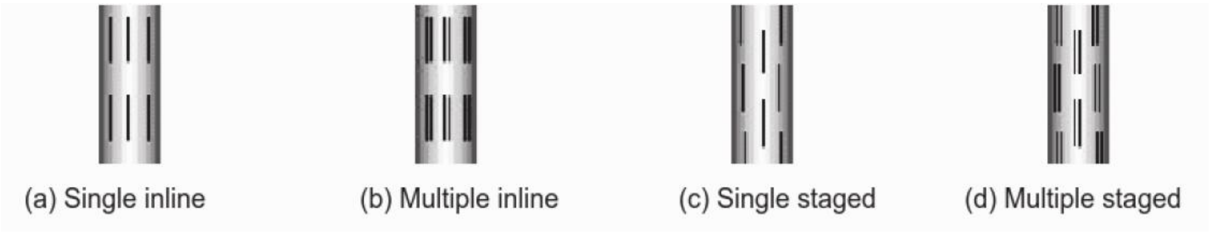


Figure 6 Types of slotted liners [5]

2.4.2.2 Sand screens

Screens are more efficient and reliable sand control in unconsolidated formations, which contain fine sand. This control mechanics is better than using slotted liners. There are three main screen types available and used in horizontal completions. These are wire wrap screens, meshed screens (premium) and expandable screens. In horizontal well, screen lies on the low side of the well. This is as a result makes open spaces on the topside and may leads to unstable/unsupported topside of the wellbore. For this problem, an expandable screen reduces/eliminates annular space as illustrated on Figure 7.

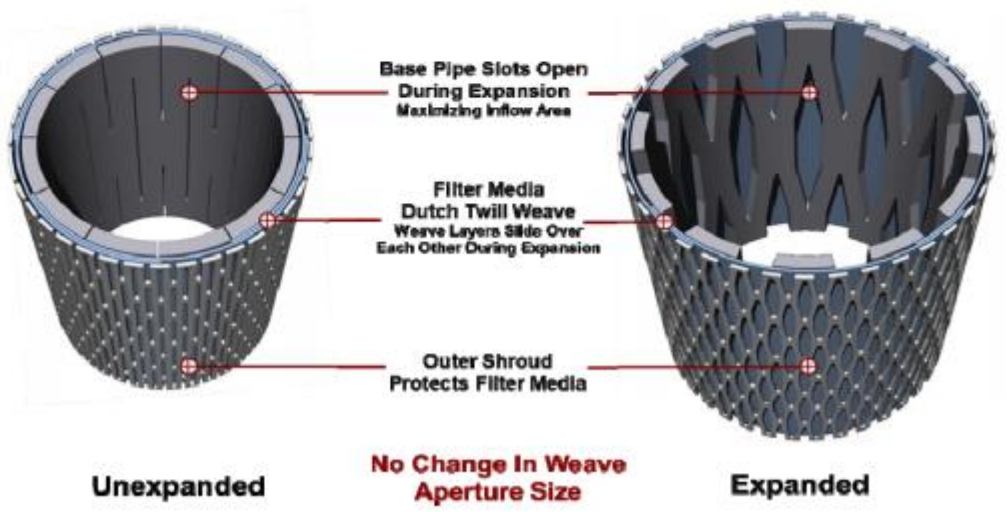


Figure 7 Expandable sand screens construction [12]

Wire wrapped screens

This screen consists of an outer jacket that is produced on a special wrapping machines. The shaped wire is wrapped and welded to longitudinal rods to form a single helical slot with any desired width. The jacket is then placed over and welded at each end to a base pipe containing drilled holes to provide structural support. This is a standard-commodity design manufactured by several companies.

Another method of producing the wire wrapped screen is direct wrap on pie screens. These screens are produced with a wire jacket shrink-wrapped directly to the basepipe. Screen components are welded to each other, but there is no welding between the screen and the basepipe, enabling the screen and basepipe to act as a single unit and ensuring that the tension, compression, and torque ratings of the screen are nearly the same as those of the basepipe. Basepipe perforations are designed to optimize flow while retaining strength. This type of screen is commonly used in long horizontal gravel packed wells in the north sea.

A schematic of the screen construction is shown in Fig. 8 Screen tolerances are typically plus 0.001 and minus 0.002 in.; hence, a specified 0.006-in. slot could vary in slot width from 0.004 to 0.007 in.

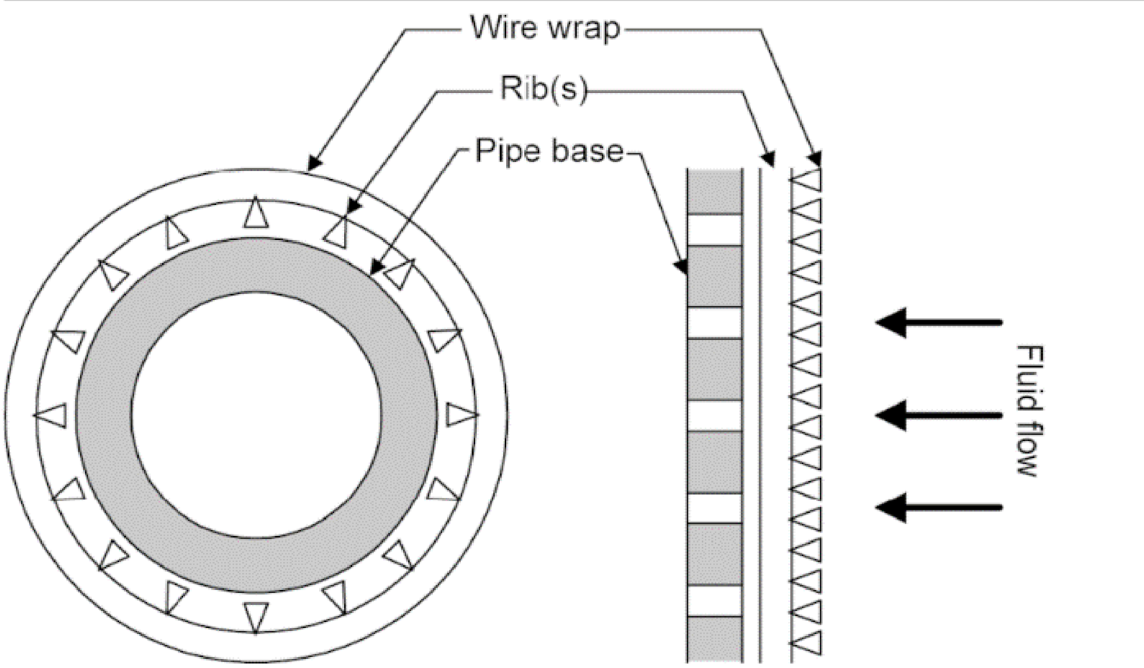


Figure 8 Wire wrapped screens [4]

Premium screens

Premium screens were originally developed for stand-alone installations in horizontal wells rather than a gravel-packed completion; however, this type of screen has been installed in several wells worldwide in combination with a grave pack. Proprietary designs are premium designs that surpass the performance of either a standard wire-wrapped screen or a prepacked screen in their ability to resist plugging and erosion and are equipped with torque-shouldered connections to permit rotation.

These screens have a single layer or multiple layers of woven wire mesh, sometimes sintered, forming a resilient filter and providing weld integrity and mechanical stability. Mesh screens maintain their strength during installation without altering the filter pore openings. With drainage layers, and an optimized design of basepipe perforations, these screens evenly distribute flow across the full area of mesh and reduce the risk of plugging at the screen face.

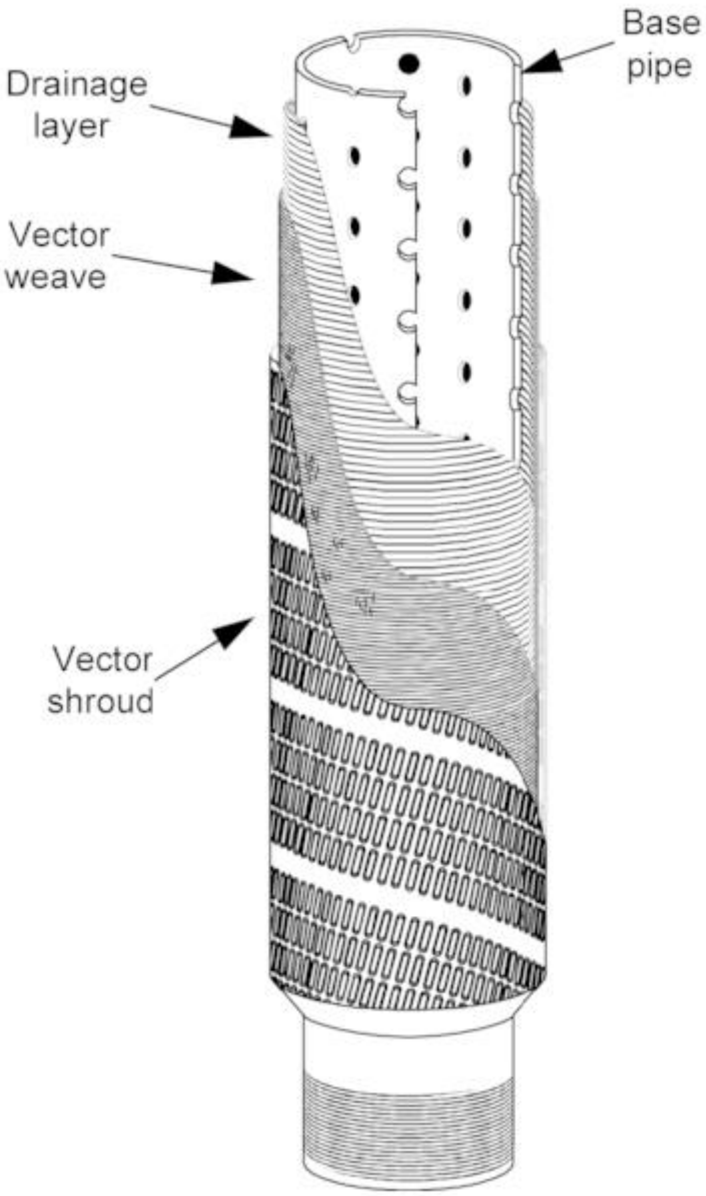


Figure 9 Premium screen [4]

These type of screens have increased inflow areas to as much as 30% of the surface area of the screens which is significantly more than wire wrapped screens. The materials used and the designs differ from conventional wire-wrapped screens. They consist of various designs like:

- Lattice
- Dutch weave
- Porous membrane
- Sintered metal
- Corrugated weave

Commonly used weave pattern are

- Plain square (fig 10, A)
- Plain Dutch (fig 10, B)
- Twilled squared (fig 10, C)
- Twilled Dutch (fig 10, D)

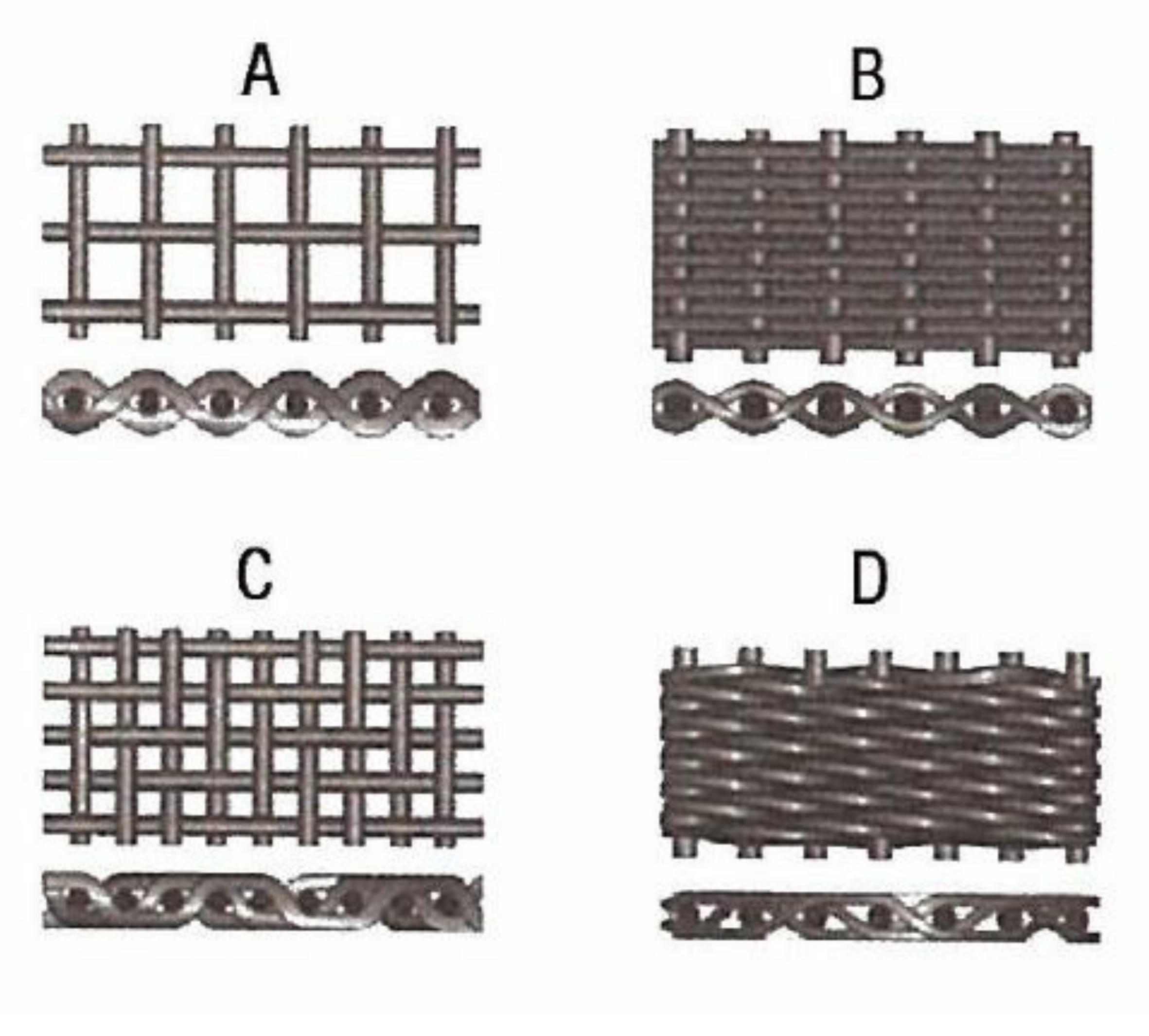


Figure 10 Weave patterns for premium screens [5]

The logic used in these designs was that they were better than wire wrap screens because these screens have inflow areas of about 30% compared to about 5% to 10 % with wire wrapped screens. Most of these screens have an outer shroud to protect the screen during installation. Premium connections are typically used for horizontal service because of their high strength and the ability to rotate if necessary.

Alternate path screens

The classical problem in gravel packing occurs when premature sand bridges form in the annulus between the sand retainer screen and the casing wall, for a cased hole gravel pack, or the formation, for an open-hole gravel pack. The bridges usually form either at the top of the screen or adjacent to zones of higher permeability. Once a bridge forms, slurry flow past that point ceases, leaving an incomplete pack below the bridge.

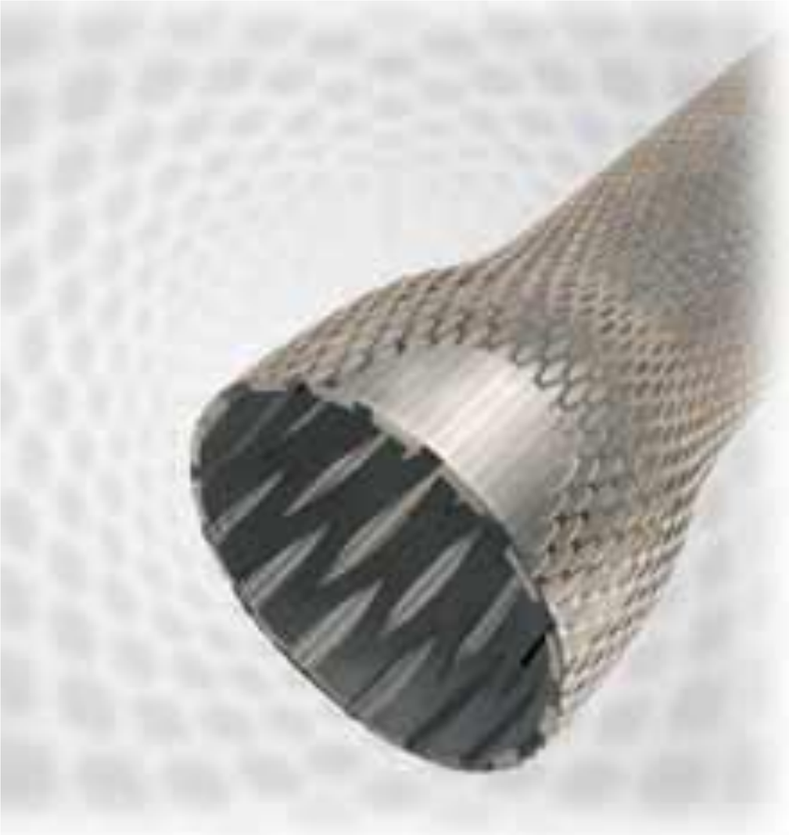


Figure 11 Expandable screens [13]

Many mechanical variations for gravel packing apparatus have been developed or proposed for avoiding sand bridging, and a large body of literature exists reporting studies of the effects of gravel packing variables such as fluid rheology, pumping rates, sand density and concentration, etc. However, major problems still exist, especially where long intervals and/or highly deviated wells are involved.

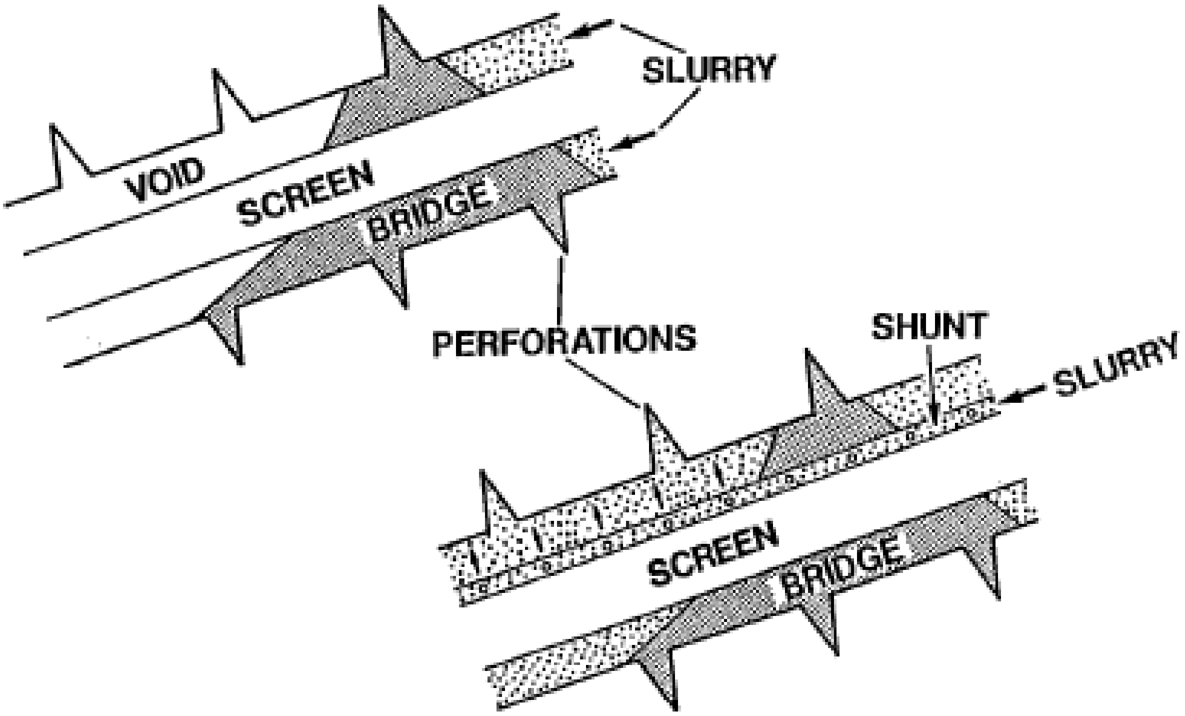


Figure 12 Gravel pack with alternate path technology [16]

A way to solve this issue is to use alternate path gravel packing which can eliminate bridging problems. In this system, there is an additional alternate path for slurry flow adjacent to the screen. This path could either be inside or outside the screen, although the mechanical assembly is much simpler if the alternate paths are placed in the annulus. The alternate paths consist of small separate tubes or pipes attached to the screen and perforated with small holes every few feet (shunts). Slurry can perforate through small holes every few feet and overcome a potential bridge between the screens and the open hole. This system also accepts high losses during the gravel pack operation which also could be a big challenge when running a standard setup. Some of these systems requires a viscous carrier fluid for the gravel pack.

2.4.2.3 Gravel pack

A gravel pack acts as a downhole filter used to prevent unwanted formation sand production. This can be achieved by properly designed gravel pack and proper size screen. The gravel is placed in the annulus between the sand screens and the open hole or casing in order to prevent sand production.

Compared with standalone screen gravel is more reliable both in controlling sand production and it gives a better borehole stability.

As illustrated on Figure 14, gravel is a sand or ceramic proppant, which is placed around a screen or inside a fracture in order to prevent sand production.

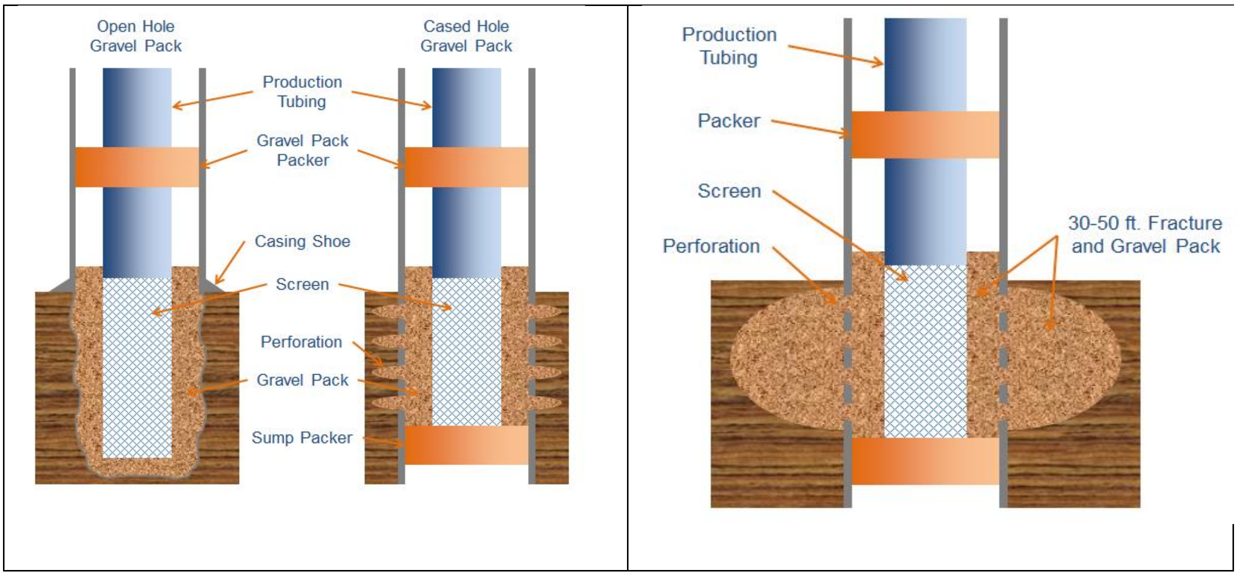


Figure 13 Open hole and cased hole gravel pack.

There are two types of gravel packing

- Open hole gravel packing where the sand is placed between the sand screens and the formation/open hole.
- Cased hole gravel packing where the sand is placed between the sand screens and the casing.

2.4.3 Various techniques

2.4.3.1 Maintenance and workover

Maintenance and workover is a passive approach to sand control. This method basically involves tolerating the sand production and dealing with its effects, if and when necessary. Such an approach requires bailing, washing, and cleaning of surface facilities routinely to maintain well productivity. It can be successful in specific formations and operating environments. Due to the high cost of well operations in the north sea this method is not very common in Norway.

The maintenance and workover method is primarily used where there is:

- Minimal sand production
- Low production rate
- Economically viable well service

2.4.3.2. Rate restriction

Restricting the well’s flow rate to a level that reduces sand production is a method used occasionally. The point of the procedure is to sequentially reduce or increase the flow rate until an acceptable value of sand production is achieved. The object of this technique is to attempt to establish the maximum sand-free flow rate. It is a trial-and-error method that may have to be repeated as the reservoir pressure, flow rate, and water cut change. The problem with rate restriction is that the maximum flow rate required to establish and maintain sand free production is generally less than the flow potential of the well. Compared to the maximum rate, this may represent a significant loss in productivity and revenue.

2.5 Gravel pack

2.5.1 Open hole gravel pack

Gravel packing is a commonly applied technique to control formation sand production from open-hole oil and gas wells. In a gravel pack completion, a screen is placed in the well across the productive interval and specially sized, high permeability gravel pack sand is mixed in a carrier fluid and circulated into the well to fill the annular space between the screen and the formation. The size of the gravel pack sand is selected to prevent formation sand invasion and the size of the screen openings are selected to retain the gravel pack sand. A complete gravel pack in the open-hole/screen annulus creates a very stable, long lasting downhole environment where only well fluids (not formation sand) are produced. Gravel packing has been successfully applied in conventional wells for several decades, and increasingly, the technique is being applied in extended-reach open-hole horizontal wells.

Horizontal gravel packing is process intensive and requires special attention to drill-in fluid selection, well displacement and service tool operation to ensure successful gravel placement and well productivity. Specialized downhole tools facilitate circulation of the gravel pack sand in place. The tools create a circulating path for the gravel slurry down the workstring, out into the annulus below a packer and down the annulus outside the screen. The screen retains the gravel and the carrier fluid flows into the screen, up the washpipe, out in the annulus above the packer and back to surface.

The washpipe extending down inside the screen directs the point of fluid returns to the end of the screen. As well deviation increases, large washpipe becomes a critical factor in achieving complete gravel fill around the outside of the screen. Test data and field experience show that the washpipe OD to screen ID ratio needs to be approximately 0.8. The large OD washpipe restricts the amount of carrier fluid that diverts into and flows down the screen/washpipe annulus.

The gravel is round natural or synthetic material that is small enough to exclude formation grains and particles from production, but large enough to be held in place by screens.

Gravel packs are operationally challenging to install, however, when successfully installed, they prevent the formation from collapsing.

Skin effects is a challenge for gravel packs (both open hole and cased hole). This dimensionless factor is calculated to determine the efficiency of the production by comparing the actual conditions with the theoretical conditions. A positive skin value means that it exist some kind of effect that is impairing the well productivity, while a negative value means enhanced productivity. Placement of gravel-packs can lead to high positive skin values in a well. This is often due polymer based carrier fluid invading the formation or insufficient cleanup of wellbore prior to gravel palcement, which may lead to a detrimental pressure drop between the formation and the well. Open hole gravel packs can be subdivided into two main forms: circulating packs and alternate path (shunt tubes). Both can be used with wire wrapped screens and mesh (premium) screens. Figure 14 shows a schematic of an openhole gravel pack

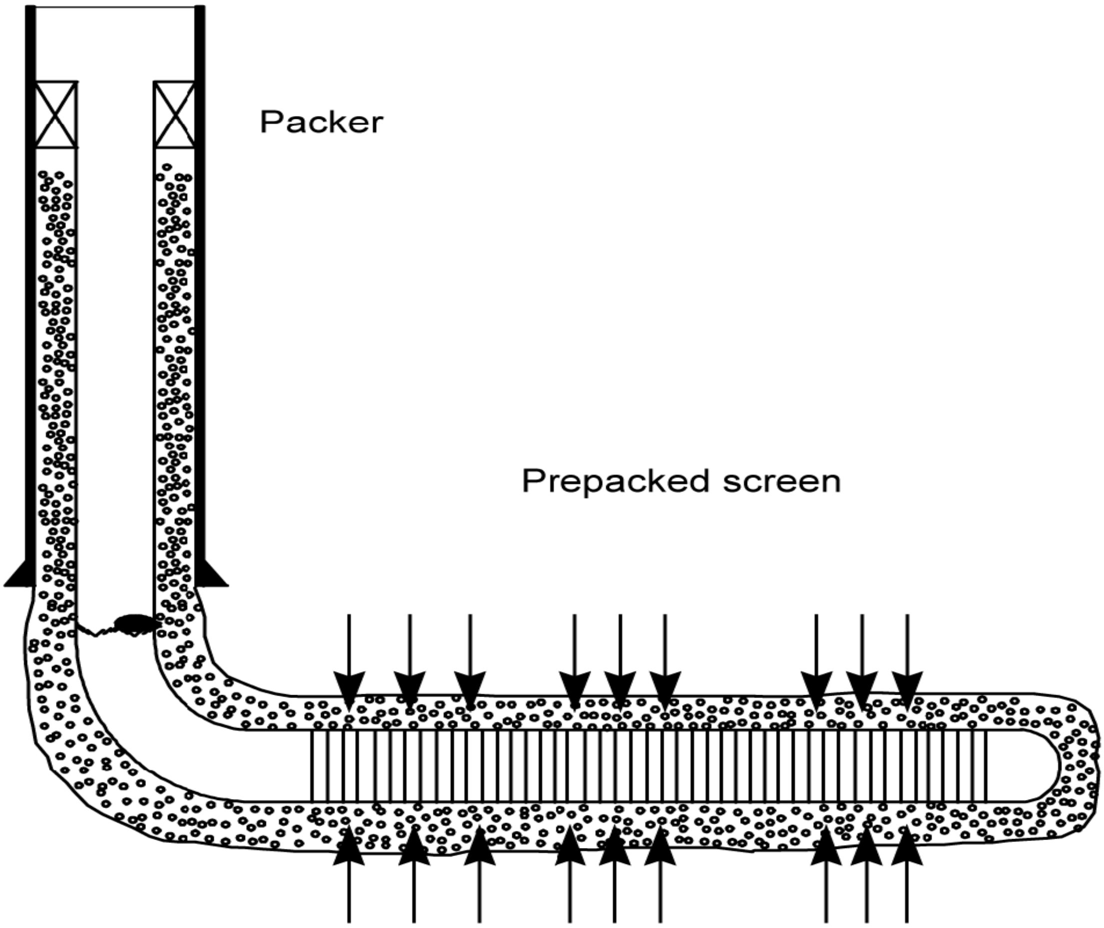


Figure 14 Open hole gravel pack with pre packed screens [4]

2.5.2 Cased hole gravel pack

Cased hole gravel pack use similar techniques to open hole gravel packing. This includes using similar tools, similar rates and they have the same desire to be able to squeeze and circulate.

In cased hole gravel packs it is desired to be able to squeeze and circulate. If pure circulation is done, it will lead to the perforations not being packed. To achieve squeezing, the BOP is closed to restrict the return flow. However, circulation will assist in getting the gravel to the toe of the interval for long intervals. Further, pre-packing the perforations prior to running the screens can aid in the placing of gravel into the perforations. Tubing conveyed guns in the hole can be used for pre-packing.

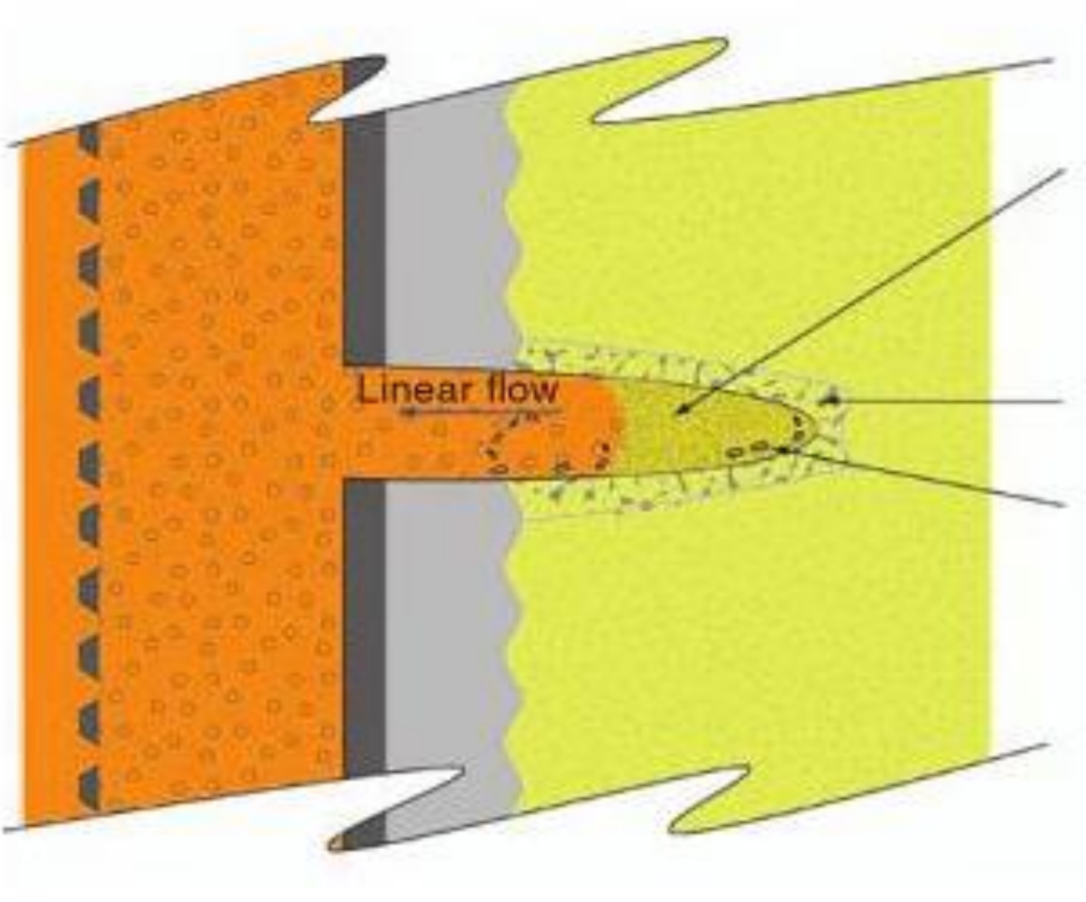


Figure 15 Invasion of gravel into an open perforation [6]

2.6. Gravel packing procedures

2.6.1 Gravel pack assembly

Gravel packing is being performed with a gravel pack assembly typically consisting of, from top to bottom;

- X-over from drill pipe to gravel pack assembly
    - In order to connect the gravel pack assembly with the drill pipe a converter with the correct size and treads is utilized.
- Retrievable lower completion packer/screen hanger
    - A hanger that supports the weight of the sand screens. This item remains in the well after the gravel pack operation is completed.
- Gravel pack port
    - A sliding sleeve that covers the port where the gravel exits the tool during the gravel pack operation. This port is RIH on a closed position and is shifted open when the gravel pack assembly is prepared to gravel pack prior to the gravel is being pumped.
- Formation isolation valve
    - This valve isolates the formation after the gravel is placed around the sand screens. This prevents losses and it is qualified as a well barrier according to NORSOK D-10. Prior to production start this valve is shifted open hydraulically (remotely) or with a mechanical shifting tool.
- Sand Screens
    - Acts as a filter for the produced hydrocarbons. It also supports and holds the gravel in place between the screens and the wellbore.

- Float collar

Inside the gravel pack assembly there is a service tool that is being manipulated during the gravel pack operation. The service tool is connected to the washpipe and at the end of the washpipe there are shifters for the sliding sleeve and the Formation isolation valve.

The open hole gravel pack tool usually has 3 to 4 positions

1. Run in hole position; with possibility to pump down washpipe through float to overcome difficult areas in the open hole section.
2. Gravel pack position; where slurry is being pumped down drillpipe through gravel pack port. Returns are taken through washpipe and up annulus between drillpipe and casing.
3. Reverse position; clean fluid is being pumped down annulus through a port in the service tool located just above the packer into the drillpipe and up to surface. This is being done after screen out to displace the slurry in the drillpipe. It is critical to get the gravel out of the drillpipe before it starts to settle and starts filling up the drillpipe.
4. Post treatment position; this position is optional if there is a need for a filter cake removal operation after the gravel has been placed. The position is being activated after slurry is reversed out and service tool is being recovered to surface. The position makes it possible to pump filter cake dissolver down drillpipe through washpipe and into the formation while POOH.

2.6.2 Operational steps

Typical operational steps in a horizontal open hole gravel pack operation:

- Drill open hole section
- Clean the well and displace well to clean brine
- Run Screens to TD
- Drop ball and set packer hydraulically
- Release service tool from packer
- Test packer hydraulically and/or mechanically
- Find and mark positions on the drillpipe
- Rate test with clean carrier fluid in reverse and gravel pack position
- Start adding gravel to the carrier fluid and pump slurry until screen out
- Pick up tool to reverse position and reverse out the gravel in the drillpipe
- Convert tool to post treatment position
- POOH while pumping filter cake dissolver until end of washpipe is pulled through screen section
- Recover service tool to surface.

2.6.3 Circulation packs

This method is widely used - especially in areas such as offshore Norway and Brazil. Figure 16 shows a typical sequence for a horizontal well.

There exist many variations of this sequence, although with a common fundamental requirement; a hydraulically isolated formation, which means that the filter cake must remain intact during the gravel packing. If this requirement is not present, the gravel pack fluid will be dehydrated by the losses causing the alpha wave to stall. This creates a sand bridge between the formation and screen, thus preventing gravel from packing downstream of the bridge.

Water-based muds is preferred when using circulating packs. However, in some cases, oil based mud has to be used to overcome challenges in the well. Alternate path pack may be more suited in these environments as these are more capable of dealing with severe hole stability and losses. The main argument for switching to alternate path pack, which is more complex, is the requirement to avoid losses when using circulating packs.

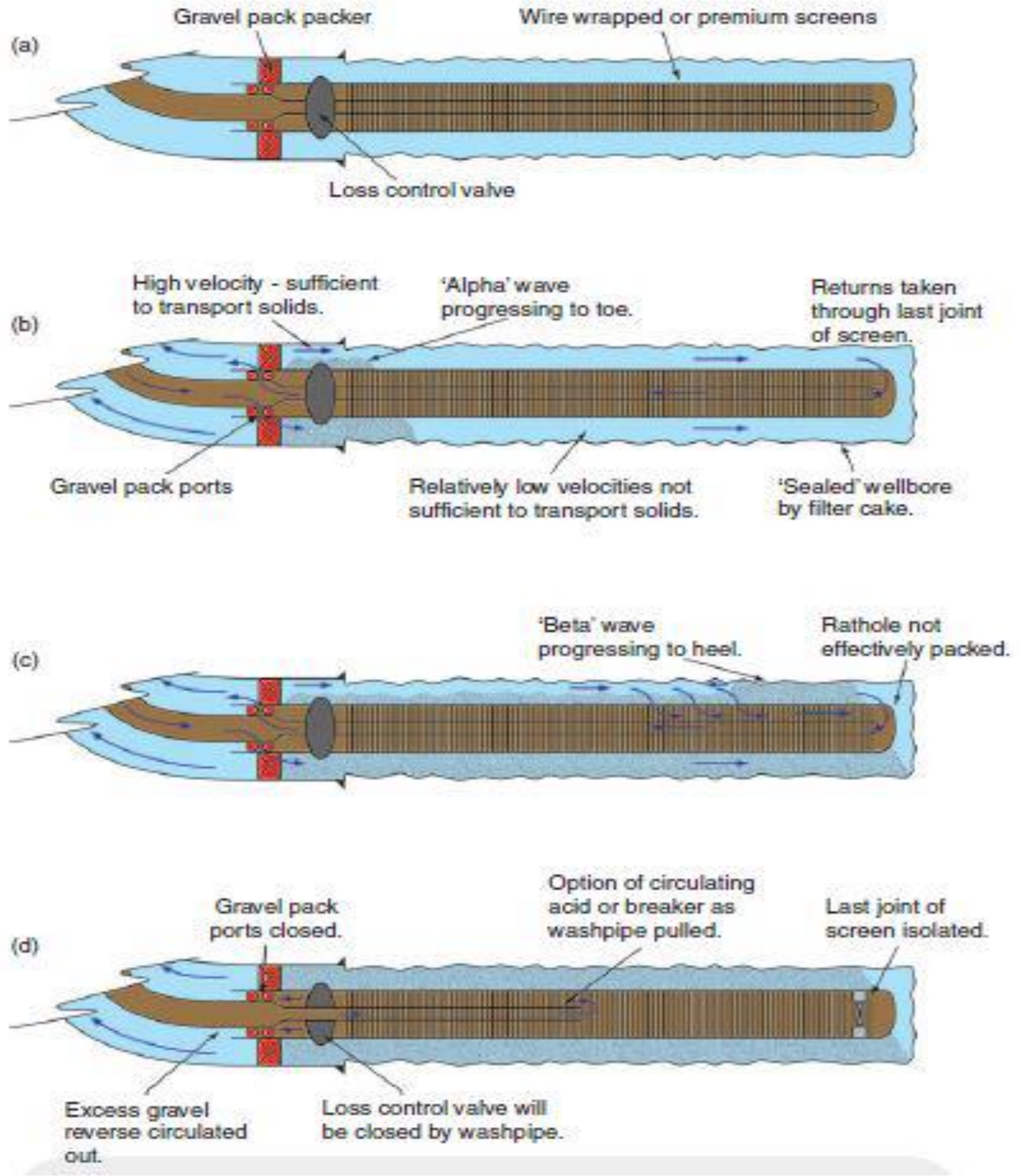


Figure 16 Typical sequence of a circulation pack in a horizontal well [6]

2.7 Pressure behavior during gravel placement

During Alpha wave the pump pressure is slightly increasing due to the additional frictional pressure when the flow area becomes smaller over the dune. When the alpha wave dune reaches the bottom of the well the Beta wave, which is the back filling process, starts. From now on until screen out there is an increase in pump pressure due to the additional frictional pressure the fluid experiences between the washpipe and the inside of the screen. This additional pressure affects the ECD and it could potentially cause the well being fractured if the bottom hole pressure exceeds the fracture pressure.

During Alpha wave build up the pump rate should be high enough such that the Alpha wave dune height does not exceed the maximum height of the open hole. Several key parameters will affect the wave height; including wellbore geometry, bottom hole effective gravel concentration, fluid divergence to the screen/washpipe annulus and fluid leak off to the formation.

During Beta wave, the pump rate is limited to the fracture pressure; the ECD should not exceed the fracture pressure during the operation. These two top and bottom limit flow rates defines the safe operational window. Inside this safe operational window a pump rate will create an alpha wave dune height within the designed maximum height and at the same time this pump rate maintains a bottomhole pressure within the limit not to fracture the well.

This operational window may not exist if the horizontal section is very long or/and the reservoir fracture gradient is low. In these types of situations other measures needs to be taken at the same time to reduce the bottom hole pressure. Such methods could be:

- Using multiple beta wave rates
- Include a differential valve on the washpipe
- Use lightweight gravel instead of regular gravel.

When the alpha wave reaches the bottom of the well bore, the beta wave is initiated. This is also identified on the plot by an increase in pressure-time slope.

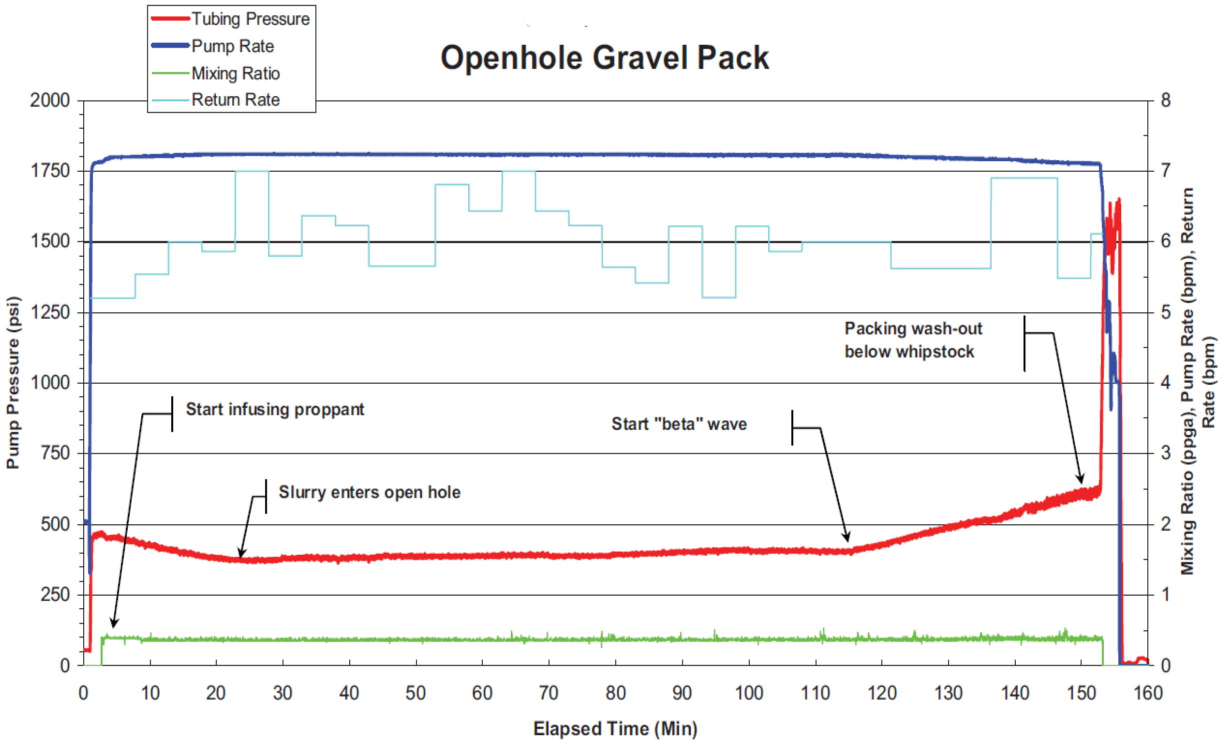


Figure 17 A typical pressure chart from a horizontal gravel pack treatment [17]

2.7.1 Bottomhole effective gravel concentration

The surface gravel concentration is common to use when designing a gravel pack pumping operation. The bottom hole effective gravel concentration can increase significantly due to the effect of fluid leak off to the formation and the divergence of flow to screen washpipe annulus. During the Alpha Beta wave build up and propagation process the gravel will settle and the fluid will flow along the path of least resistance. The diverged fluids results in less fluid to carry the gravel, thus a much higher bottom hole effective gravel concentration compared to the initial surface gravel concentration. The higher gravel concentration downhole forces to build up a higher Alpha wave dune than the estimation done prior to the job with surface gravel concentration. A chain of events will follow the under estimated Alpha wave dune height;

- Smaller open flow path above the dune with greater possibilities of a premature bridge build up an uncompleted pack.

- The bottom hole pressure will be higher due to the smaller flow area on top of dune. Which transforms to higher pressure difference between wellbore and reservoir that could lead to an undesired fracture.

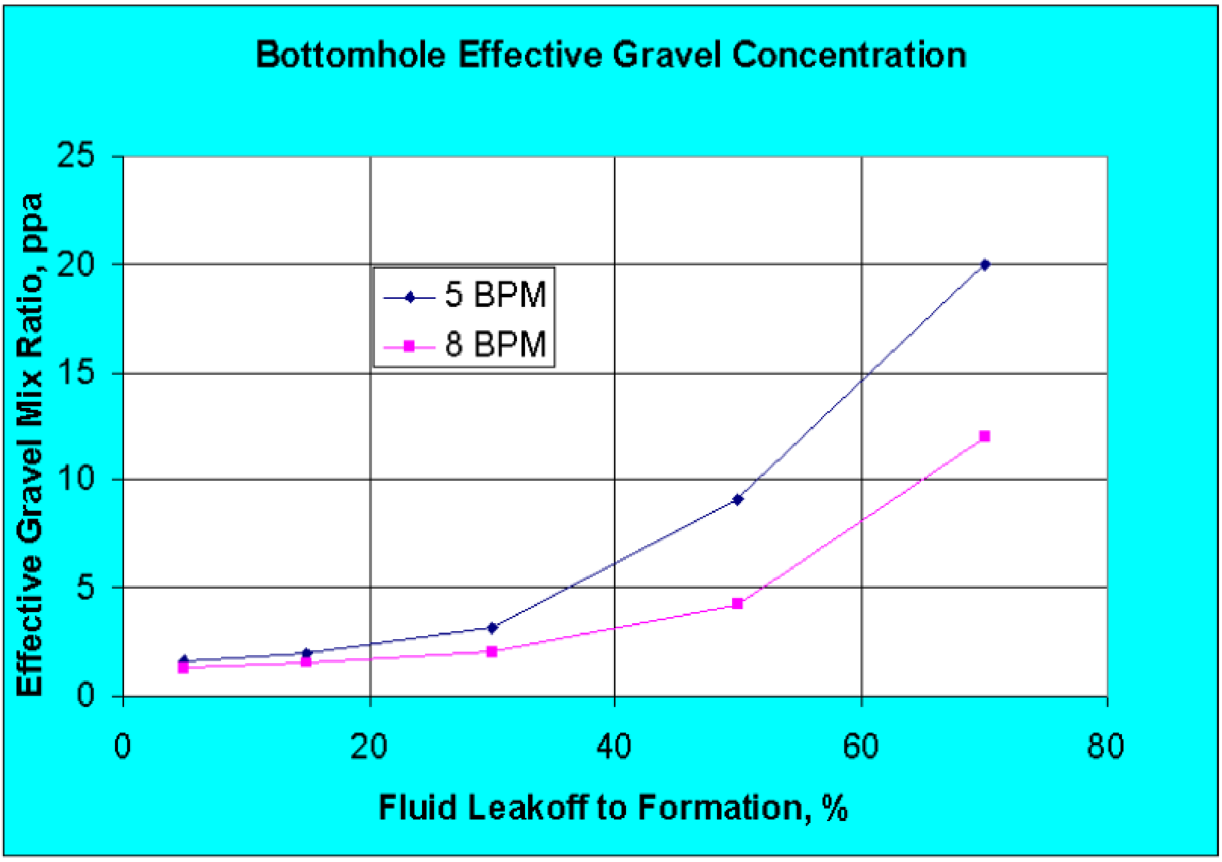


Figure 18 Bottomhole effective gravel concentration vs. leak off [18]

2.7.2 Methods to cope with extensive downhole pressure during gravel pack

2.7.2.1 Multiple beta rates

Based on testing this method is not recommended in common practice but is to be used as a last option. For cases where the fracture gradient is so low that for any acceptable minimum alpha wave pump rates the well would still be fractured during Beta wave.

In this case decreasing the pump rate during the beta wave packing may be the only option. During the execution of the operation, the bottomhole pressure should be monitored carefully. Whenever the bottomhole pressure approaches the fracture pressure, the pump rate is reduced by a minimum controllable rate to lower the bottomhole pressure. This procedure is repeated as many times as necessary until the pack is completed. Every new rate will force a rebuild of a higher alpha wave on top of the previous alpha wave.

2.7.2.2 Light weight gravel

This gravel is a proppant with a much lighter density than conventional gravel. The density of this kind of proppant ranges from 1.25 SG to 2.0 SG. Conventional grave has a density of 2.5 SG to 3.00 SG. When using this kind of gravel for gravel packing a much lower Alpha dune height can be achieved at the same pump rate, or a much lower pump rate is required for the same Alpha wave dune height. At certain pump rates we may have only a Beta wave packing process. Smaller pump rates will lower the ECD and then reduce the risk of fracturing the formation. By increasing the gravel concentration on a job the pumping time will be shorter and the cost of the operation will then be reduced.

2.7.2.3 Differential valve on wash pipe

This mechanical device provides a short cut to the fluid during beta packing. The valve is placed on a certain place on the washpipe and is designed to open after the beta wave has passed that certain point in the wellbore. The force to open the valve is the pressure differential between the inside of the washpipe and the screen washpipe annulus. A number of valves can be placed on the washpipe and they should be designed in a way that the bottom one opens first and the valve closest to the heel of the well opens last.

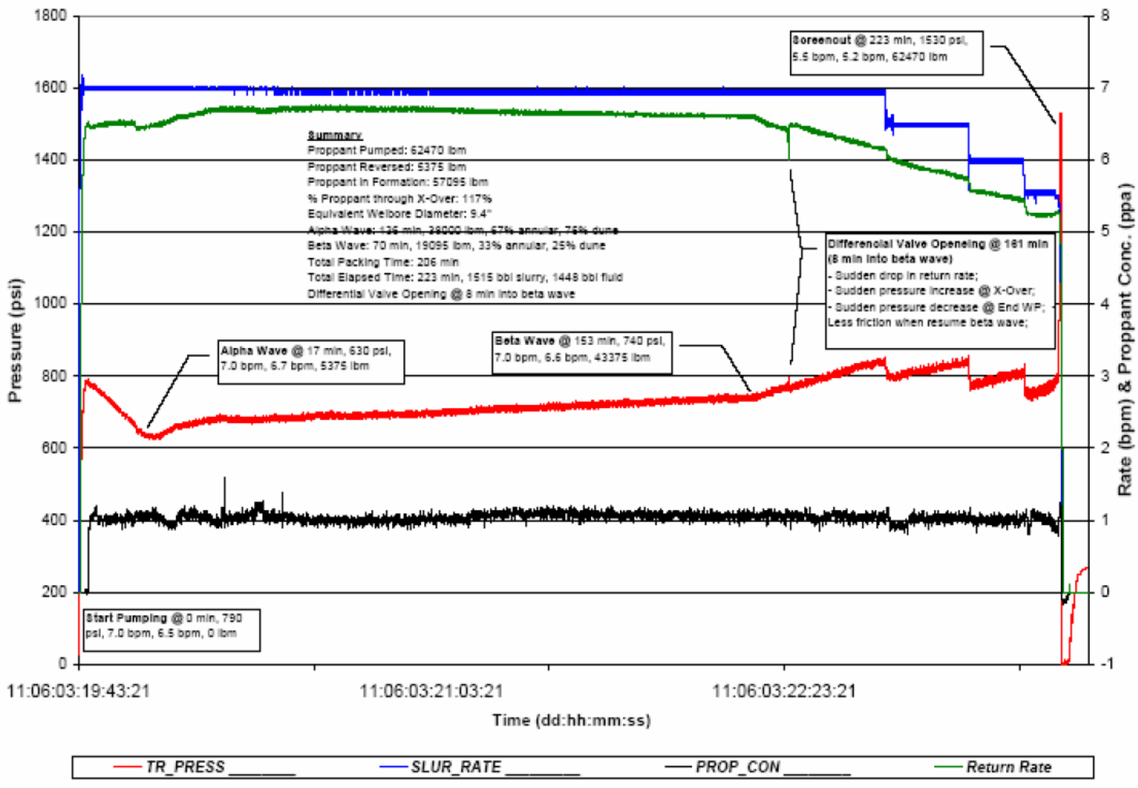


Figure 19 Typical pressure chart for an open hole horizontal gravel pack with differential valve on washpipe [19]

2.8 Gravel pack design

For the successful application and performance of gravel pack, during design phase it is important to determine the right size of gravel. To determine the proper size of gravel at first the median grain size of the formation needs to be determined. In addition, the quality of sand used is also another important parameter as the proper sizing. The American Petroleum Institute (API) has defined minimum specifications required for gravel-pack sand in API RP 58.

2.8.1 Sieve analysis

The median particle determination needs to be performed from a core specimen taken from a formation. A sieve analysis sort out the formation grain matrix in different size spectrum. From the result of sieve analysis, on can determine the cumulative % and weight retained.

Figure 20 shows the plot of cumulative weight percent of each sample retained versus the corresponding screen mesh size on semi log. The median size diameter of sand corresponds to the 50% cumulative weight. This size often referred to as d50, which is the basis of gravel-pack sand size-selection procedures. Table 2 shows a mesh size versus sieve opening.

U.S. Series Mesh Size	Sieve Opening, in.	Sieve Opening, mm	U.S. Series Mesh Size	Sieve Opening, in.	Sieve Opening, mm
2.5	0.315	8.000	35	0.0197	0.500
3	0.265	6.730	40	0.0165	0.420
3.5	0.223	5.660	45	0.0138	0.351
4	0.187	4.760	50	0.0117	0.297
5	0.157	4.000	60	0.0098	0.250
6	0.132	3.360	70	0.0083	0.210
7	0.111	2.830	80	0.0070	0.177
8	0.0937	2.380	100	0.0059	0.149
10	0.0787	2.000	120	0.0049	0.124
12	0.0661	1.680	140	0.0041	0.104
14	0.0555	1.410	170	0.0035	0.088
16	0.0469	1.190	200	0.0029	0.074
18	0.0394	1.000	230	0.0024	0.062
20	0.0331	0.840	270	0.0021	0.053
25	0.0280	0.710	325	0.0017	0.044
30	0.0232	0.589	400	0.0015	0.037

Table 2 Mesh size versus sieve opening [4]

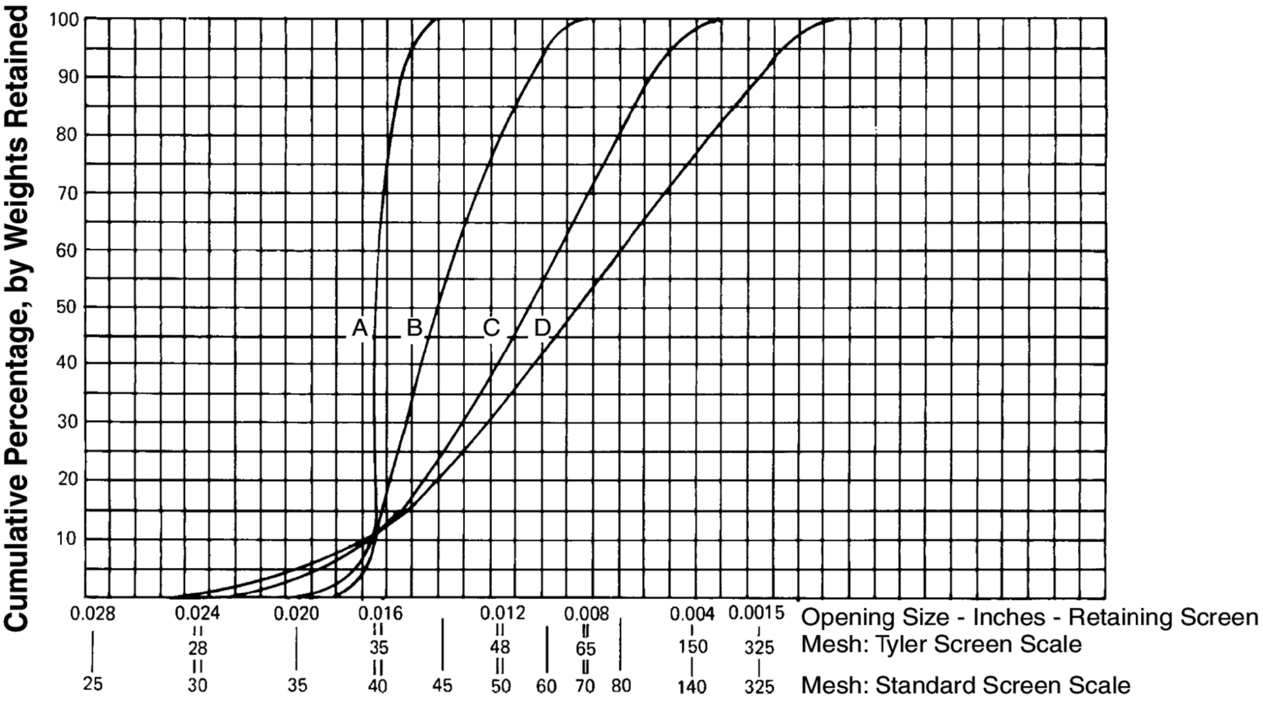


Figure 20 Sand size distribution plot from sieve analysis [4]

2.8.2 Gravel pack sand sizing

There have been several published techniques for selecting a gravel-pack sand size to control the production of formation sand. The most widely used sizing criterion1 provides sand control when the median grain size of the gravel-pack sand, D50 , is no more than six times larger than the median grain size of the formation sand, d50 . The upper case D refers to the gravel, while the lower case refers to the formation sand.

In practice, the proper gravel-pack sand size is selected by multiplying the median size of the formation sand by 4 to 8 to achieve a gravel-pack sand size range, in which the average is six times larger than the median grain size of the formation sand. Hence, the gravel pack is designed to control the load-bearing material; no attempt is made to control formation fines that make up less 2 to 3% of the formation. This calculated gravel-pack sand size range is compared to the available commercial grades of gravel-pack sand. Select the available gravel-pack sand that matches the calculated gravel-pack size range. In the event that the calculated gravel-pack sand size range falls between the size ranges of commercially available gravel-pack sand, select the smaller gravel-pack sand. Table 3 contains information on commercially available gravel-pack sand sizes.

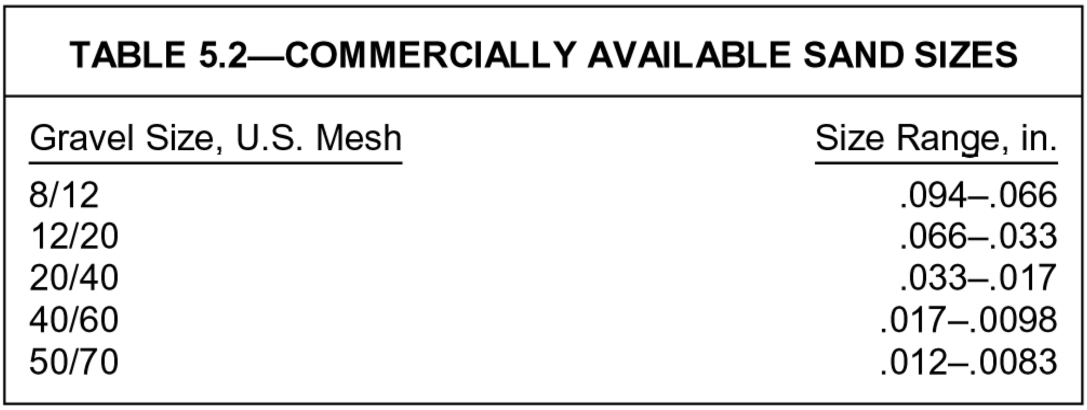


TABLE 5.2—COMMERCIALLY AVAILABLE SAND SIZES

Gravel Size, U.S. Mesh	Size Range, in.
8/12	.094–.066
12/20	.066–.033
20/40	.033–.017
40/60	.017–.0098
50/70	.012–.0083

Table 3 Common sand sizes available [4]

The sieve analysis plot, discussed earlier, can be used to obtain the degree of sorting in a particular formation sample. A near vertical sieve analysis plot represents good sorting (most of the formation sand is in a very narrow size range) vs. a highly sloping plot, which indicates poorer sorting as illustrated by curves “A” and “D,” respectively, in Fig. 20. A sorting factor, or uniformity coefficient, can be calculated as

$$C_\mu = \frac{d_{40}}{d_{90}}, \qquad 1$$

Where

- C_μ = sorting factor or uniformity coefficient,
- d_{40} = grain size at the 40% cumulative level from sieve analysis plot,
- d_{90} = grain size at the 90% cumulative level from sieve analysis plot.

If C_μ is less than 3, the sand is considered well sorted (uniform); from 3 to 5, it is nonuniform, and if greater than 5, it is highly nonuniform.

3 Theory related to gravel packing

3.1 Rheological models

The transport and deposition behaviour of gavel pack carrier fluid highly dependent on their rheological properties. As illustrated on Figure 21, fluids in general categorised in to Newtonian and Non-Newtonian fluid. The rheological properties of fluid systems influenced by its composition, temperature and pressure. This section review rheology model, which describes these fluid types. Figure 22 illustrate the apparent viscosities as a function of shear rate, which is the function of flow speed

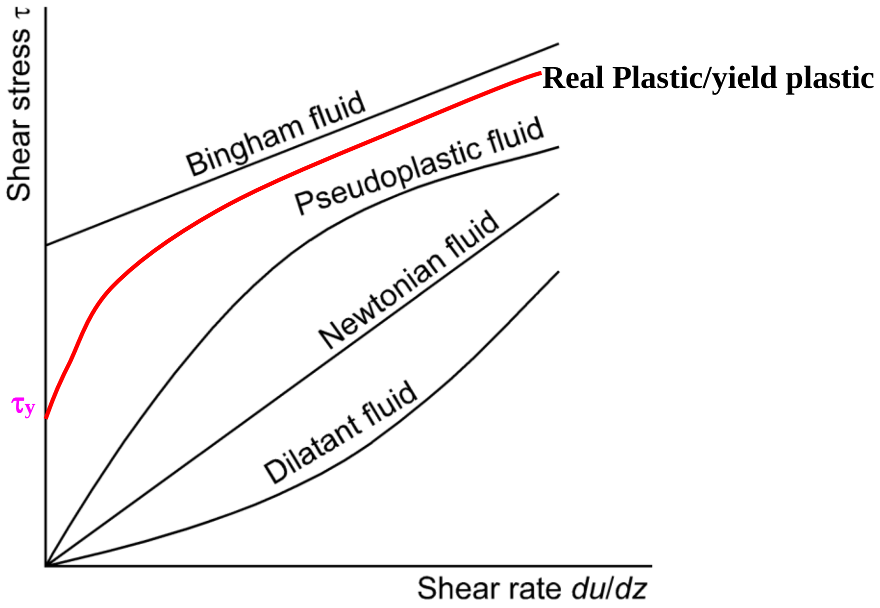


Figure 21 Illustration of Newtonian fluid and non-Newtonian fluid behaviour [14]

Some examples of Newtonian particle free fluid are; Water, sugar solutions, glycerine, oils, light-hydrocarbons oils, air and other gases.

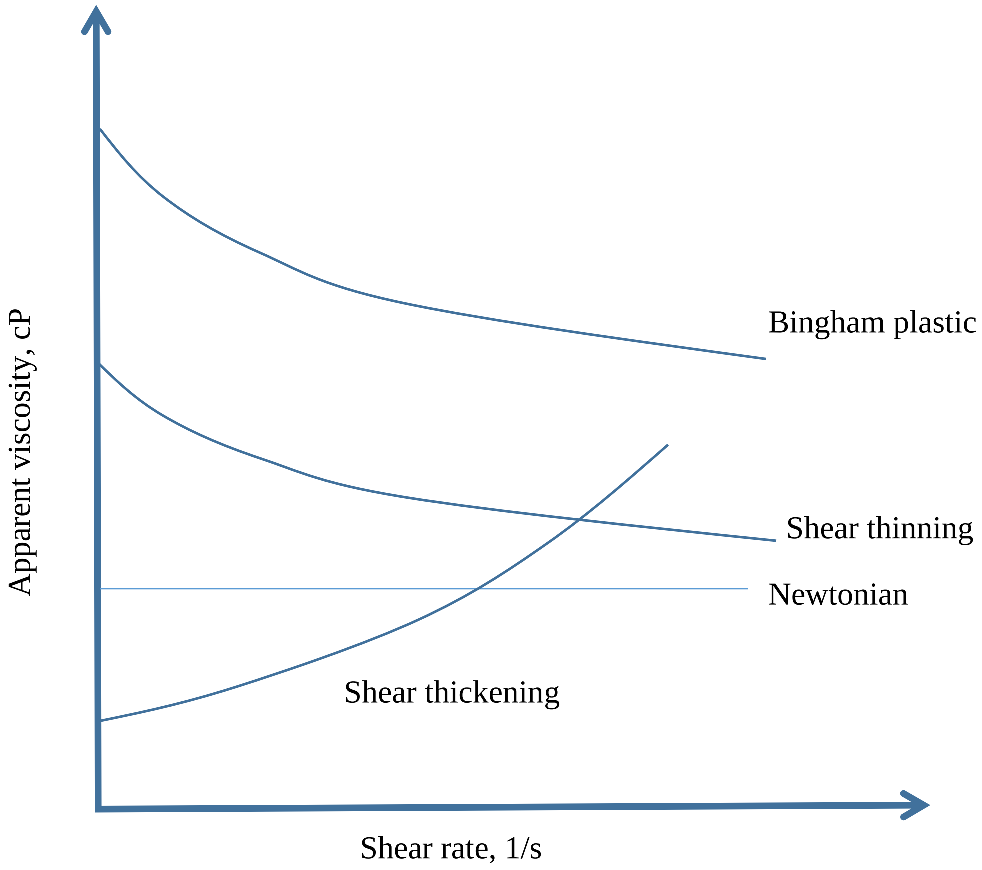


Figure 22 Apparent viscosity against shear rate flow curves for time independent fluids

3.2 Newtonian Fluids behaviour

The Newtonial fluid is in general fluid which is described by a shear rate proportional to shear rate with a proportionality constant called viscosity. These types of fluid do not contain solid particles. The viscosity is constant at all shear rates at a constant temperature and pressure. This model has one parameter and can be given as.[15]

$$\tau = \mu\gamma \qquad 2$$

Where τ is shear stress, γ is shear rate and μ is viscosity

3.3 Non Newtonian fluids behaviour

A fluid whose viscosity is not constant at all shear rates and does not behave like a Newtonian fluid and is therefore called “Non-Newtonian” fluids.

Non-Newtonian fluids also refer as Pseudo-plastic and are a descriptive term for a fluid with shear-thinning characteristics that does not exhibit thixotropy. Pseudo-plastic rheology, low viscosity at high shear rates and high viscosity at low shear rates, benefits several aspects of particle transport. These fluids can be de described by the following three rheological models that set up a relationship between the shear stress and shear rate.

- Bingham Plastic Fluids.
- Power-Law Fluids
- Modified Power-Law or Herschel-Bulkley Fluids

Several studies have shown that slurries of gravel pack carrier fluids can demonstrate non-Newtonian characteristics.

3.3.1 Bingham plastic model

The Bingham Plastic Model is described by two parameters, namely plastic viscosity (PV) and Yield stress (YS). According to this model, in order to set the fluid system into motion, the applied pressure should overcome the yield strength of the fluid at zero shear rate. This model is commonly used oil industry to characterize the mud systems. The model also assume that the fluid system has a viscosity, which is independent of the shear rate. Mathematically the model reads: [15]

$$\tau = YP + PV\gamma \qquad 3$$

Fluids obeying this model are called Bingham plastic fluids and exhibit a linear shear-stress, shear-rate behaviour after an initial shear-stress threshold has been reached. Plastic viscosity (PV) is the slope of the line and yield point (YP) is the threshold stress (y-intercept).

3.3.2 Power law model

The Power Law Model describes a non-Newtonian fluid by a two- parameter rheological model. The viscosity decreases of Power Law fluids decrease according to law:[15]

$$\tau = K\gamma^{n} \qquad 4$$

where k is consistency index, and n is flow index

3.3.3 Modified Power-Law or Herschel-Bulkley Model

This is a three-parameter rheological model. A Herschel-Bulkley fluid can be described mathematically as follows:[21]

$$\tau = \tau_{o} + K\gamma^{n} \qquad 5$$

The Herschel-Bulkley equation is preferred to Power Law or Bingham relationships because it results in more accurate models of rheological behaviour when adequate experimental data are available. The yield stress is normally taken as the 3 rpm reading in a standard 6-speed rheometer, with the n and K values then calculated from the 600 or 300 rpm values or graphically.

3.4 Apparent viscosity of Newtonian and non-Newtonian Fluids

3.4.1 Apparent viscosity of Newtonian fluid

The viscosity of a non-Newtonian fluid varies with shear rates. An apparent viscosity μ_a can be defined as follows: [15]

$$\mu_a = \frac{\tau}{\gamma} \qquad 6$$

Fluids for which the apparent viscosity decreases with increasing shear rate are called shear thinning or pseudo-plastic fluids, while those with the opposite behaviour are known as shear thickening fluids. Based on Power law fluid behaviour, the shear thinning behaviour corresponds to n < 1 and shear thickening behaviour to n > 1. When n = 1, is Newtonian behaviour and in this case the consistency coefficient K is identical to the viscosity μ .

3.4.1 Apparent viscosity of Non-Newtonian fluid

In addition to the gravel and flow properties, the rheological characteristics of gravel pack carrier fluids do have great impact on gravel packing. Some studies indicate that gravel pack fluids behaves like non-Newtonian characteristics [25]. Among others, non-Newtonian fluids reviewed in the previous section, assuming that the Power-law model describe the gravel pack slurries, one can derive the effective viscosity of the suspension as:

$$\mu_m = K_m \gamma^{n_m - 1} \tag{7}$$

The shear rate in tubing flow is given as:

$$\gamma = \frac{8u}{D} \tag{8}$$

Similarly, the shear rate in the annulus is:

$$\gamma = \frac{12u}{D_2 - D_1} \tag{9}$$

3.5 Settling velocity of particles

Forces acting on solid particles submerged in a liquid have their origin either in a particle-liquid or in particle-particle interaction. Particles moving in a conduit may also interact with a conduit boundary. The forces acting on a single particle in a dilute suspension are the body forces. The particle-liquid forces are Buoyancy force, Drag force and Lift force.

The settling velocity of the particle is the velocity at which particles will settle under gravity in a fluid. This velocity is primarily determined by the relative magnitude of the gravity and the viscous drag forces acting on the particle.

Three settling laws are required to cover the possible range of settling conditions from low Reynolds Numbers i.e. small particle diameter/high viscosity fluid to settling with high Reynolds Numbers i.e. large particle diameter/low viscosity fluid.

Force in the direction of flow exerted by the fluid on the solid is called drag. Figure shows a stationary smooth sphere of diameter DP situated in a stream, whose velocity far away from the sphere is u to the right.

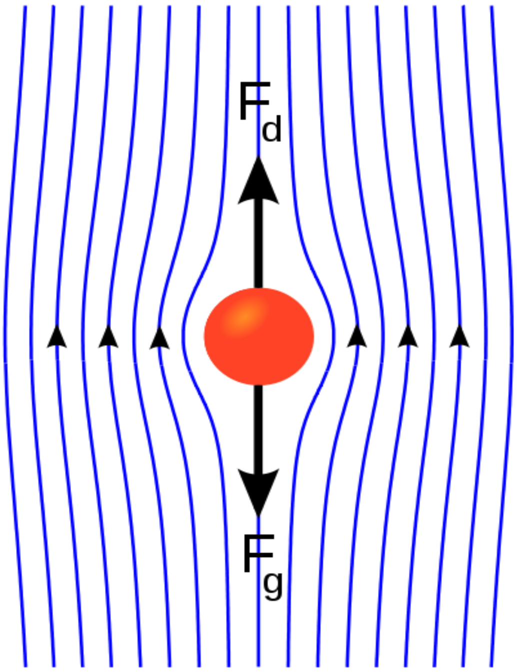


Figure 23 Drag forces on a solid particle in fluid[22]

3.5.1 Derivation of Terminal settling velocity

Gravitational force: This is the apparent weight of the particle. [23]

$$F_g = \pi \frac{d_p^3}{6}(\rho_p - \rho_f).g \qquad 10$$

Drag force

The primary force associated with the interaction between a moving fluid and a solid sphere immersed in the fluid is the drag resulting from the relative velocity between the fluid and the particle. [24]

$$F_D = \frac{\pi}{8} d_p^2 \rho_f v_s^2 . C_D \qquad 11$$

C_D= Drag Coefficient = f (Particle Reynolds No, Particle Shape)

For terminal settling velocity, balancing the drag force and gravitational force, one obtains the settling velocity as: [24]

$F_D = F_g$

$$v_s = \left(\frac{4.gd_p(\rho_p - \rho_f)}{3\rho_f . C_D} \right)^{0.5} \qquad 12$$

The experimental results of the drag on a smooth sphere may be correlated in terms of two dimensionless groups - the drag coefficient C_D and particles Reynolds number, N_{Rep}:

The Reynolds Number relative to a settling particle is known as the particle Reynolds Number (N_{Rep}), and is used in the defining drag coefficient for the particle.

This Reynolds Number describes a situation of external flow relative to the particle. The situation is equivalent to the carrier phase liquid flowing past a stationary particle at a velocity equal to the terminal settling velocity of the particle.

Particle Reynolds Number [24]

$$N_{\mathrm{Re}\,p} = \frac{\rho_f v_s d_p}{\mu} \qquad 13$$

μ is fluid viscosity

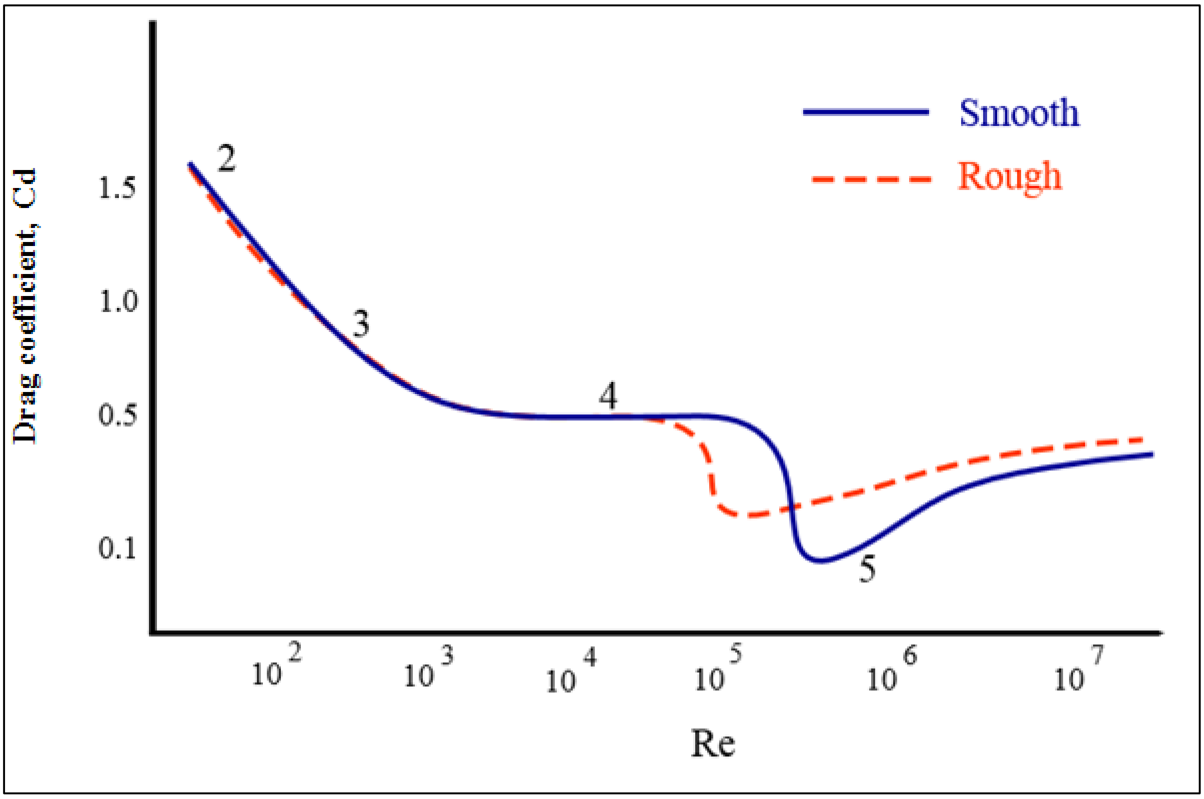


Figure 24 Particle drag coefficient [22]

Figure 24 illustrate drag coefficient C_d as a function of particle Reynolds number Re. The solid line represents for spherical particle with a smooth surface, and the dashed line represents for a rough surface. The numbers indicate flow regimes as a function of change in changes in the drag coefficient. The Regions show:[22]

- Stokes flow and
- laminar flow boundary layer
- turbulent
- post-critical separated flow, with a turbulent boundary layer

Case 1: For $1 < N_{Re} < 10^5$ (typically for non-smooth sphere), we may approximate the expression: [23]

$$C_D \approx \frac{24}{N_{Re}} \sqrt{1 + 0.2N_{Re} + 0.0003N_{Re}^2} \qquad 14$$

Case 2: [23]

For values $N_{Rep} > 10^5$, C_D is about 0.1

Case 3: [23]

For sufficiently small grain particles, $N_{Re} < 1$, the drag coefficient is approximated as:

$$C_D \approx \frac{24}{N_{Re}} \qquad 15$$

This gives the settling velocity as: [23]

$$v_s \approx \frac{g d_p^2 (\rho_p - \rho_f)}{18\mu_{eff}} \qquad 16$$

This expression is often referred to as Stokes' law.

Stokes Flow describes a situation where the drag force imparted by the moving fluid on the particle is caused only by viscous forces e.g. force required to shear the fluid. The flow velocities are so low that the inertial forces i.e. the force needed to accelerate the fluid out of the path of the particle are negligible. In Stokes law, the particle drag coefficient is inversely proportional to the particle Reynolds Number.

3.6 Particle transport models and critical velocity

The optimal alpha dune height is typically around 50% to 70%. This dune height is a controlled by parameters such as carrier fluid density, gravel density, gravel size, gravel concentration, injection rate/return rate and the ration between washpipe OD and screen base pipe ID. The clean fluid will flow through the screens and up the washpipe to surface, or if you have losses, the fluid will flow into the formation. High losses can cause problems to a standard gravel pack operations, it causes bridge to the formation that again can cause a premature screen out.

A basic flow path during a gravel pack operation is illustrated in figure 25 below.

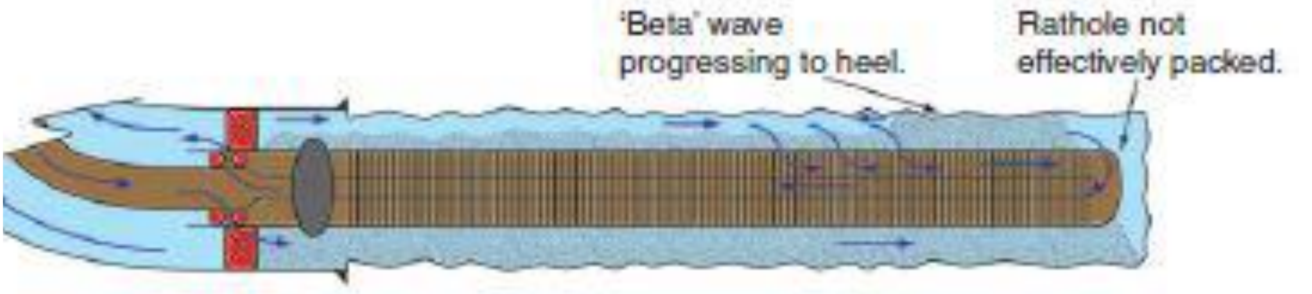


Figure 25 Gravel pack circulating path [6]

Alpha wave packs from the heel of the well towards the toe of the well. When slurry velocity reaches the **critical velocity,** no more gravel settles out of the slurry and the Beta wave starts packing the area above the alpha dune from the toe of the well to the heel. When beta wave starts a pump pressure increase is occurring. This increased pressure is due to the clean fluid has to flow through the packed gravel towards the end of the screen section to get access to the washpipe or/and it flows through the annulus between the wash pipe OD and sand screen ID. When the beta wave reaches the heel of the well and starts to pack inside the casing a rapid pump pressure is observed; this is what is called screen out. At this stage, ideally, the annulus between screen OD and OH ID is completely packed with gravel (≥ 100 % packing efficiency). If a premature screen out occurs the pack efficiency is definitely less than 100%.

3.6.1 The model of Gruesbeck et al

Gruesbeck et al's [1] experiments show that if the fluid velocity on the top of the due is high enough, then the dune attains an equilibrium height. The fluid velocity for which this is observed is called critical velocity, v*. If the actual fluid velocity is greater than the critical value (v_o > v*), then the height if the dune will decrease. This means more gravel particles will be stripped from the top of the dune than deposited. They also found that annular pack efficiency increased with decreasing gravel concentration.

Gruesbeck et al. [1] studied the gravel packing efficiency in deviated and horizontal wellbores. The experiment that led to this model were conducted in a 5 ½ "OD Lucite tube with length of 10 feet to simulate the casing. A ¼ "OD pipe was inserted into the tube to simulate screens

$$V_c = 15 v_s \left(\frac{r_h v_s \rho_l}{\mu_l}\right)^{0,39} \left(\frac{d_p v_s \rho_l}{\mu_l}\right)^{-0,73} \left(\frac{\rho_p - \rho_l}{\rho_l}\right)^{0,17} [C_v]^{0,14}. \qquad 17$$

Both the effect of screen/wash pipe and fluid leak off to the formation were not included. The gravel carrying fluids were from 1,00 SG to 1,75 SG and viscosities from 0 to 200 cp. All fluids used were essentially Newtonian. The gravel that was used had a specific gravity of 2.6 to 3.72. Five particle sizes were studied: 40/60, 20/40, 15/18, 10/20 and 6/9 US meshes. The particle concentration varied from 24 kg/m3 to 1120 kg/m^3.

Several tests were done and the critical velocity model was a best fit to the test results.

3.6.2 The model of Penberthy et al

The Penberthy et al's [2] model was originally presented in the Chemical engineer's handbook. The test was performed in relatively small diameter field scale test model; 1 500 ft long and 4 ½ "diameter pipe. A centralized 2 1/16 "screen was placed into the pipe. The washpipe diameter was 1,315 inch. Fluid leak off was simulated with 400 perforation. Fluids used were low viscosity fluids

The test result conclude that the critical velocity can be predicted for a horizontal well as:

$V_c = \max(V_1, V_2)$

Where

1) When the particle size under 0.04in. (1 mm), the velocity to keep the particle in suspension is given as: V1(ft/sec)

$$V_1 = \left[0.0251 g.d_p \left(\frac{\rho_g - \rho_l}{\rho_l} \right) \left(\frac{D_H \rho_m}{\mu_l} \right)^{0.775} \right]^{0.816} \qquad 18$$

If the particle size is greater than 0.08 inch, the critical velocity is given as:

$$V_2 = 1.35 \left[2g.D_H \left(\frac{\rho_g - \rho_l}{\rho_l} \right) \right]^{0.5} \qquad 19$$

The selection of the velocity should be based on the particle size mentioned above.

Where, D_H = hydraulic diameter

Note:

- Caution when calculating with gravel concentration and viscosity out of testing range
- Fluid viscosity and gravel concentration is not in the V_2 calculation
- More testing is need to verify its reliability and accuracy

3.6.3 The Model of Oroskar and Turian

A correlation developed by Oroskar and Turian [3] incorporated the earlier work of several authors. This correlation takes into account both the hindered settling velocity and the dissipation of turbulent energy. The critical or equilibrium velocity is calculated by

$$u_{st} = u_d \left[5c(1-c)^{2n-1} \frac{D_d}{D} \left(N_{\mathrm{Re}\,p}\right)^{\frac{1}{8}} x^{-1} \right]^{\frac{8}{15}} \tag{20}$$

After regression analysis on 357 data points, they presented the correlation as:

$$u_e = 1{,}85 u_d c^{0{,}1536} (1-c)^{0{,}3564} \left(\frac{D_d}{D} \right)^{-0{,}378} \left(N_{\mathrm{Re}}\right)^{0{,}09} x^{0{,}3} \tag{21}$$

The two Oroskar and Turian correlations consist of a semi-theoretical (Eq. 20) and an empirical (Eq. 21) equation. Critical velocity is proportional to the velocity of the settling particulate (u_d).

$$u_d = \sqrt{G \cdot D \left(\frac{\rho_p}{\rho_f} - 1 \right)} \tag{22}$$

Where x in (Eq. 20 & 21) is the correction factor for dissipation of turbulent energy, which can be written as follows:

$$x = \frac{2}{\sqrt{\pi}} \gamma \exp\left(\frac{-4}{\pi} \gamma^2 \right) + \left(1 - erf\left(\frac{2}{\sqrt{\pi}} \gamma \right) \right) \tag{23}$$

In this relation, γ is the ratio of particle settling velocity to critical velocity.

$$\gamma = \frac{U_{hindered}}{U_{critical}} \tag{24}$$

The parameter γ is used to describe the velocity of the turbulent fluid eddies within the pipe which keeps solid particulate suspended in the fluid. The fraction of turbulent fluid eddies that have a velocity greater than the particulate settling velocity is described by the parameter x. In the calculations, x is determined for a range of values for γ. For the settling velocities it is observed and for a reasonable range of critical velocities (0.06 to 5.31 ft/s), the value of x is roughly 0.96. This method gives similar but generally slightly higher values than the other methods.

4 Simulation study

This part of the thesis present simulation study on gravel packing. The reviewed models namely Gruesbeck et al (Eq.17), Penberthy et al. (Eq. 18 and Eq. 19) and Oroskar and Turian (Eq.20 &21) will be used to evaluate the effect of single and combined parameters on dune height and settling velocity.

4.1 Simulation arrangement

For this simulation the open hole size and screen size were 8,5 inch and 6 inch respectively. It is common practice that for an optimal gravel pack the difference in diameter between the screen and the open hole should be at least 1 inch.

Based on this geometry the hydraulics diameter were calculated as described below.

Area available for flow when there is no gravel in the annulus:

$$A_{an} = \frac{\pi}{4}\left(8.5in^2 - 6in^2\right) = \underline{0,0184m^2}$$

Velocity at a given flow rate (1000 lpm), when no gravel is filled:

$$v = \frac{Q}{A_{an}} = \frac{0,0167\ m^3/s}{0,0184\,m^2} = \underline{0,91\ m/s}$$

Equivalent diameter available to flow can be calculated as:

$$D_{equivalent} = \sqrt{\frac{4}{\pi}\left(A \cdot unfilled\%\right)}$$

Hydraulic Diameter can be calculated as

$$D_{hy} = \frac{D_{equivalent}}{S}$$

Where S is the shape factor given by 0.67 for concentric annulus, Penberthy et al [2]

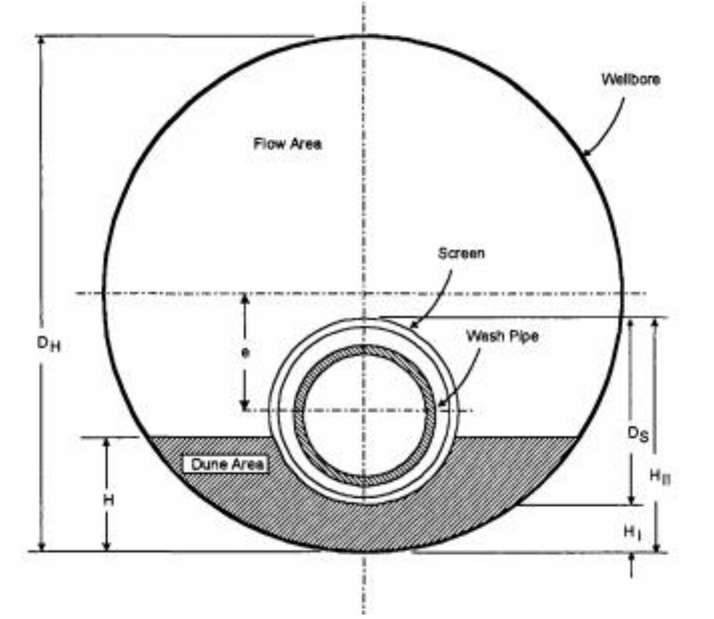


Figure 26 The wellbore cross sectional schematic during a gravel pack [2]

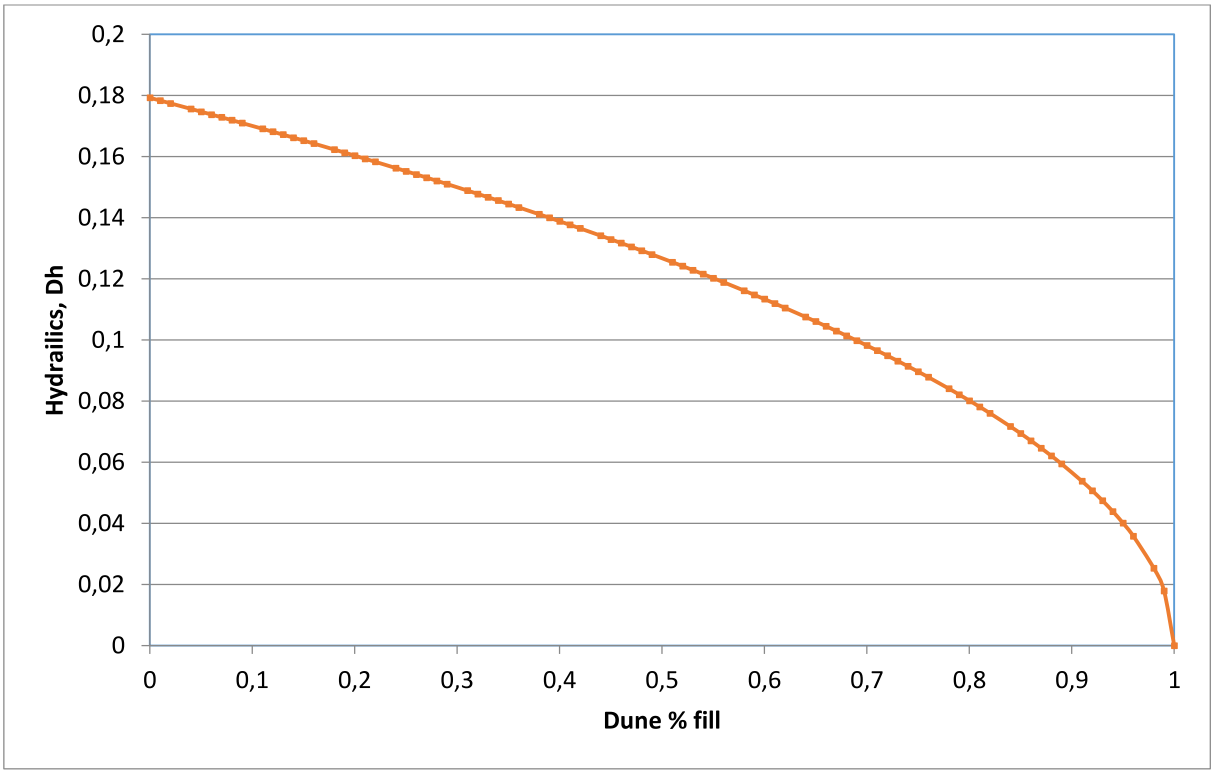


Figure 27 Calculated Dh with 8,5 inch OH, 6 inch OD sand screens

4.2 Effect of single parameters on bed height

The gravel pack models are a function of several parameters, which includes flow rate, gravel concentration, gravel size and density of gravel. In addition fluid behaviors such as density and viscosity.

All simulations in this evaluation was done with a gravel density of 2.71 SG. This is the density of a lightweight ceramic gravel (proppant) that is frequently used for gravel packing in the North Sea and worldwide.

With a realistic parameter variation, the responses/the influence of these parameters on bed height will be evaluated. The objective of this evaluation is to investigate which parameter is sensitive to the bed height and compare the results obtained from the three models.

- Penberthy, version 1 and 2
- Oroskar and Turian
- Gruesbeck

In thesis, the average value of 'Oroskar and Turian' and 'Gruesbeck' is also included in the plots from the simulations.

4.2.1 Effect of density of carrier fluid

For this simulation, the density of the carrier fluid was varied from 1.04 SG to1.8 SG, while keeping the other parameters constant. 1.04 SG water based carrier fluid (NaCl brine) is a commonly used brine weight in the industry.

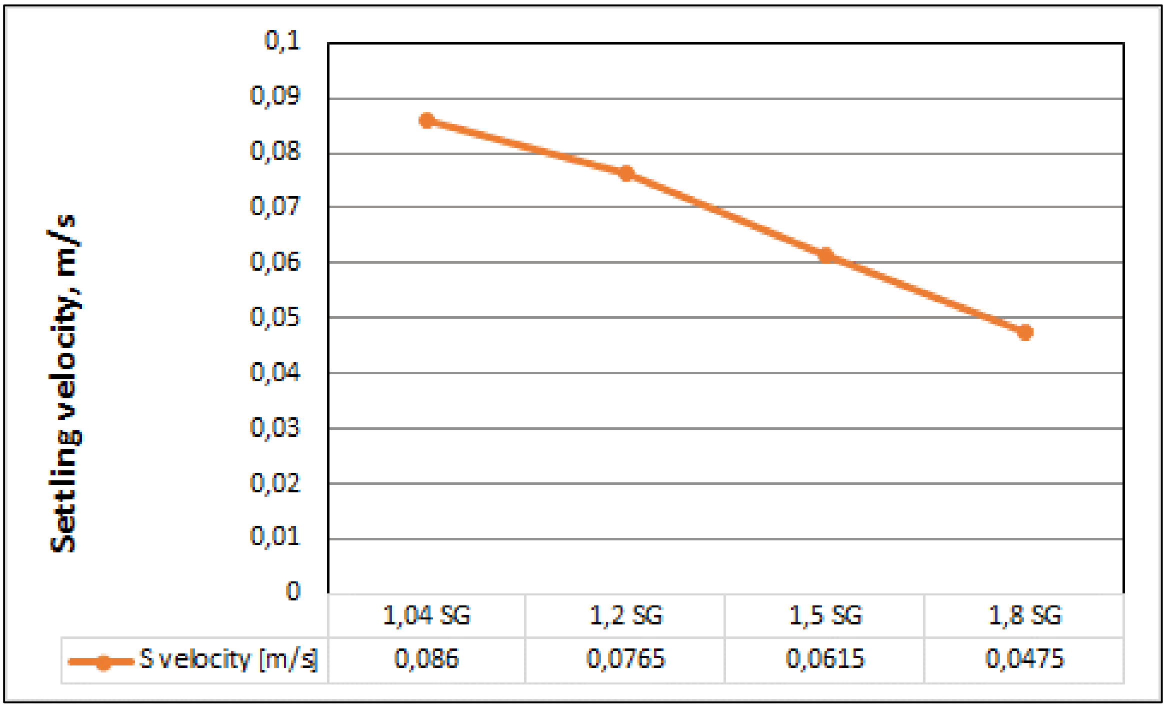
Table 4 presents the input simulation parameters.

	Reference	Sim#1	Sim#2	Sim#3	Units
Flow rate	1000	1000	1000	1000	[LPM]
Gravel concentration	36,4	36,4	36,4	36,4	[KG/M^3]
Gravel size	625	625	625	625	[MICRON]
Apparent gravel SG	2,71	2,71	2,71	2,71	[SG]
Viscosity of carrier fluid	1,3	1,3	1,3	1,3	[cP]
Density of fluid	1,04	1,2	1,5	1,8	[SG}

Table 4 Input parameters for simulation with various density of carrier fluid

Based on this simulation, as density increase from 1.04 SG to 1.8 SG, the settling velocity decrease by 44,8 % which confirms that the higher density of the carrier fluid the lower the settling velocity of the particle. If the density of the carrier fluid is equal to the density of the particle there will be no downwards movement of the particle in the fluid.

The simulated results are shown on Figure 28.



	1,04 SG	1,2 SG	1,5 SG	1,8 SG
S velocity [m/s]	0,086	0,0765	0,0615	0,0475

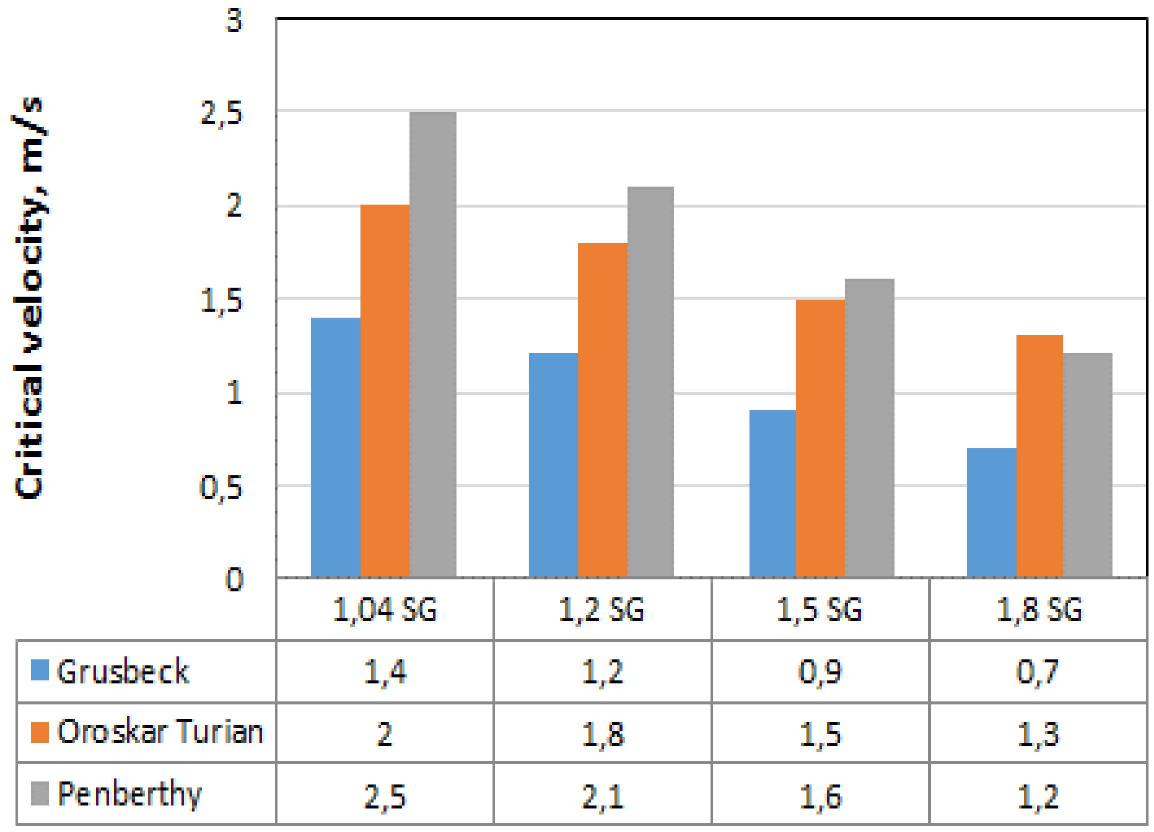
Figure 28 Settling velocity for four different carrier fluid densities.

The settling velocities were used as input parameter for dune height prediction. Actual velocity at 1000 liter/min, 1.04 SG carrier fluid and critical velocity from the three models concerning dune height are plotted in figure 31.

The tree models included in this evaluation gives different prediction of the critical velocity and dune height.

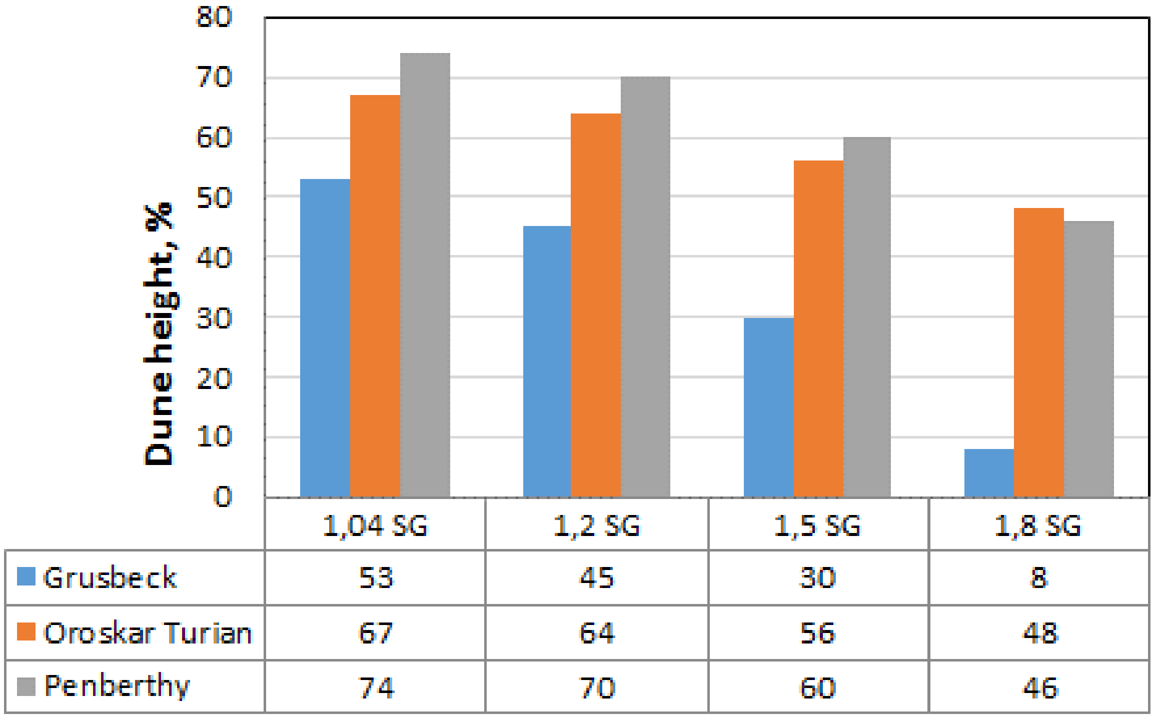
Figure 29 below presents a summary of the critical velocities from the simulations with the four different densities.

Figure 30 presents the dune height prediction for the three different carrier fluid density.



	1,04 SG	1,2 SG	1,5 SG	1,8 SG
Grusbeck	1,4	1,2	0,9	0,7
Oroskar Turian	2	1,8	1,5	1,3
Penberthy	2,5	2,1	1,6	1,2

Figure 29 Prediction of the critical velocity with various carrier fluid density



	1,04 SG	1,2 SG	1,5 SG	1,8 SG
Grusbeck	53	45	30	8
Oroskar Turian	67	64	56	48
Penberthy	74	70	60	46

Figure 30 Prediction of dune height with various carrier fluid density

To investigate which model is more sensitive to certain parameters table 5 below presents a summary of the simulations with the different carrier fluid densities concerning increase or decrease of the critical velocity and bed height value when moving from one carrier fluid density to another.

Model		**Gruesbeck**	**Oroskar/ Turian**	**Penberthy**
%change from 1.04SG to 1.2SG		Vcrit=-14,3% Dune=-15,1%	Vcrit=-10% Dune=-4,5%	Vcrit=-16m/s Dune=-74%
%change from 1.2SG to 1.5SG		Vcrit=-25% Dune=-33,3%	Vcrit=-16,7% Dune=-12,5%	Vcrit=-23,8m/s Dune=-70%
%change from 1.5SG to 1.8SG		Vcrit=-22,2% Dune=-73,3%	Vcrit=-13,3% Dune=-14,3%	Vcrit=-25% Dune=-60%
%change from 1.04SG to 1.8SG		**Vcrit=-50%** **Dune=-84,9%**	**Vcrit=-28,4%** **Dune=-28%**	**Vcrit=-52%** **Dune=-46%**

Table 5 Summary of predicted % increase/decrease of critical velocity and dune height

Interpretation of plot from simulations

When the slurry enters the annulus between the open hole and the sand screens, the velocity of the slurry is

V=rate/area

At this point, there are no gravel in the open hole/screen annulus. The slurry flows outside along with the sand screens. There is also some flow of clean fluid in the annulus between the sand screen ID and wash pipe OD. Assume isolated wellbore, no leak off to formation.

- If the velocity of the slurry is higher than the critical settling velocity all the sand will be transported to the end of the screens and there will be no alpha wave building. When the slurry enters the end of the screen section, the clean fluid will enter the sand screens and leave the gravel on the outside of the screen jacket. This sand will create a Beta wave that will grow from the bottom of the screens towards the heel of the well.

- If the velocity of the slurry is lower than the critical velocity the sand will start to settle out. When the gravel settles out in the annulus between the screens and the open hole this is called the alpha wave/dune. When this dune is building the area to flow becomes smaller and the velocity of the slurry increases. When the velocity of the slurry is equal to the critical settling velocity all the gravel in the slurry is kept in suspension and there is no more gravel settling out. At this stage, as long as the pump rate and properties of the slurry is kept constant, the alpha dune becomes stabile, all the gravel is transported above this dune from now on.

In the plot, the predicted critical velocity and corresponding dune height value is obtained in the intersection between the green "wave curve" and the curve from the actual model. At the left side of the intersection the gravel settles out and at the right side of the intersection, following the green curve, the gravel is in suspension in the carrier fluid. At the point of intersection the mode of the dune change from alpha (settling modus) into beta wave (suspension modus) and the wellbore fills up with gravel from toe to heel.

Ideally, the alpha dune should cover the screens before the beta wave commences. The reason for this is if you get an unwanted premature screen out during beta wave progression, some of the screen section will not be fully packed with gravel. When the alpha dune is covering the screens there will still be some gravel on top of the screens protecting them from production inflow.

Figure 31 and 32 compares the outcome of the simulation with the highest density carrier fluid (1,8 SG) and the lowest density carrier fluid (1.04 SG) . Plots from the simulations with 1.2 SG carrier fluid and 1.5 SG carrier fluid are included in the appendix (#1 & #2).

Comparison between the two extreme cases, 1,04 SG carrier fluid and 1,8 SG carrier fluid is illustrated in fig 31 and 32.

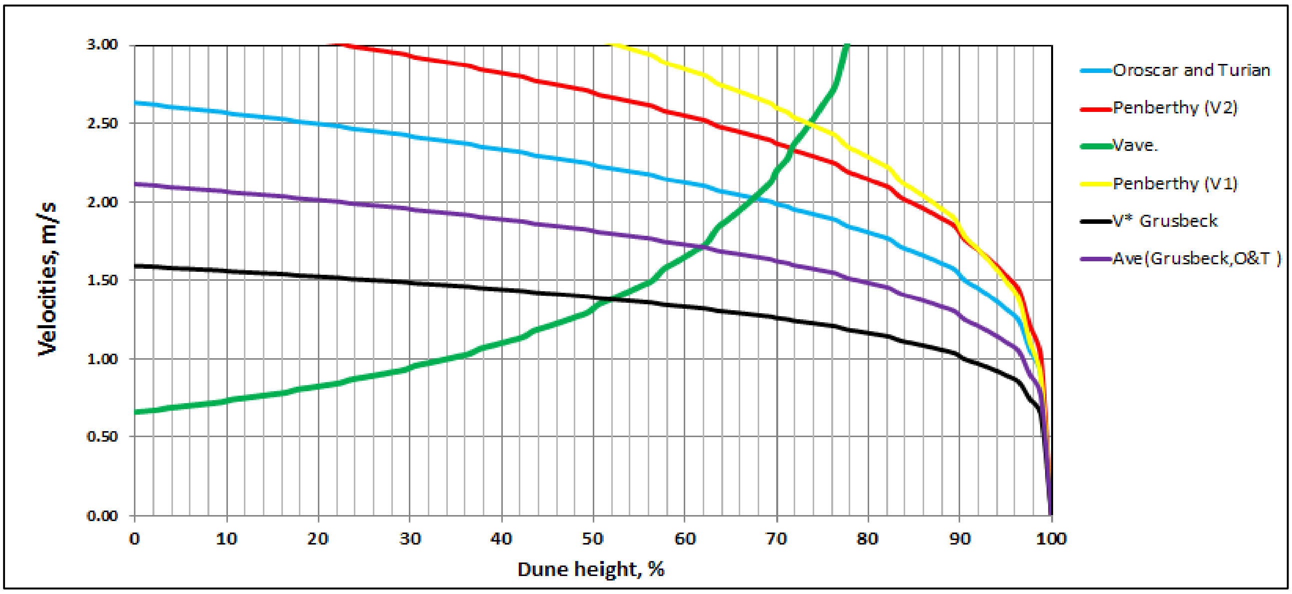


Figure 31 Critical velocity and dune height prediction for the three models, base case parameters with 1,04 SG carrier fluid.

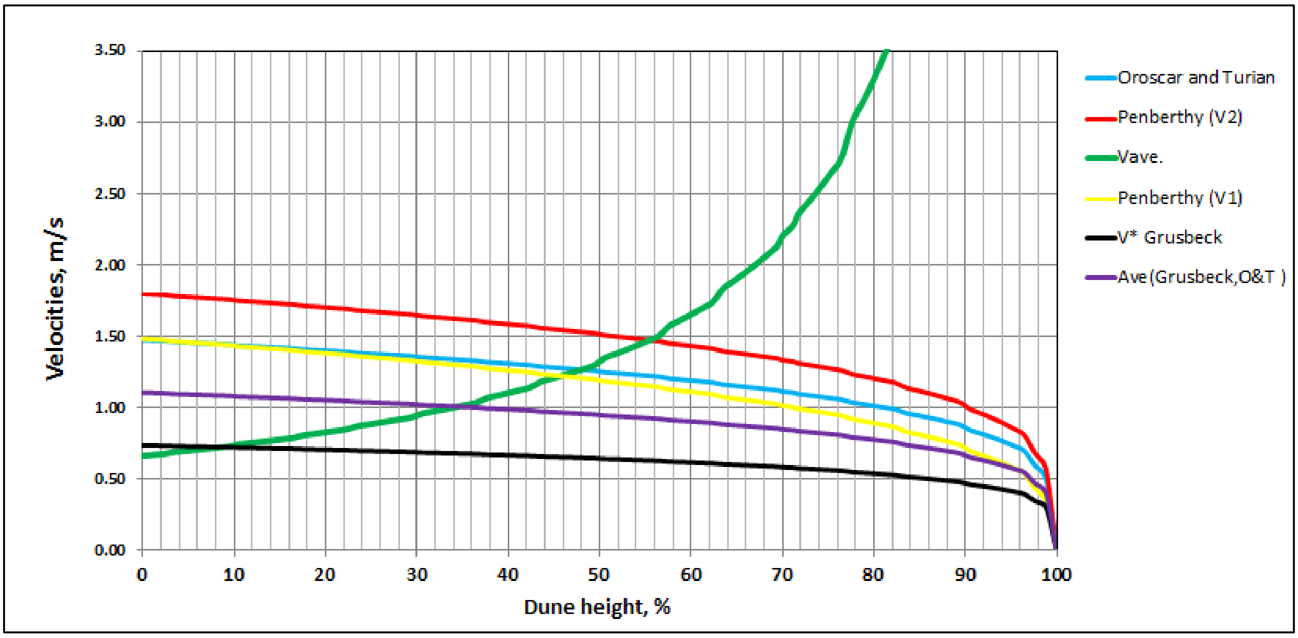


Figure 32 Critical velocity and dune height prediction for the three models, base case parameters with 1,8 SG carrier fluid.

4.2.2 Effect of gravel concentration

For this simulation, the gravel concentration in the slurry was varied from 36,4 kg/m^3 to 120 kg/m^3 while keeping the other parameters constant.

A number of wells in the north sea has been gravel packed successfully using ceramic proppant and a gravel concentration of 36,4 kg/m^3.

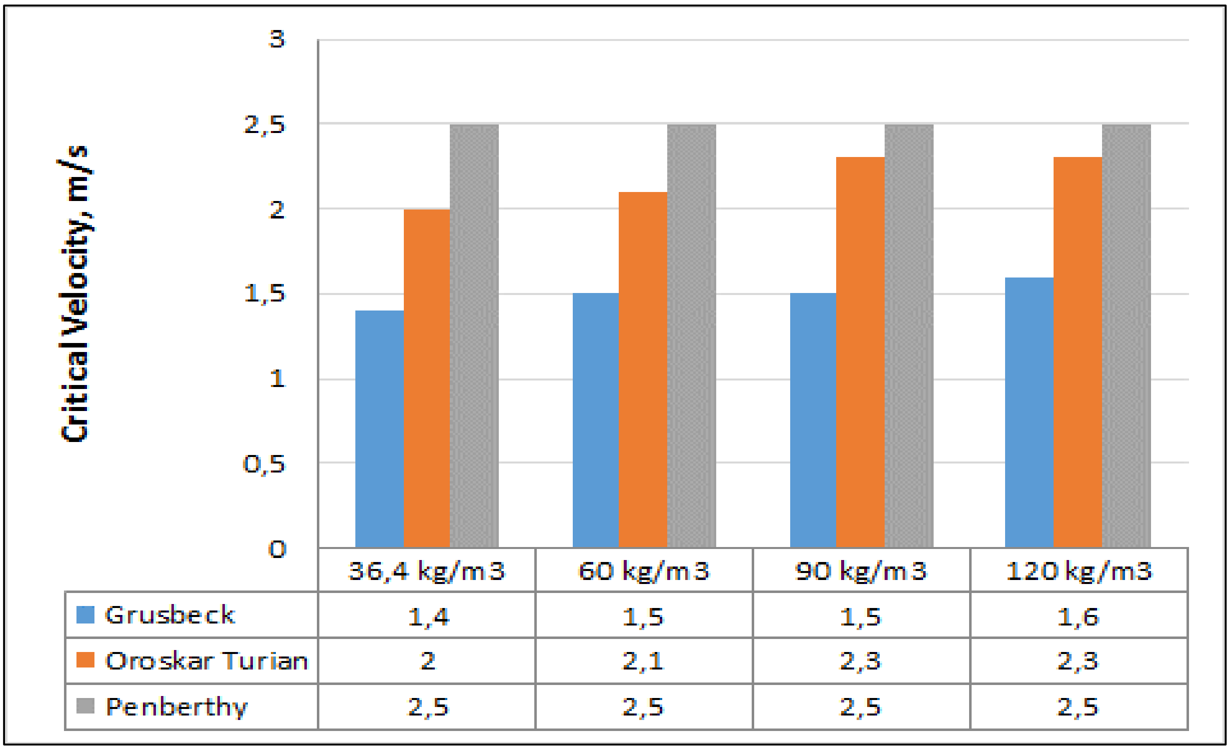
Table 6 presents the input simulation parameters.

	Reference	Sim#1	Sim#2	Sim#3	Units
Flow rate	1000	1000	1000	1000	[LPM]
Density of fluid	1,04	1,04	1,04	1,04	[SG]
Gravel size	625	625	625	625	[MICRON]
Apparent gravel SG	2,71	2,71	2,71	2,71	[SG]
Viscosity of carrier fluid	1,3	1,3	1,3	1,3	[cP]
Gravel concentration	36,4	60,0	90,0	120,0	[KG/M^3]

Table 6 Input parameters for the simulations with various gravel concentrations

The settling velocity is not affected as gravel concentration increase from 36,4 kg/m^3 to 120 kg/m^3 in the slurry. The settling velocity of 0,086 m/s was used as input parameter for dune height prediction for the three different gravel concentrations.

Figure 33 presents a summary of the predicted critical velocity from the three models while figure 34 presents the predicted dune height.



	36,4 kg/m3	60 kg/m3	90 kg/m3	120 kg/m3
🟦 Grusbeck	1,4	1,5	1,5	1,6
🟧 Oroskar Turian	2	2,1	2,3	2,3
⬜ Penberthy	2,5	2,5	2,5	2,5

Figure 33 Predicted critical velocities from simulations with various gravel concentrations

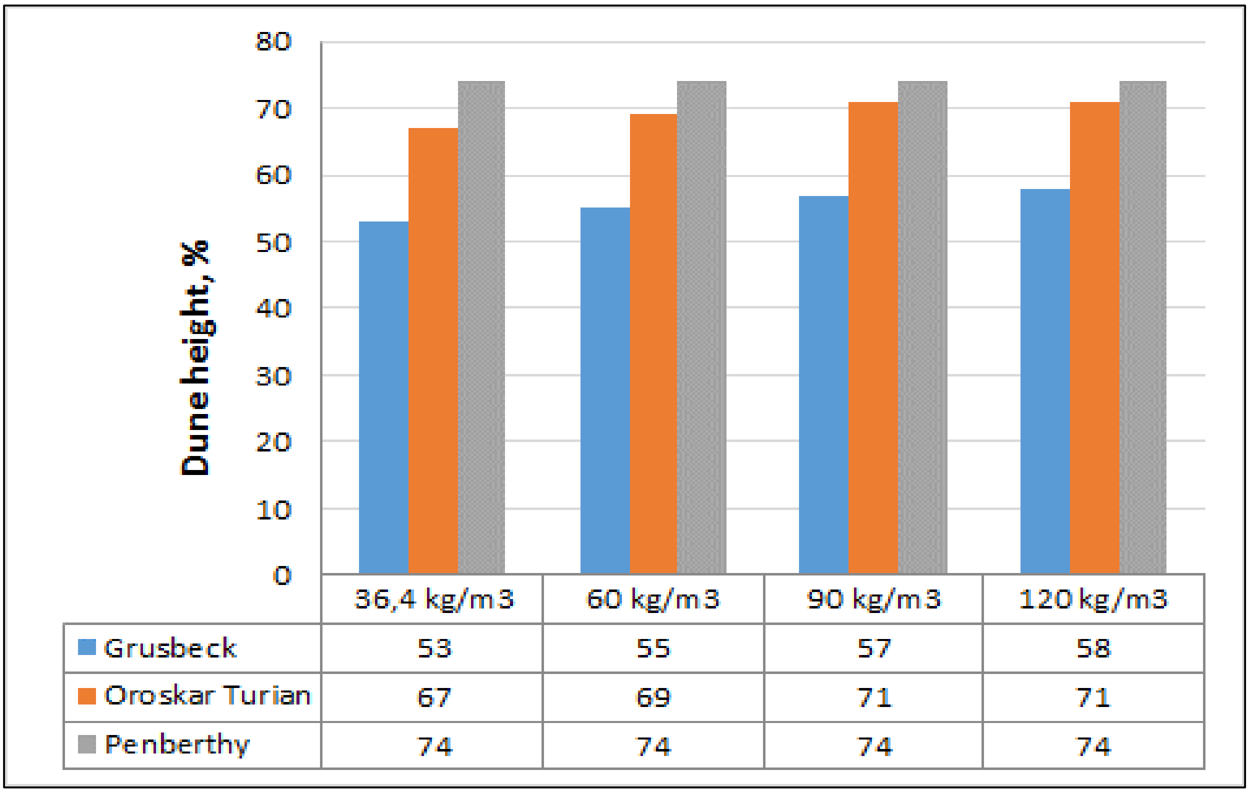


Figure 34 Predicted dune height from simulations with various gravel concentrations

The table below presents the percentage increase/decrease in critical velocity and dune height when moving from one gravel concentration to another.

Model		**Gruesbeck**	**Oroskar/ Turian**	**Penberthy**
%change from 36,4 kg/m^3 to 60 kg/m^3)		Vcrit=7% Dune=3,8%	Vcrit=5% Dune=3%	Vcrit=0% Dune=0%
%change from 60 kg/m^3 to 90 kg/m^3		Vcrit=0% Dune=3,6%	Vcrit=9,5% Dune=2,9%	Vcrit=0m/s Dune=0%
%change from 90 kg/m^3 to 120 kg/m^3		Vcrit=6,7% Dune=1,8%	Vcrit=0% Dune=0%	Vcrit=0% Dune=0%
%change from 36,4 kg/m^3 to 120 kg/m^3		**Vcrit=14,3% Dune=9,4%**	**Vcrit=15% Dune=6%**	**Vcrit=0% Dune=0%**

Table 7 Percentage increase/decrease from one simulation to another – gravel concentration

Figure 35 and 36 presents the plots from the actual simulation. The two plots compares the outcome of the simulation with the highest gravel concentration (120 kg/m3) and the lowest gravel concentration (36.4 kg/m^3).

Similar plots were obtained from the simulations with the simulations with 60 kg/m^3 and 90 kg/m^3. These two plots is included in the appendix (#3 & 4#).

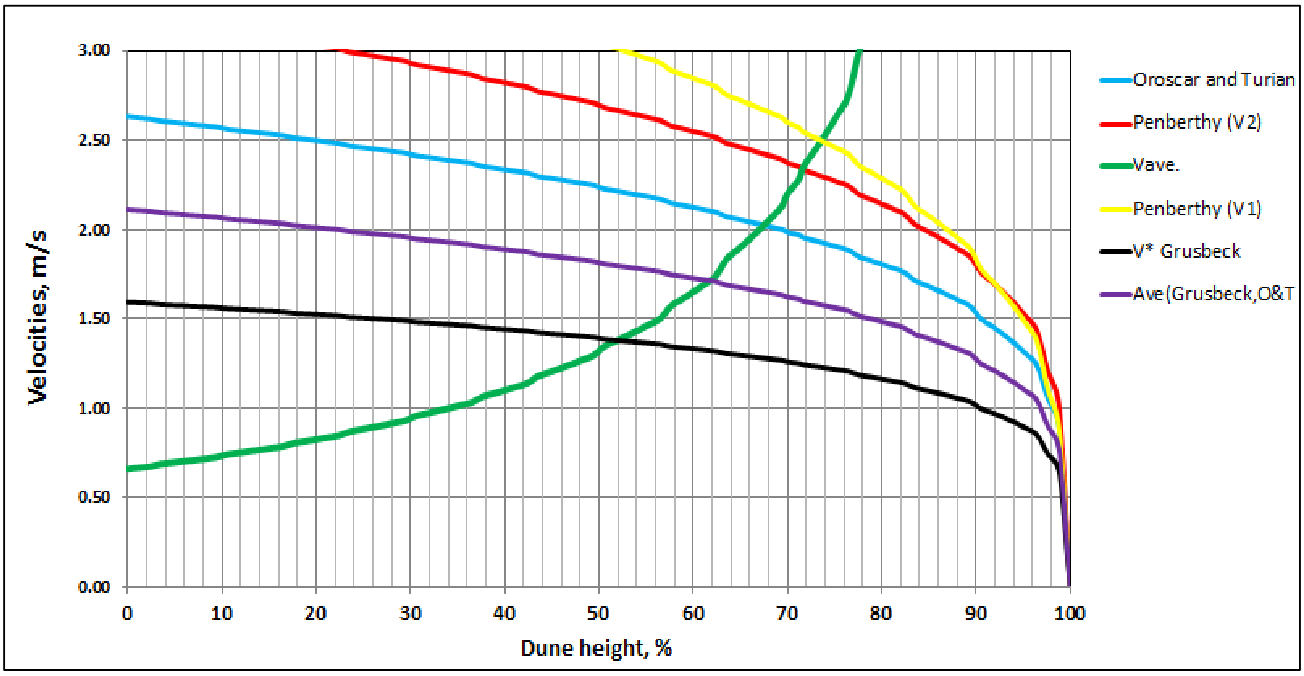


Figure 35 Plot from simulation with base case parameters.

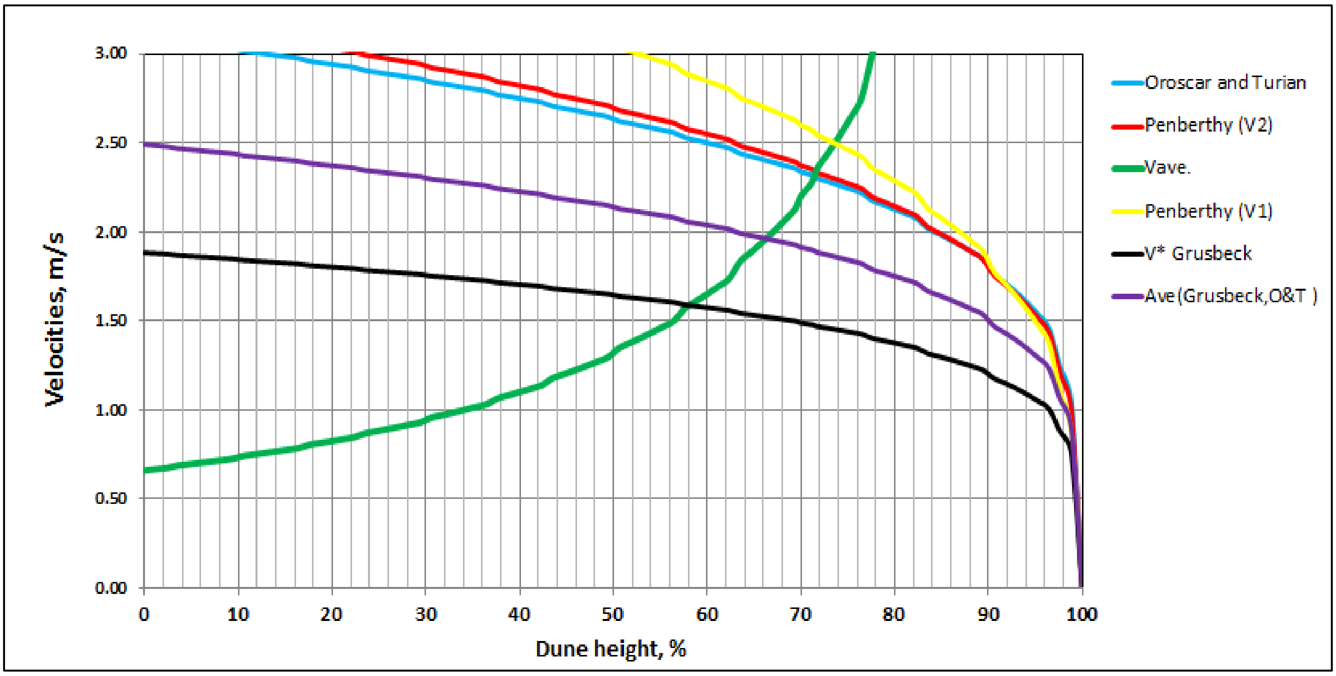


Figure 36 Plot from simulation with 120 kg/m3 gravel concentration in the slurry.

4.2.3 Effect of viscosity of carrier fluid

For this simulation, the viscosity of the slurry was varied from 1,3 cP to 10 cP while keeping the other parameters constant.

In some cases a polymer is added to the carrier fluid to increase its viscosity and carrying capacity for the gravel. When increasing the viscosity of the carrier fluid the beta wave starts earlier because more gravel is transported to the end of the well. A very high viscosity could result in an unpredictable packing pattern, no clean alpha beta wave progression. High viscosity slurry can also result in voids in the pack because some of the gravel could still be in suspension when screen out occurs.

Table 8 presents the input simulation parameters.

	Reference	Sim#1	Sim#2	Sim#3	Units
Flow rate	1000	1000	1000	1000	[LPM]
Gravel concentration	36,4	36,4	36,4	36,4	[KG/M^3]
Gravel size	625	625	625	625	[MICRON]
Apparent gravel SG	2,71	2,71	2,71	2,71	[SG]
Viscosity of carrier fluid	1,3	3	5	10	[CP]
Density of fluid	1,04	1,04	1,04	1,04	[SG}

Table 8 Input parameters for simulation with various slurry viscosity

Based on this simulation, as viscosity increase from 1.3 cP to 10 cP, the settling velocity decrease by 64,5 % . The higher the viscosity of the carrier fluid the lower is the settling velocity of the particle. Simulated results are shown on Figure 37.

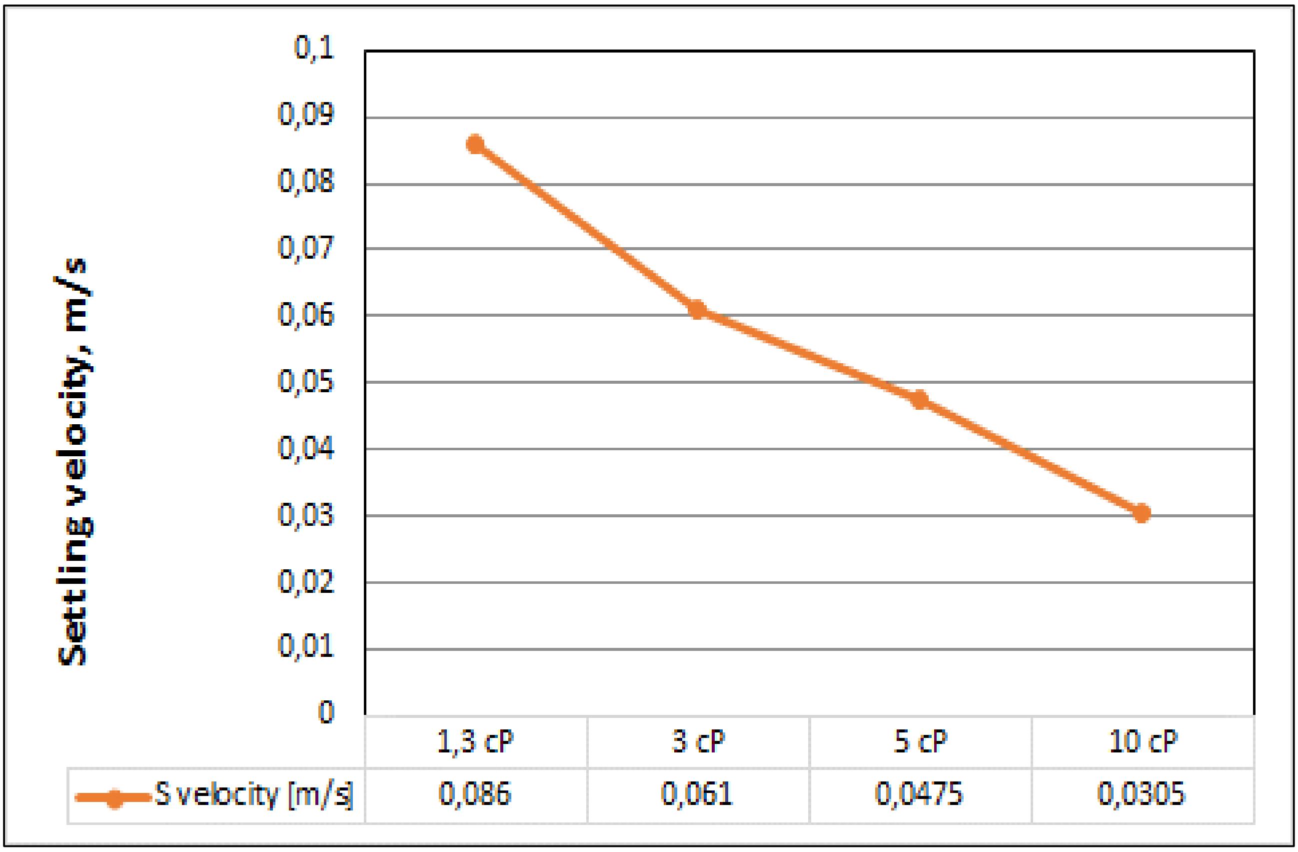
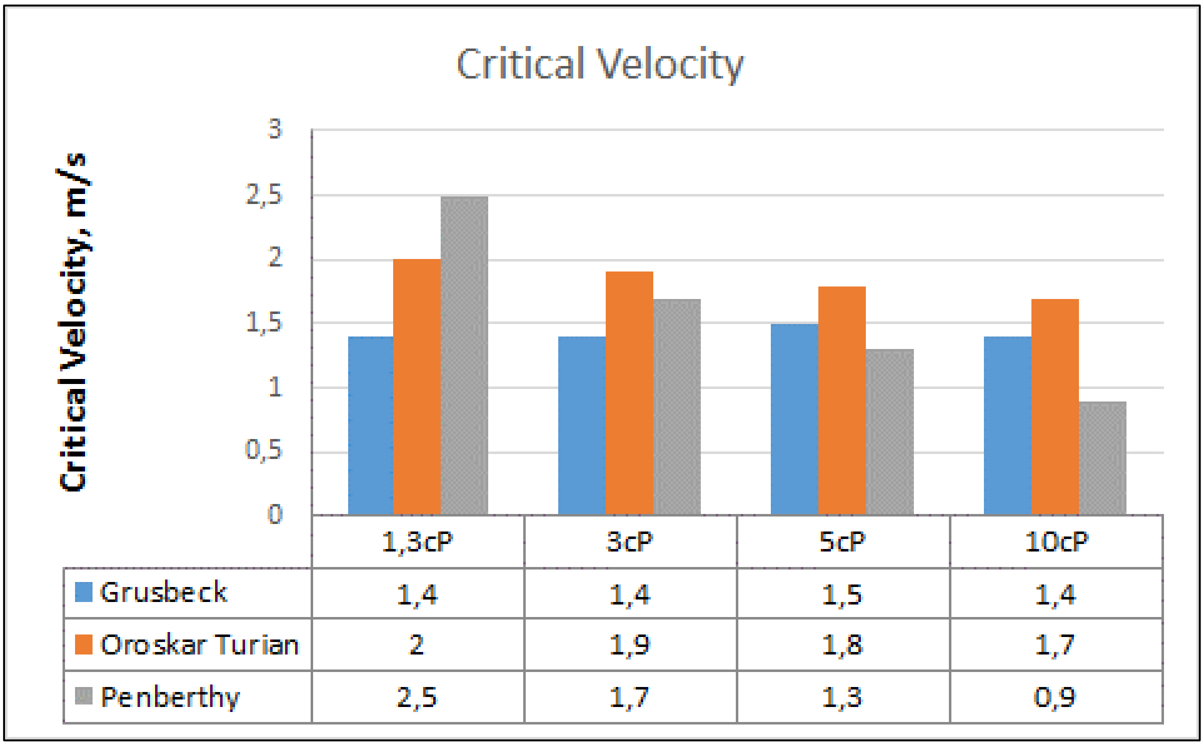


Figure 37 Plot presenting settling velocity with four different carrier fluid viscosities

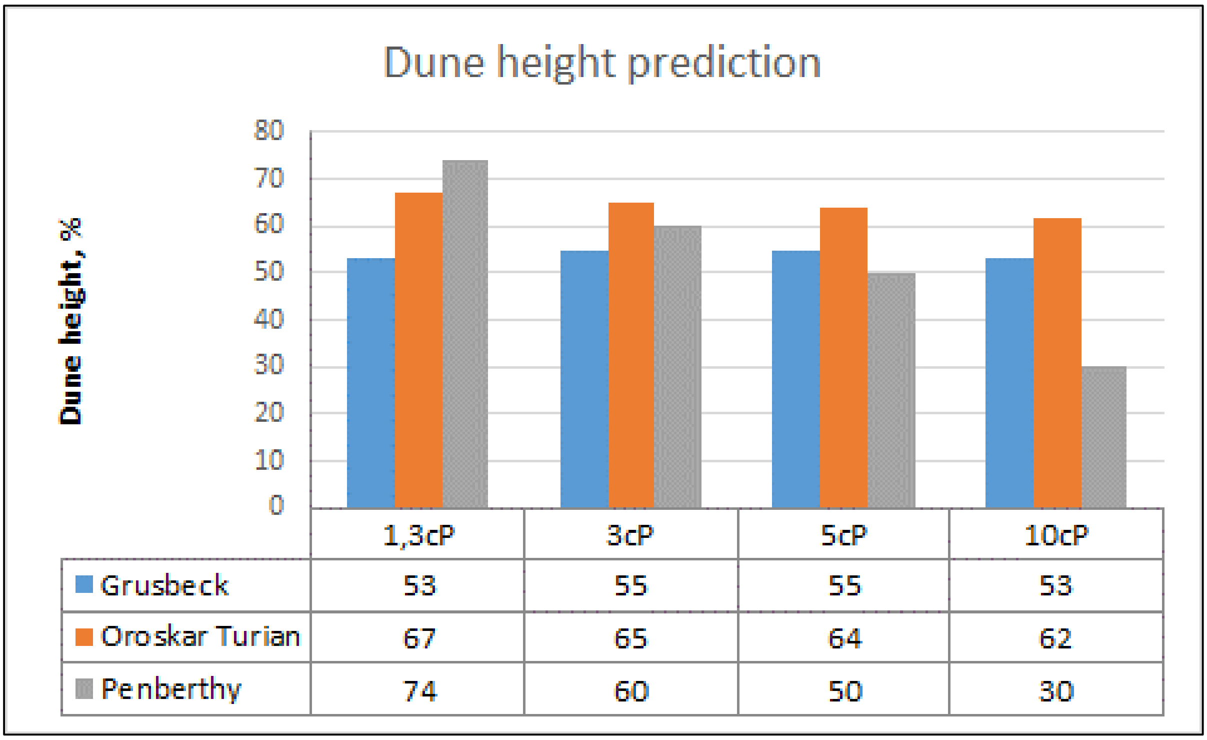
The settling velocities were used as input parameter for the dune height prediction. Actual dune height and critical velocity (green curve) with base case parameters and from the three models are plotted in figure 40.

Figure 38 below presents a summary of the predicted critical velocities for the three different models. Figure 39 presents a summary of the predicted dune heights from the simulations with the three different models.



	1,3cP	3cP	5cP	10cP
🟦 Grusbeck	1,4	1,4	1,5	1,4
🟧 Oroskar Turian	2	1,9	1,8	1,7
▨ Penberthy	2,5	1,7	1,3	0,9

Figure 38 Summary of the predicted critical velocity with different slurry viscosities



	1,3cP	3cP	5cP	10cP
🟦 Grusbeck	53	55	55	53
🟧 Oroskar Turian	67	65	64	62
▨ Penberthy	74	60	50	30

Figure 39 Summary of the predicted dune height with different slurry viscosities

Table 9 below presents the percentage increase/decrease in critical velocity and dune height when moving from one slurry viscosity to another.

Model		**Gruesbeck**	**Oroskar/ Turian**	**Penberthy**
%change from 1,3 cP to 3 cP		Vcrit=0% Dune=3,8%	Vcrit=-5% Dune=-3%	Vcrit=-32% Dune=-19%
%change from 3 cP to 5 cP		Vcrit=7,1% Dune=0%	Vcrit=-5,3% Dune=-1,5%	Vcrit=-24m/s Dune=-17%
%change from 5 cP to 10 cP		Vcrit=-6,7% Dune=-3,6%	Vcrit=-5,6% Dune=-3%	Vcrit=-31% Dune=-40%
%change from 1,3 cP to 10 cP		**Vcrit=0%** **Dune=0%**	**Vcrit=-7,5%** **Dune=6%**	**Vcrit=-64%** **Dune=-60%**

Table 9 Increase/decrease in dune height and critical velocity with varying viscosities

Figure 40 and 41 compares the outcome of the simulation with the highest viscosity carrier fluid (10 cP) and the lowest viscosity carrier fluid (1.3 cP, base case) . Plots from the simulations with 3 cP carrier fluid and 5 cP carrier fluid are included in the appendix (#5 & #6).

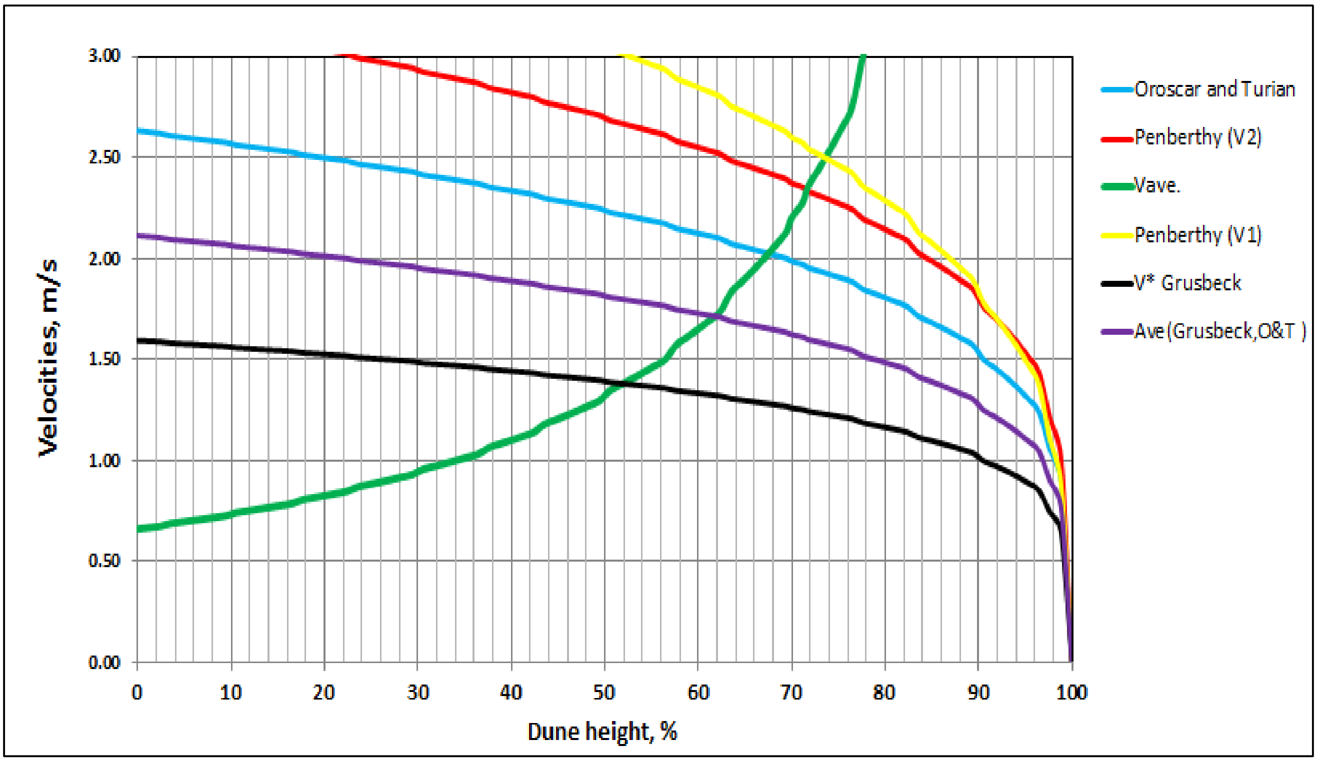


Figure 40 Plot from simulation with 1,3 cP viscous carrier fluid

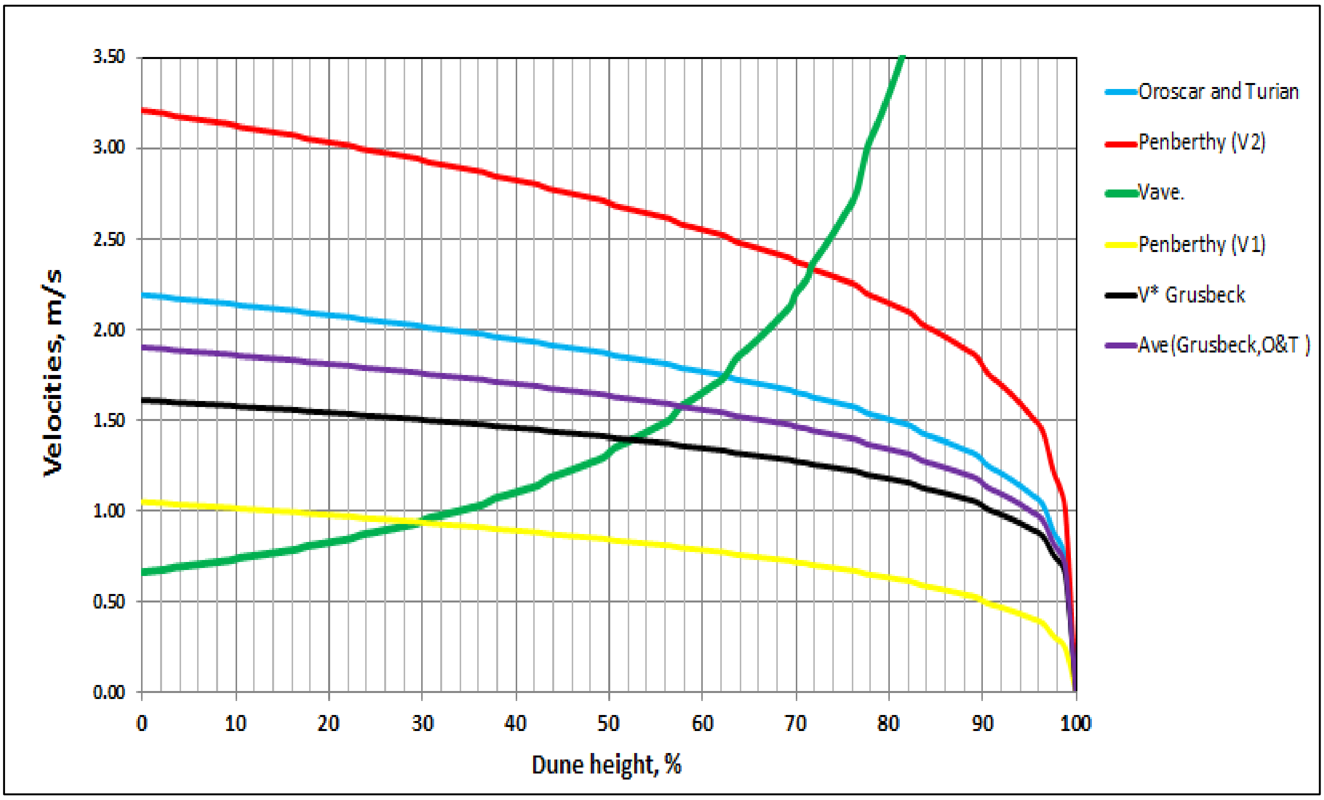


Figure 41 Plot from simulation with a carrier fluid viscosity of 10 cP

4.2.4 Effect of gravel size

For this simulation, the gravel size was varied from 625 micron to 900 micron while keeping the other parameters constant.

625 micron gravel size is a typical average gravel size for 20/40 us mesh gravel which is a size that is very commonly used for gravel pack operations in the north sea.

Table 15 is the input simulation parameters.

	Reference	Sim#1	Sim#2	Sim#3	Units
Flow rate	1000	1000	1000	1000	[LPM]
Gravel concentration	36,4	36,4	36,4	36,4	[KG/M^3]
Gravel size	625	700	800	900	[MICRON]
Apparent gravel SG	2,71	2,71	2,71	2,71	[SG]
Viscosity of carrier fluid	1,3	1,3	1,3	1,3	[cP]
Density of fluid	1,04	1,04	1,04	1,04	[SG}

Table 10 Input parameters for simulations with varying gravel size

Based on this simulation, as gravel size increase from 625 micron to 900 micron the settling velocity increase by 43 %. When gravel size increase the settling velocity in fluid also increase. Simulated results are shown on Figure 42.

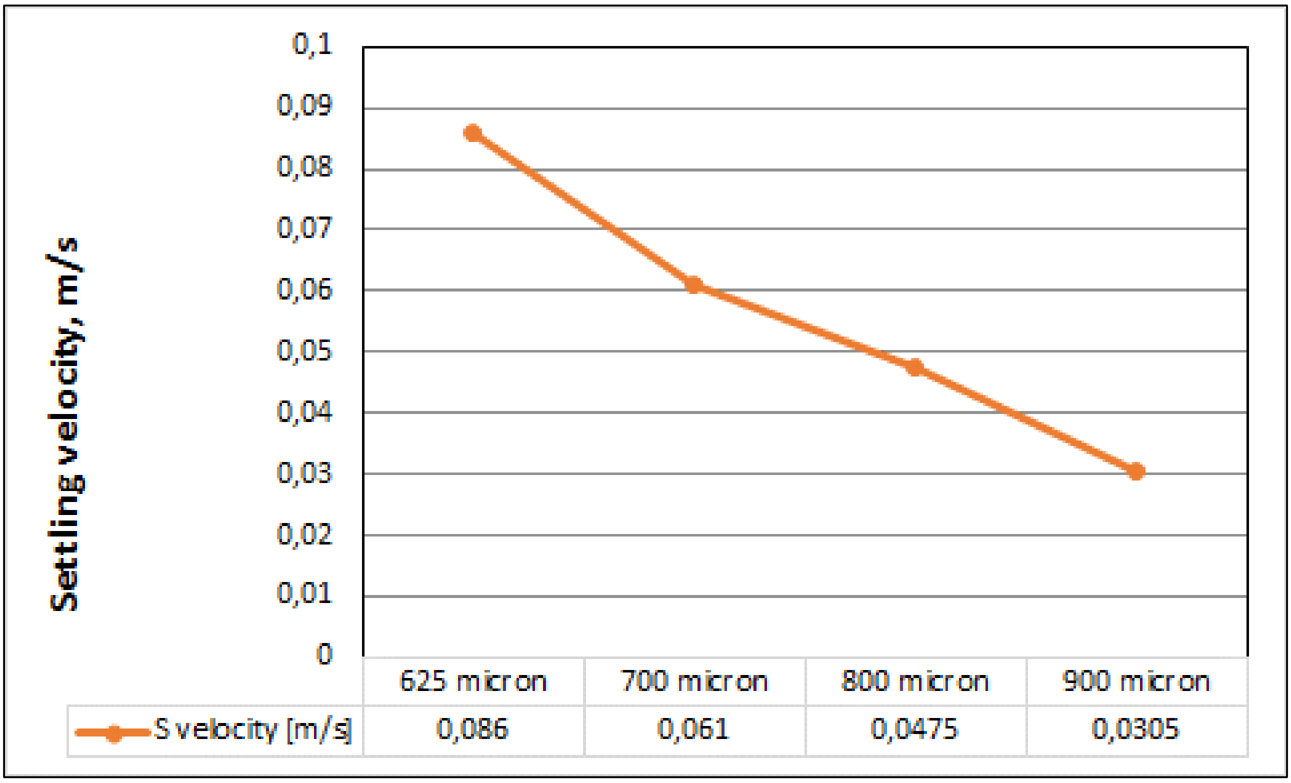
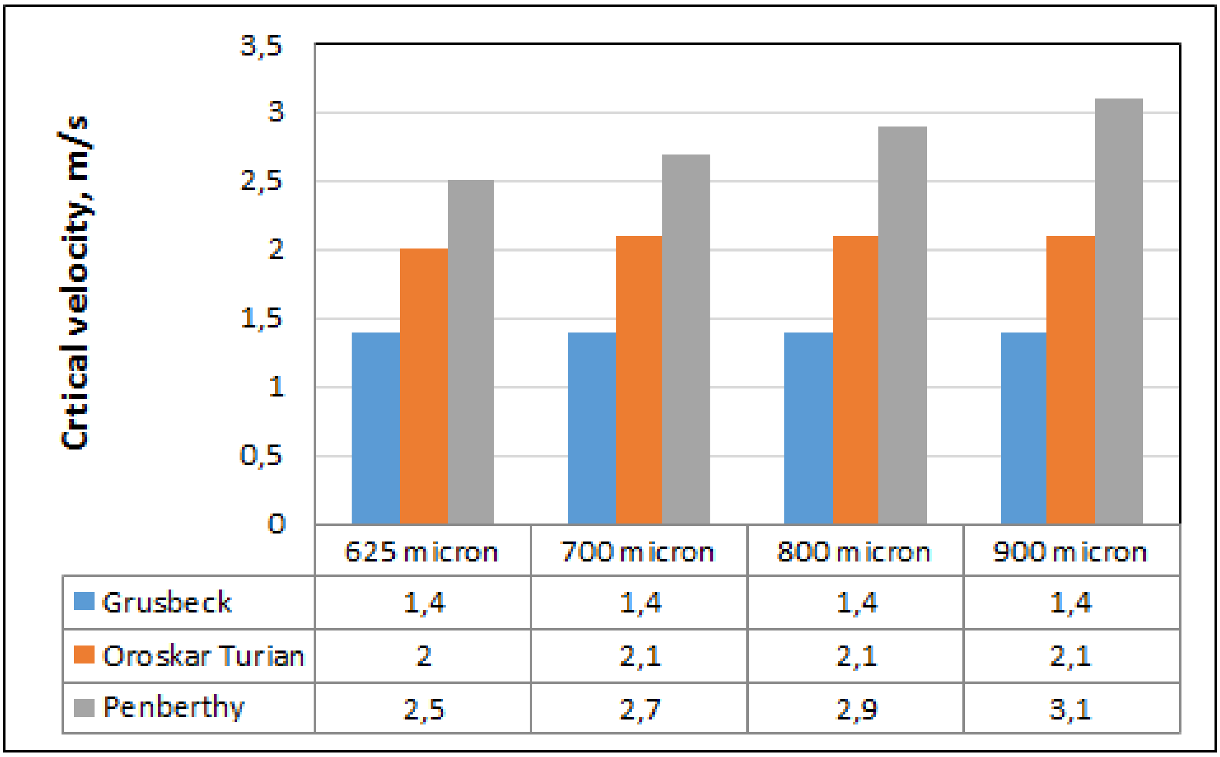


Figure 42 Settling velocity for four different gravel sizes

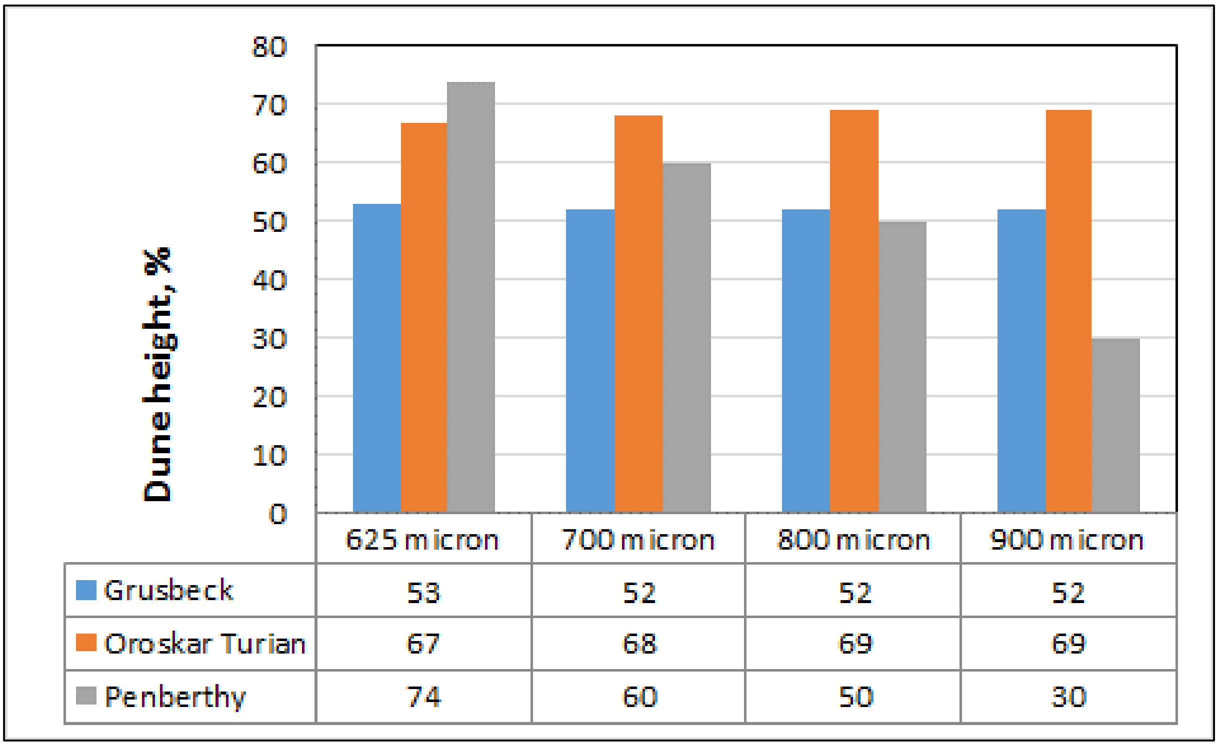
The settling velocities were used as input parameter for the dune height prediction. Actual velocity (green curve) with base case parameters and critical velocity from the three models concerning dune height are plotted in figure 45.

Figure 43 below presents a summary of the critical velocities from the simulations with the four different densities while figure 44 presents the predicted dune height from the simulations.



	625 micron	700 micron	800 micron	900 micron
■ Grusbeck	1,4	1,4	1,4	1,4
■ Oroskar Turian	2	2,1	2,1	2,1
■ Penberthy	2,5	2,7	2,9	3,1

Figure 43 Summary of predicted critical velocity from simulations with varying gravel size



	625 micron	700 micron	800 micron	900 micron
■ Grusbeck	53	52	52	52
■ Oroskar Turian	67	68	69	69
■ Penberthy	74	60	50	30

Figure 44 Summary of predicted dune height from simulations with varying gravel size.

The table below, table 11, presents a summary of the simulations with the different gravel sizes concerning increase or decrease of the critical velocity and bed height value when moving from one gravel size to another.

Model		**Gruesbeck**	**Oroskar/ Turian**	**Penberthy**
%change from 625 -> 700 micron		Vcrit=0% Dune=-2%	Vcrit=5% Dune=1%	Vcrit=8% Dune=3%
%change from 700 -> 800 micron		Vcrit=0% Dune=0%	Vcrit=0% Dune=1%	Vcrit=7m/s Dune=1%
%change from 800 -> 900 micron		Vcrit=0% Dune=0%	Vcrit=0% Dune=0%	Vcrit=7% Dune=3%
%change from 625 -> 900 micron		Vcrit=0% Dune=-2%	Vcrit=5% Dune=3%	Vcrit=24% Dune=7%

Table 11 Increase/decrease in dune height and corresponding critical velocity

Figure 45 and 46 compares the outcome of the simulation with the biggest gravel (900 Micron) and the smallest gravel (625 micron). . Plots from the simulations with 700 micron and 800 micron are included in the appendix (#7 & #8).

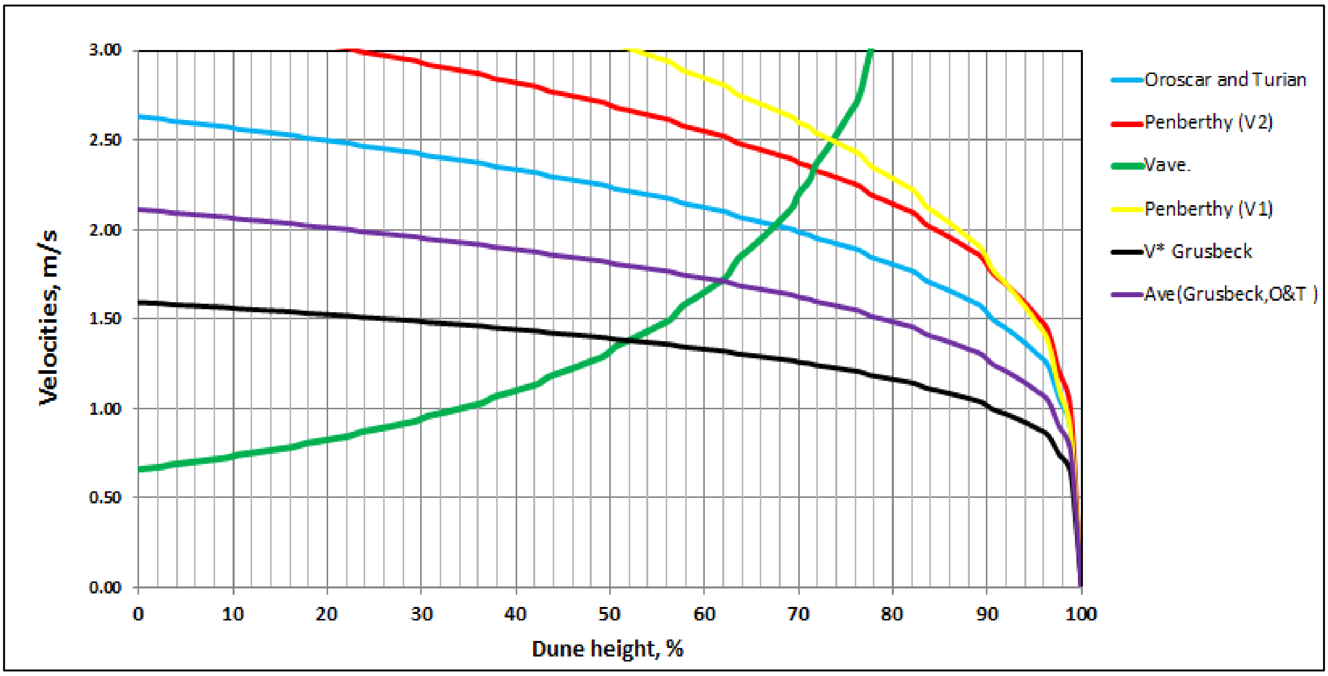


Figure 45 Plot from simulation with 625-micron gravel size

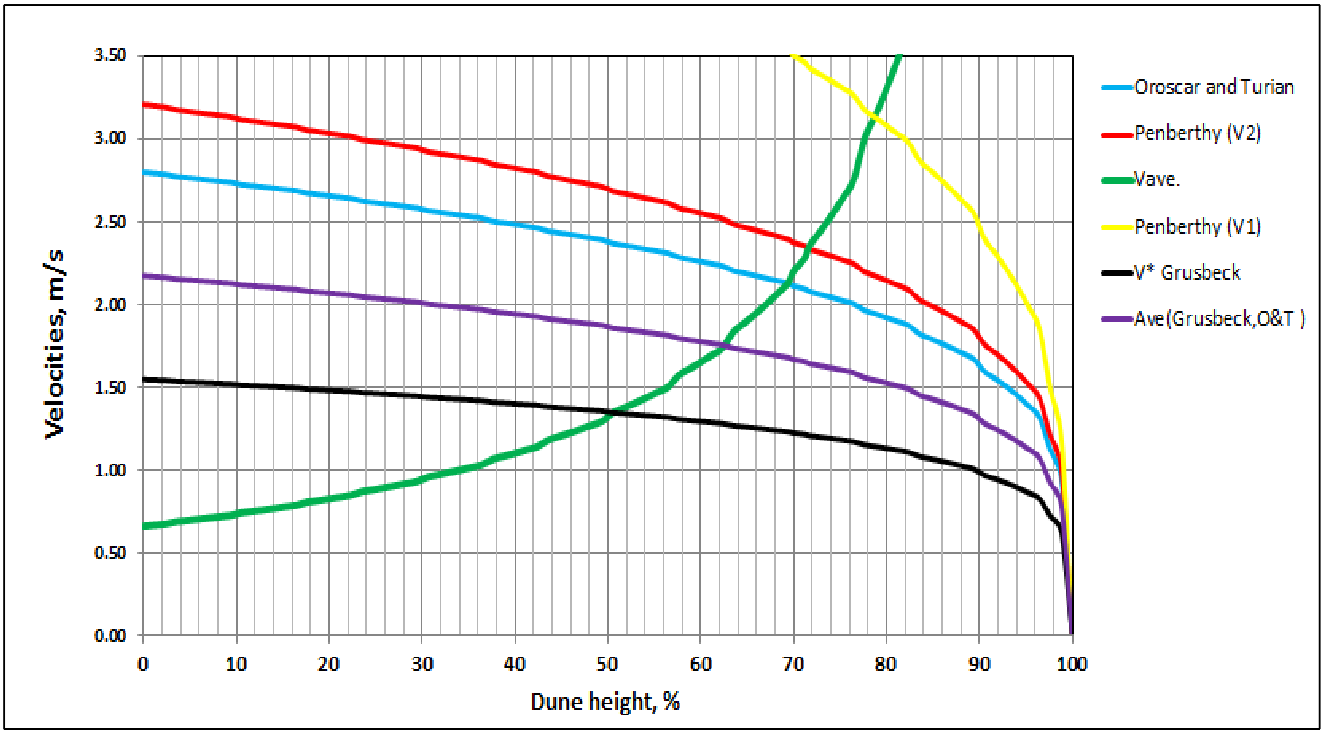


Figure 46 Plot from simulation with gravel size 900 micron

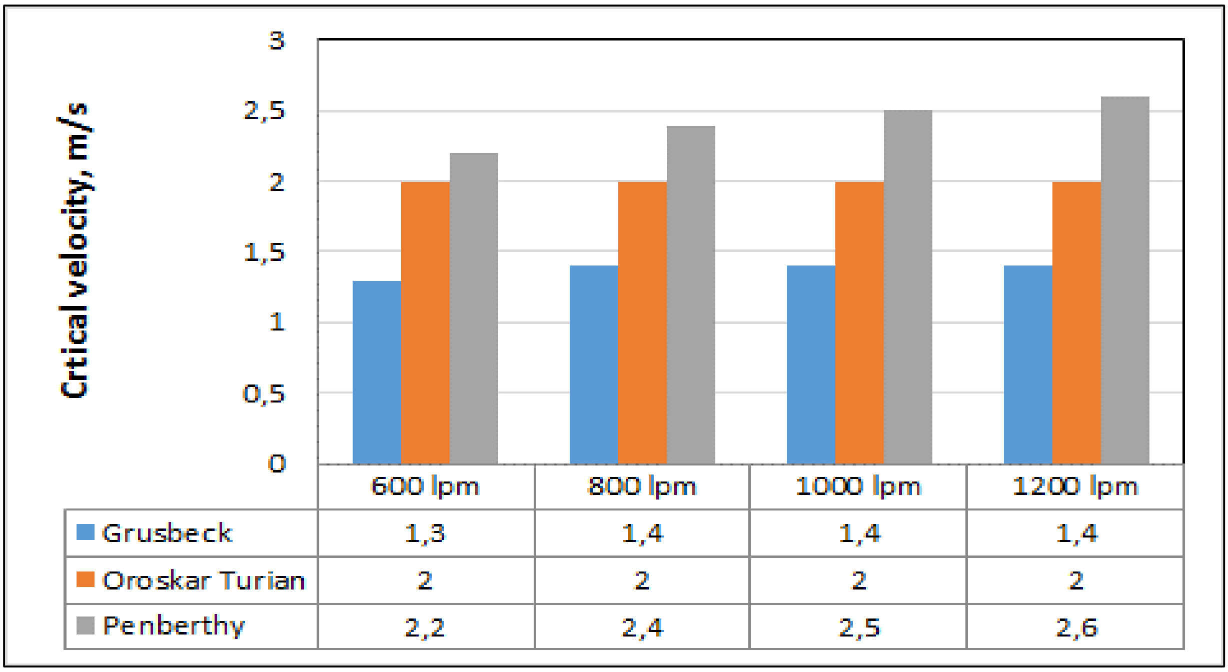
4.2.5 Effect of flow rate

For this simulation, the flow rate was varied from 600 lpm to 1200 lpm while keeping the other parameters constant. Table 12 is the input simulation parameters.

	Reference	Sim#1	Sim#2	Sim#3	Units
Flow rate	1000	600	800	1200	[LPM]
Apparent gravel SG	2,71	2,71	2,71	2,71	[SG]
Gravel concentration	36,4	36,4	36,4	36,4	[KG/M^3]
Viscosity of carrier fluid	1,3	1,35	1,45	1,3	[CP]
Gravel size	625	625	625	625	[micron]
Density of fluid	1,04	1,2	1,5	1,8	[SG}

Table 12 input parameters for simulations with varying flow rates

The settling velocity is not affected as the flow rate increase from 600 lpm to 1200 lpm. The settling velocity of 0,086 m/s was used as input parameter for dune height prediction for the three different flow rates. Figure 47 below presents a summary of the predicted critical velocity from the three different models while figure 48 presents a summary of the predicted dune height from the three different models



	600 lpm	800 lpm	1000 lpm	1200 lpm
🟦 Grusbeck	1,3	1,4	1,4	1,4
🟧 Oroskar Turian	2	2	2	2
⬜ Penberthy	2,2	2,4	2,5	2,6

Figure 47 Summary of predicted critical velocity with four different flow rates

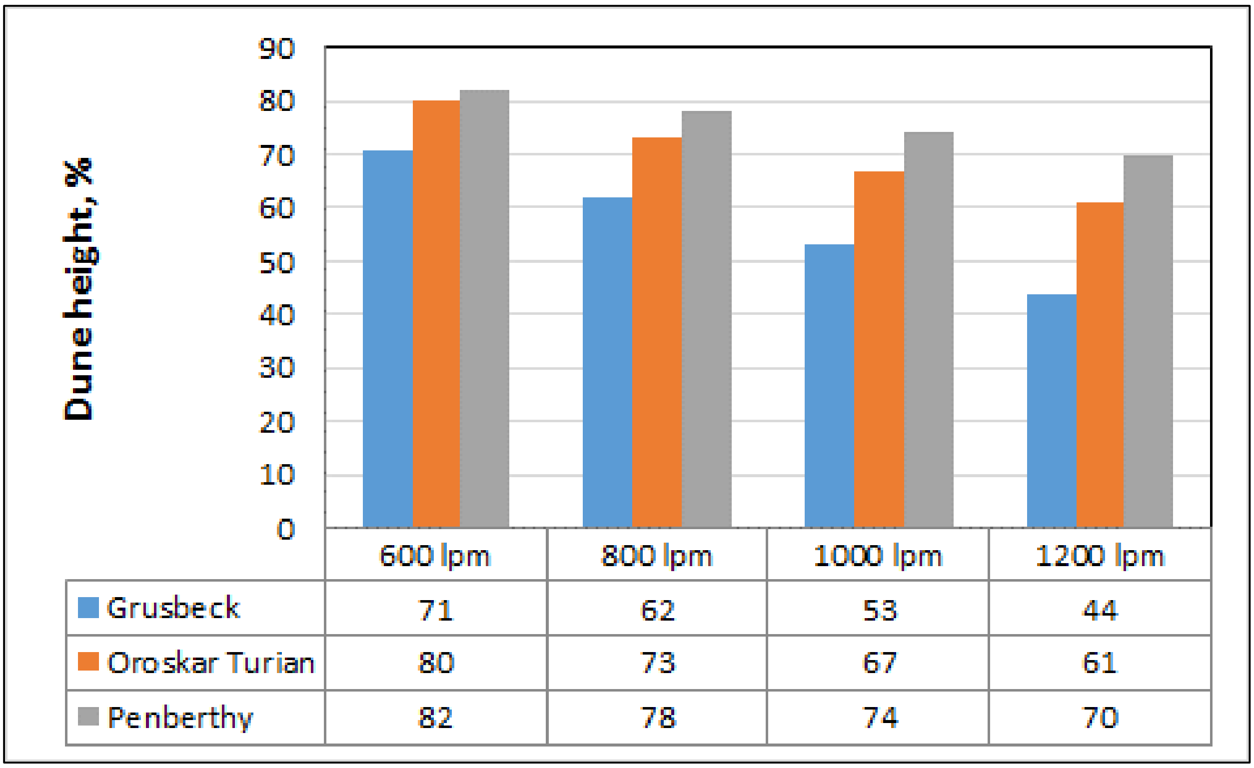


Figure 48 Summary of predicted dune height with four different flow rates

The table below presents a summary of the simulations with the different gravel sizes concerning increase or decrease of the critical velocity and bed height value.

Model		**Gruesbeck**	**Oroskar/ Turian**	**Penberthy**
%change from 600 -> 800 lpm		Vcrit=8% Dune=-13%	Vcrit=0% Dune=-9%	Vcrit=9% Dune=-5%
%change from 800 -> 1000 lpm		Vcrit=0% Dune=-15%	Vcrit=0% Dune=-8%	Vcrit=4% Dune=-5%
%change from 1000 -> 1200 lpm		Vcrit=0% Dune=-17%	Vcrit=0% Dune=-9%	Vcrit=4% Dune=-5%
%change from 600 -> 1200 lpm		Vcrit=8% Dune=-38%	Vcrit=0% Dune=-24%	Vcrit=18% Dune=-15%

Table 13 Increase/decrease in dune height from one simulation to another

Figure 49 and 50 presents the plots from the actual simulation. The two plots compares the outcome of the simulation with the highest flow rate (1200 lpm) and the lowest flow rate (600 lpm). Similar plots were obtained from the simulations with the simulations with 800 lpm and 1000 lpm (Base case). These two plots is included in the appendix (#9 & #10).

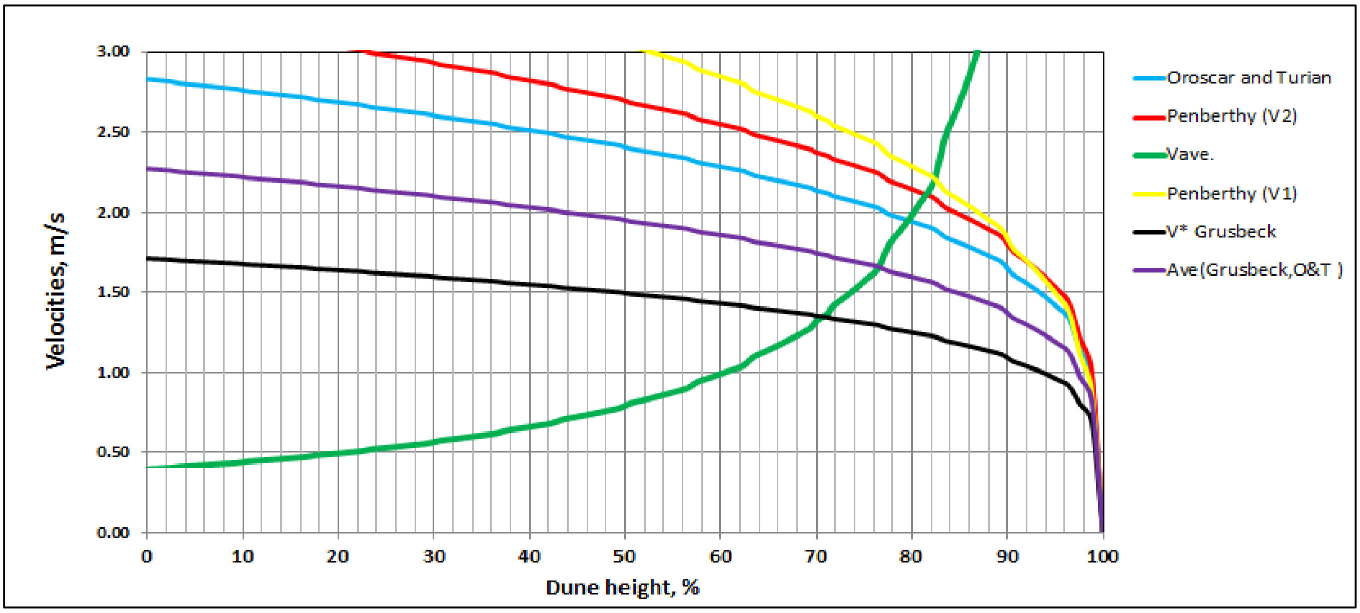


Figure 49 Simulation plot from simulation with 600 lpm

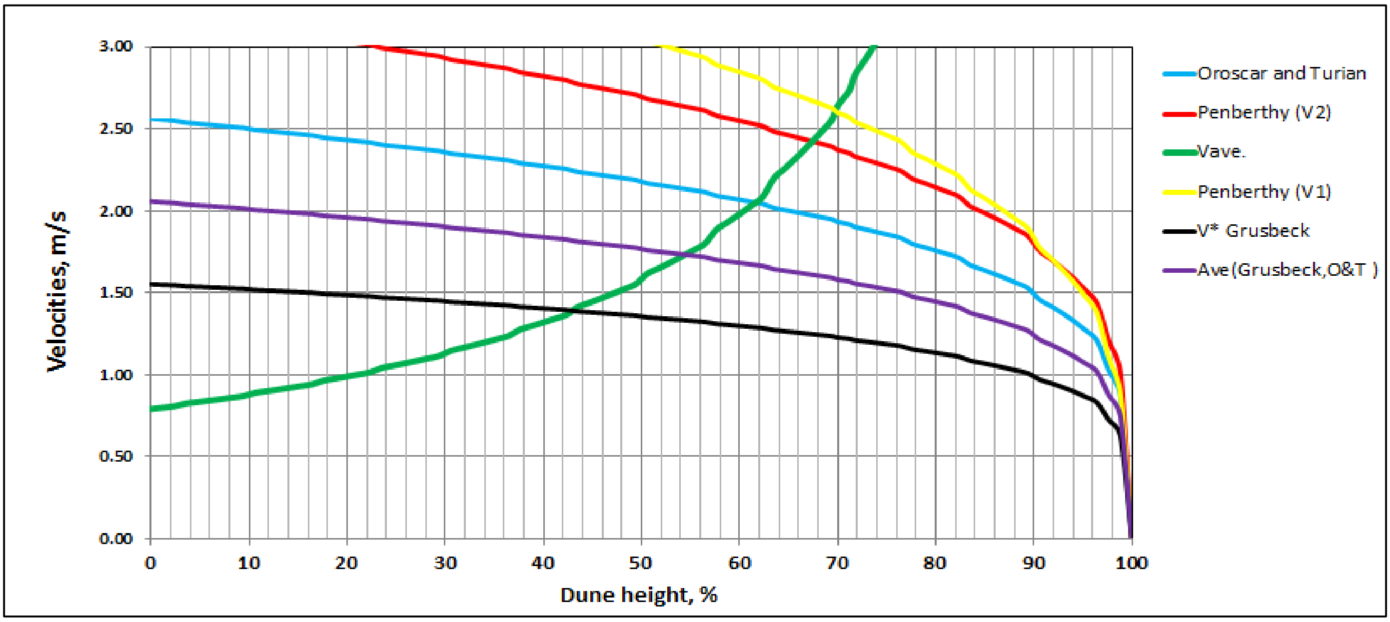


Figure 50 Simulation plot from simulation with 1200 lpm

4.3 Effect of combined parameters on bed height and critical velocity

In this part of the study two parameters has been altered in the simulation while the other parameters has been according to base case scenario. The objective is to evaluate which model is more sensitive to combined parameter change and how this change affects the predicted dune height.

4.3.1 Effect of rate and gravel concentration in combination

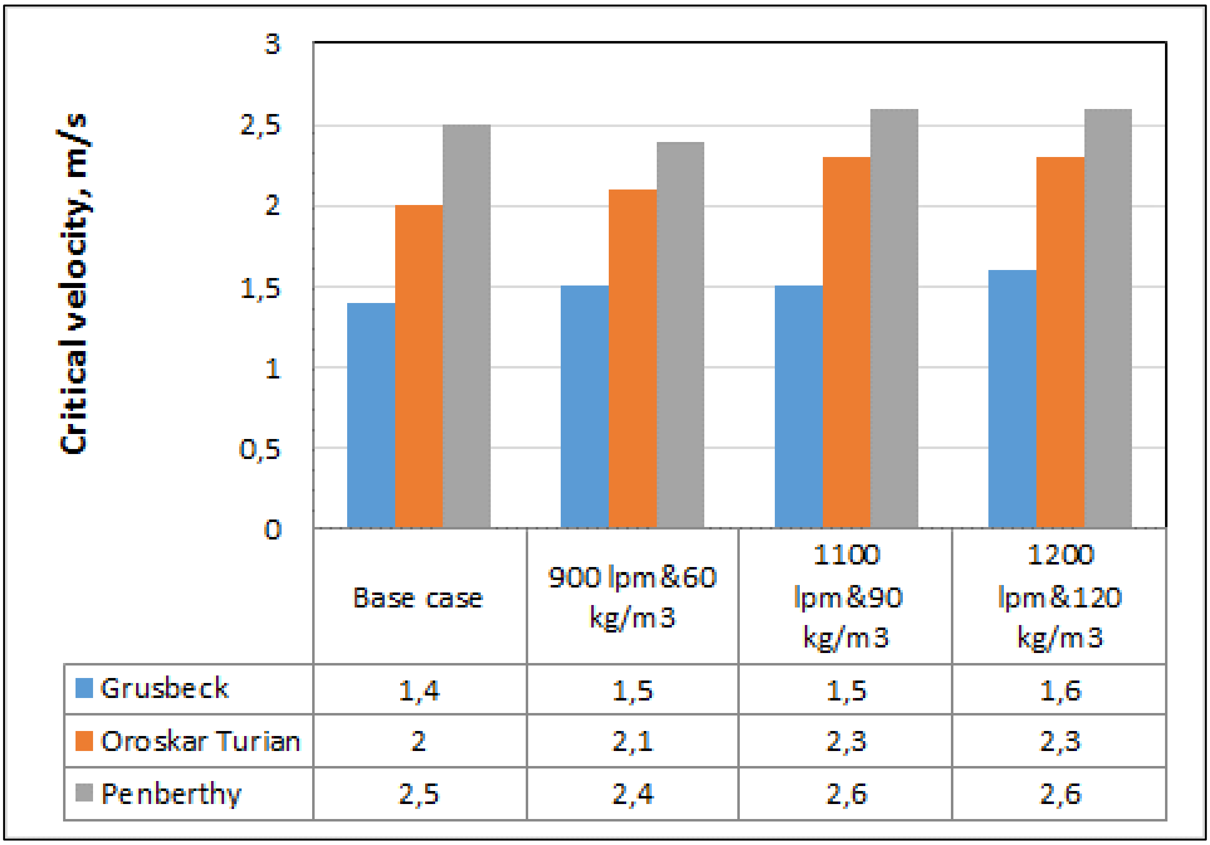
For this simulation, the flow rate was varied from 600 lpm to 1200 lpm and the gravel concentration was varied from 36,4 kg/m^3 to 120 kg/m^3 respectively while keeping the other parameters constant at base case level. Table 14 is the input simulation parameters.

	Reference	Sim#1	Sim#2	Sim#3	Units
Flow rate	1000	900	1100	1200	[LPM]
Gravel concentration	36,4	60	90	120	[KG/M^3]
Apparent gravel SG	2,71	2,71	2,71	2,71	[SG]
Viscosity of carrier fluid	1,3	1,3	1,3	1,3	[CP]
Gravel size	625	625	625	625	[micron]
Density of fluid	1,04	1,04	1,04	1,04	[SG}

Table 14 input parameters for simulations with varying flow rates and gravel concentration

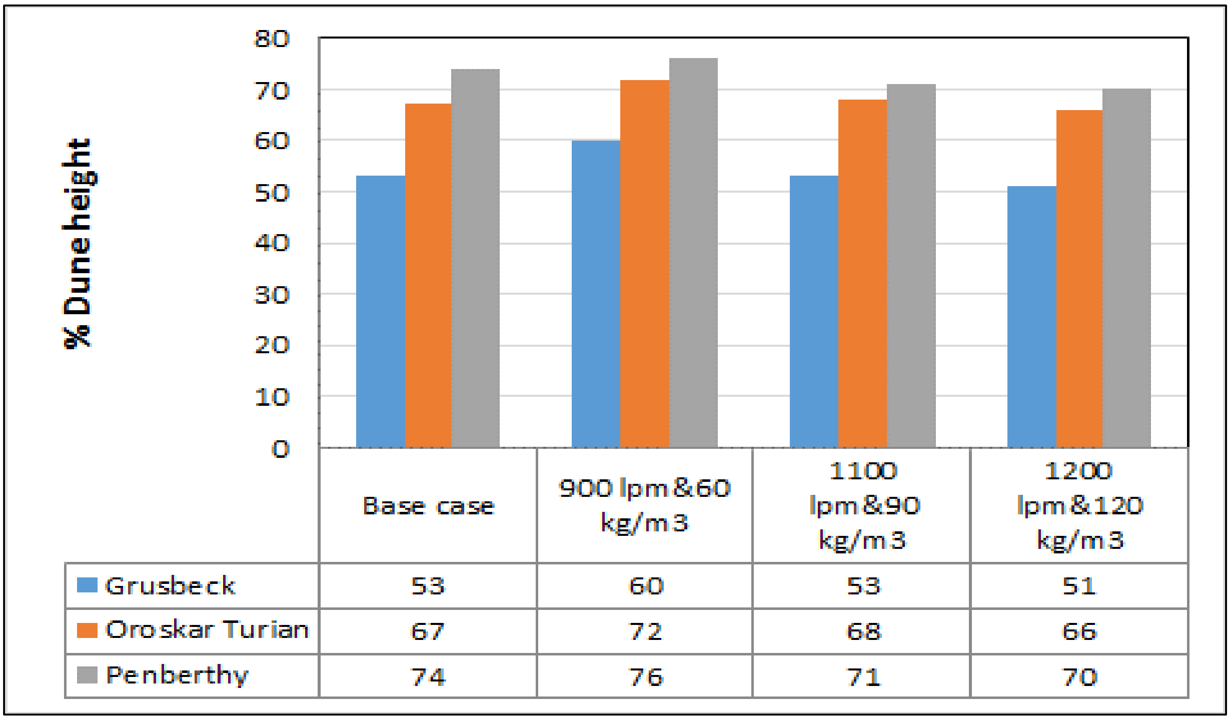
The settling velocity is not affected by flow rate or gravel concentration. The settling velocity of 0,086 m/s was used as input parameter for dune height prediction for the three different flow rates.

In figure 51 the predicted critical velocity with varying flowrate and gravel concentration is presented graphically and the different models are compared to each other. Similar figure is obtained in figure 52 but this time for the predicted dune height.



	Base case	900 lpm&60 kg/m3	1100 lpm&90 kg/m3	1200 lpm&120 kg/m3
🟦 Grusbeck	1,4	1,5	1,5	1,6
🟧 Oroskar Turian	2	2,1	2,3	2,3
▨ Penberthy	2,5	2,4	2,6	2,6

Figure 51 Summary of critical velocity prediction from simulation with varying flow rate and gravel concentration



	Base case	900 lpm&60 kg/m3	1100 lpm&90 kg/m3	1200 lpm&120 kg/m3
🟦 Grusbeck	53	60	53	51
🟧 Oroskar Turian	67	72	68	66
▨ Penberthy	74	76	71	70

Figure 52 Summary of dune height prediction from simulations with varying flow rate and gravel concentration.

Figure 53 presents the plot from the simulation with 1200 LPM injection rate and 120 kg/m^3. Similar plot is obtained with the two other combinations of flowrate and gravel concentration, these plots are included in the appendix (#11 & #12).

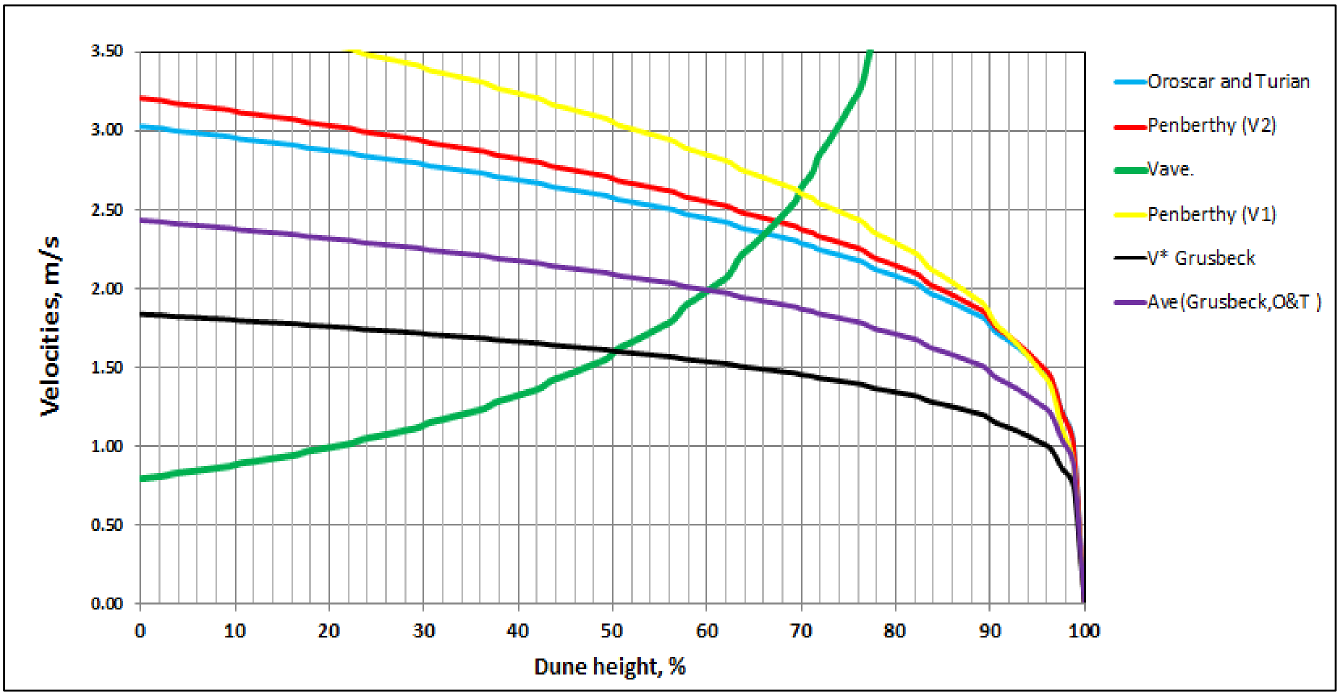


Figure 53 Plot from simulation with 1200 lpm and 120 kg/m3.

4.3.2 Effect of rate and carrier fluid density in combination

For this simulation, the flow rate was varied from 800 lpm to 1100 lpm and the carrier fluid density was varied from 1,2 SG to 1,8 SG while keeping the other parameters constant at base case level. Table 15 is the input simulation parameters.

	Reference	Sim#1	Sim#2	Sim#3	Units
Flow rate	1000	800	900	1100	[LPM]
Carrier fluid density	1,04	1,8	1,5	1,2	[SG]
Apparent gravel SG	2,71	2,71	2,71	2,71	[SG]
Viscosity of carrier fluid	1,3	1,3	1,3	1,3	[cP]
Gravel size	625	625	625	625	[micron]
Gravel concentration	36,4	36,4	36,4	36,4	[KG/M^3]

Table 15 Input parameters from simulation with varying flow rate and carrier fluid density

Based on this simulation, as density increase from 1.04 to 1.8, the settling velocity decrease by 44,8 %. The settling velocity is not affected by the flow rate. The settling velocity for the different carrier fluid densities are presented in figure 54.

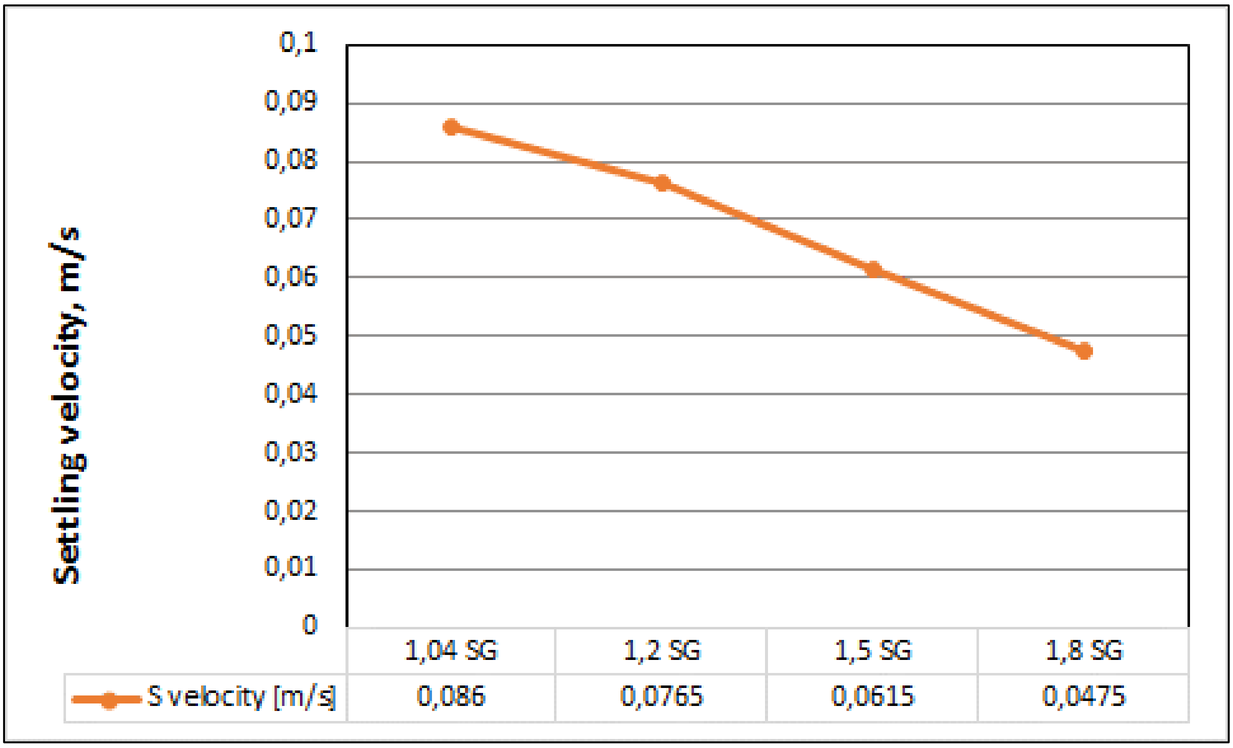
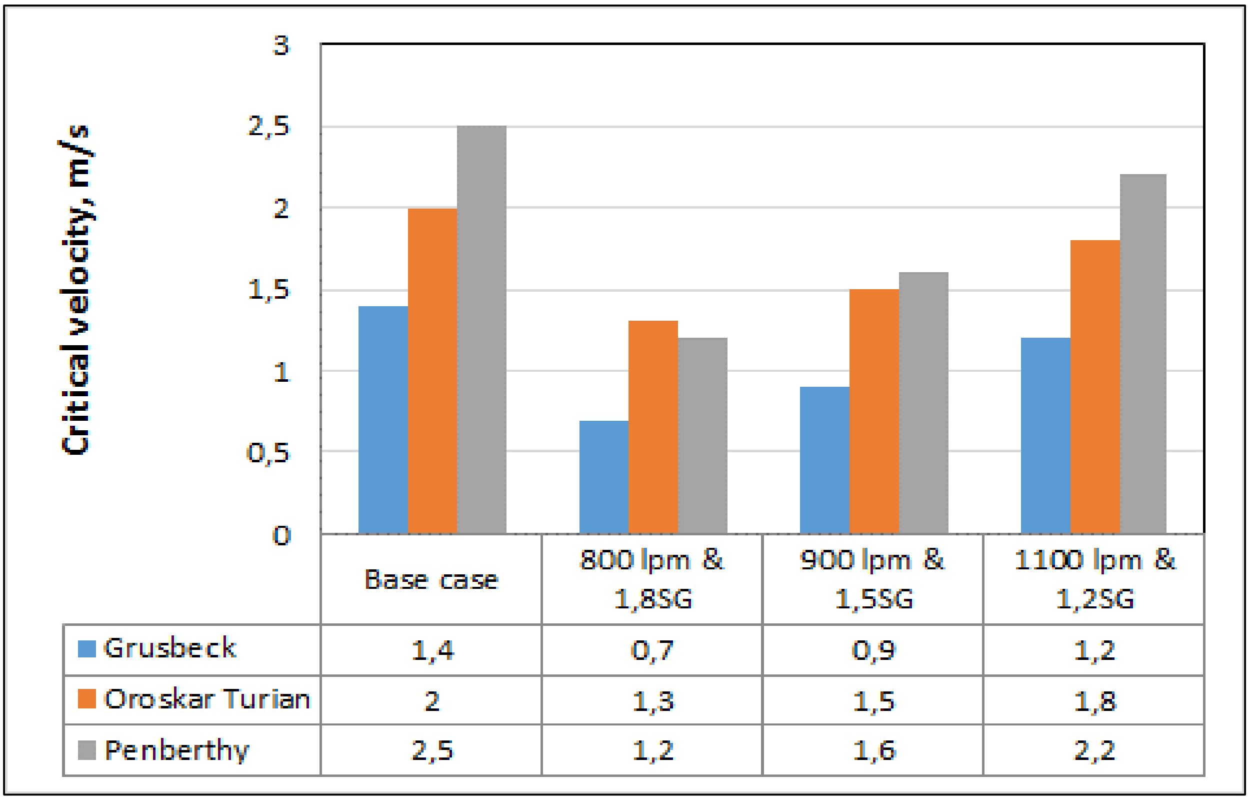


Figure 54 Settling velocities for various carrier fluid densities.

The settling velocities in figure 53 were used as input parameter for the dune height prediction and critical velocity.

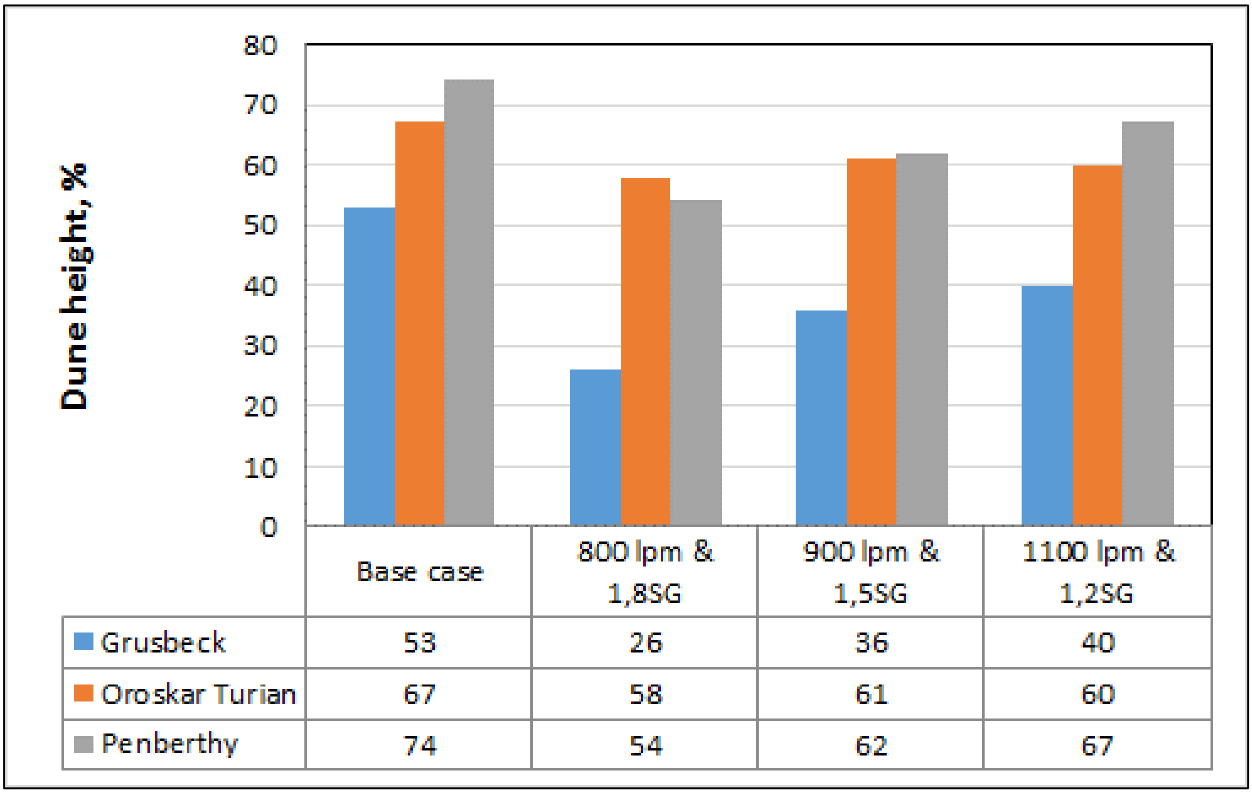
Figure 54 below presents a summary of the predicted critical velocities from the simulations with the four different parameter combinations.

Figure 55 presents a summary of the predicted dune heights from the three models.



	Base case	800 lpm & 1,8SG	900 lpm & 1,5SG	1100 lpm & 1,2SG
🟦 Grusbeck	1,4	0,7	0,9	1,2
🟧 Oroskar Turian	2	1,3	1,5	1,8
■ Penberthy	2,5	1,2	1,6	2,2

Figure 55 Predicted critical velocity with four rate and carrier fluid SG combinations



	Base case	800 lpm & 1,8SG	900 lpm & 1,5SG	1100 lpm & 1,2SG
🟦 Grusbeck	53	26	36	40
🟧 Oroskar Turian	67	58	61	60
■ Penberthy	74	54	62	67

Figure 56 Predicted dune height with four rate and carrier fluid SG combinations

Actual velocity with base case parameters and critical velocity from the three models concerning dune height are plotted in figure 57.

Figure 57 and 58 compares the outcome of the simulation with 800 lpm and 1,8 SG carrier fluid density and outcome from simulation with 1100 lpm and 1,2 SG carrier fluid. Similar plot from simulation with 900 lpm and 1,5 SG carrier fluid is included in the appendix (#13).

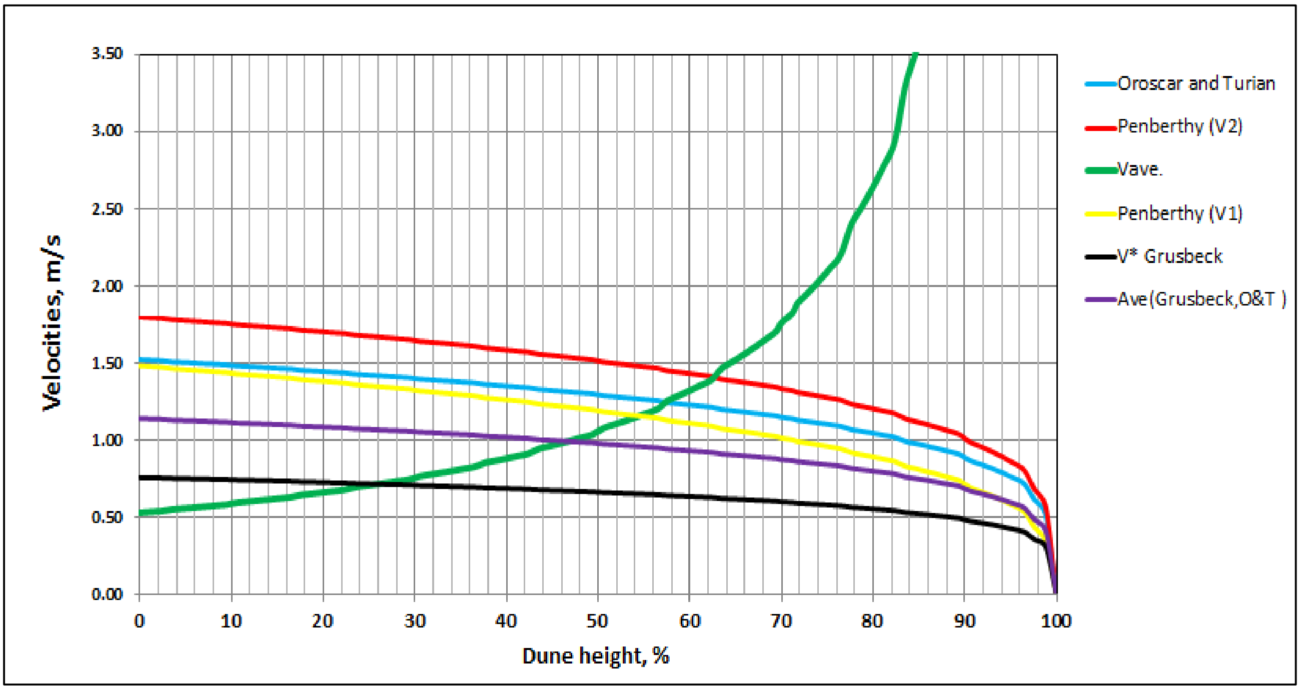


Figure 57 Plot from simulation with 800 lpm and 1,8 SG carrier fluid

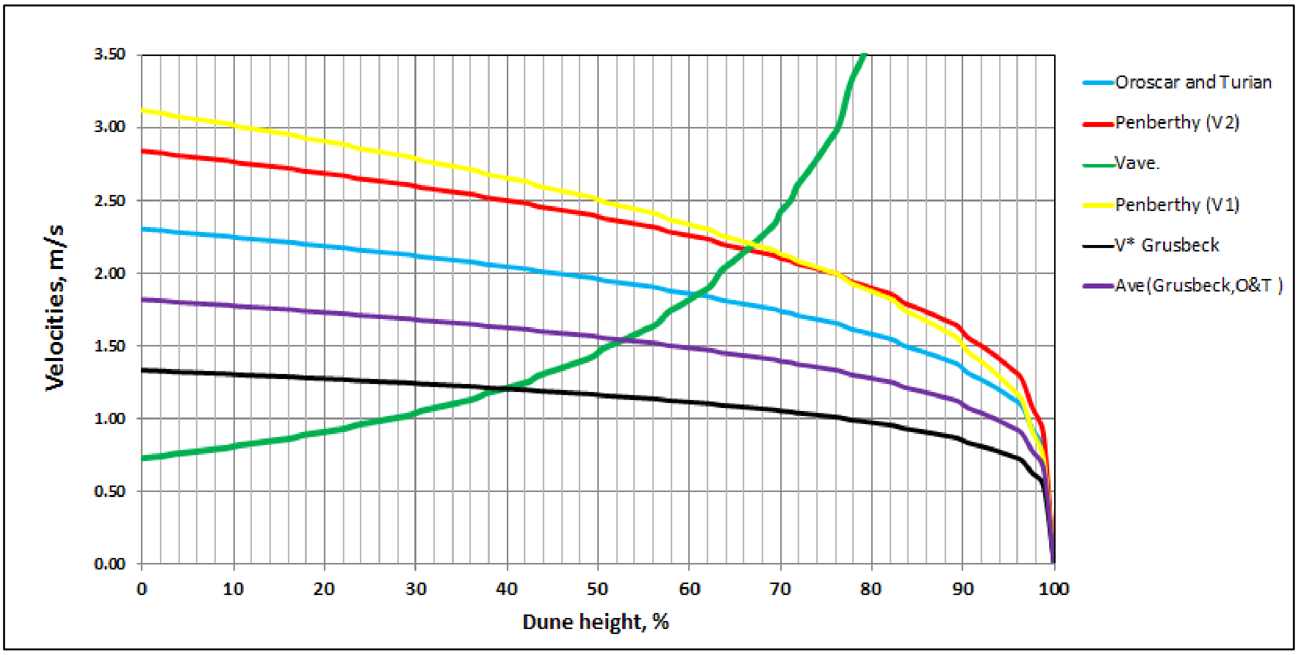


Figure 58 Plot from simulation with 1100 lpm and 1,2 sg carrier fluid

4.3.3 Effect of viscosity and carrier fluid density in combination

For this simulation, the carrier fluid density was varied from 1,2 SG to 1,8 SG and viscosity was varied from 3 cP to 8 cP while keeping the other parameters constant at base case level.

Table 16 presents the input simulation parameters.

	Reference	Sim#1	Sim#2	Sim#3	Units
Viscosity	1,3	3	5	8	[Cp]
Carrier fluid density	1,04	1,8	1,5	1,2	[KG/M^3]
Apparent gravel SG	2,71	2,71	2,71	2,71	[SG]
Flow rate	1000	1000	1000	1000	[LPM]
Gravel size	625	625	625	625	[micron]
Gravel concentration	36,4	36,4	36,4	36,4	[SG}

Table 16 Input parameters for simulation with varying density and viscosity

Based on this simulation, the settling velocity vary from 0,0325 m/s to 0,086 m/s (base case). The settling velocity for the different simulation scenarios are presented in figure 59.

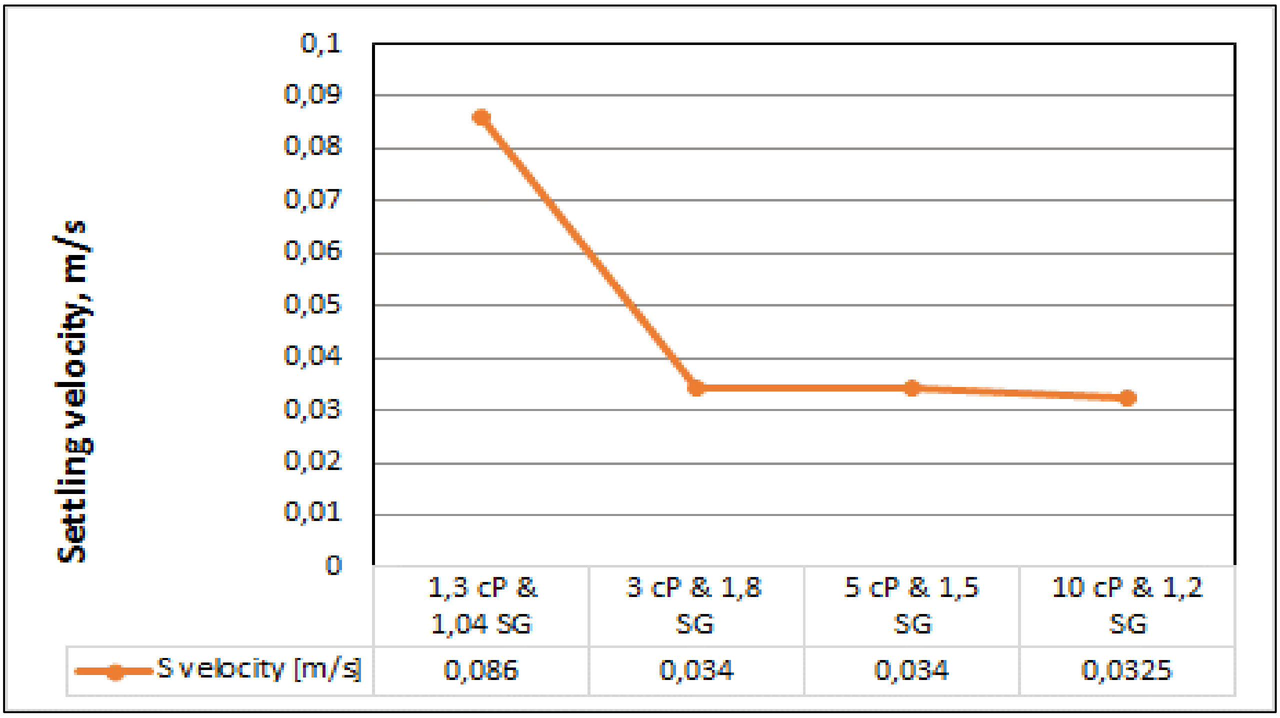
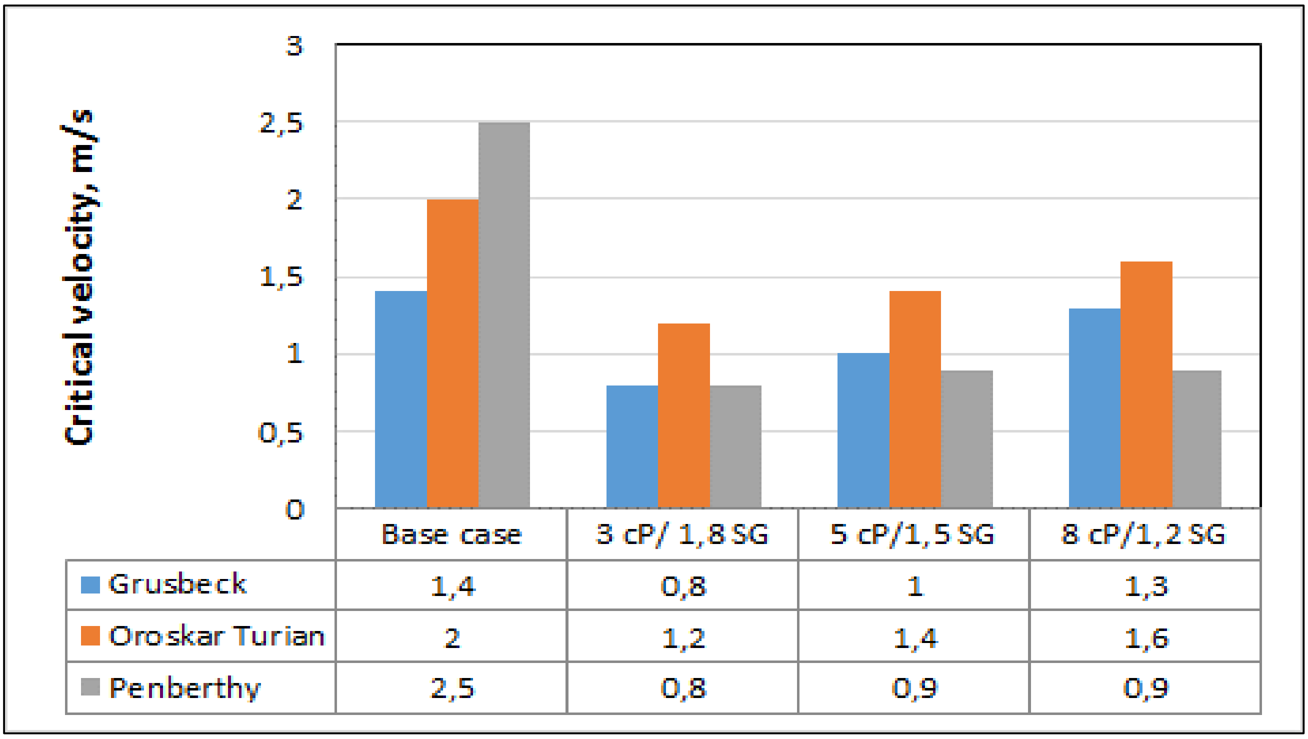


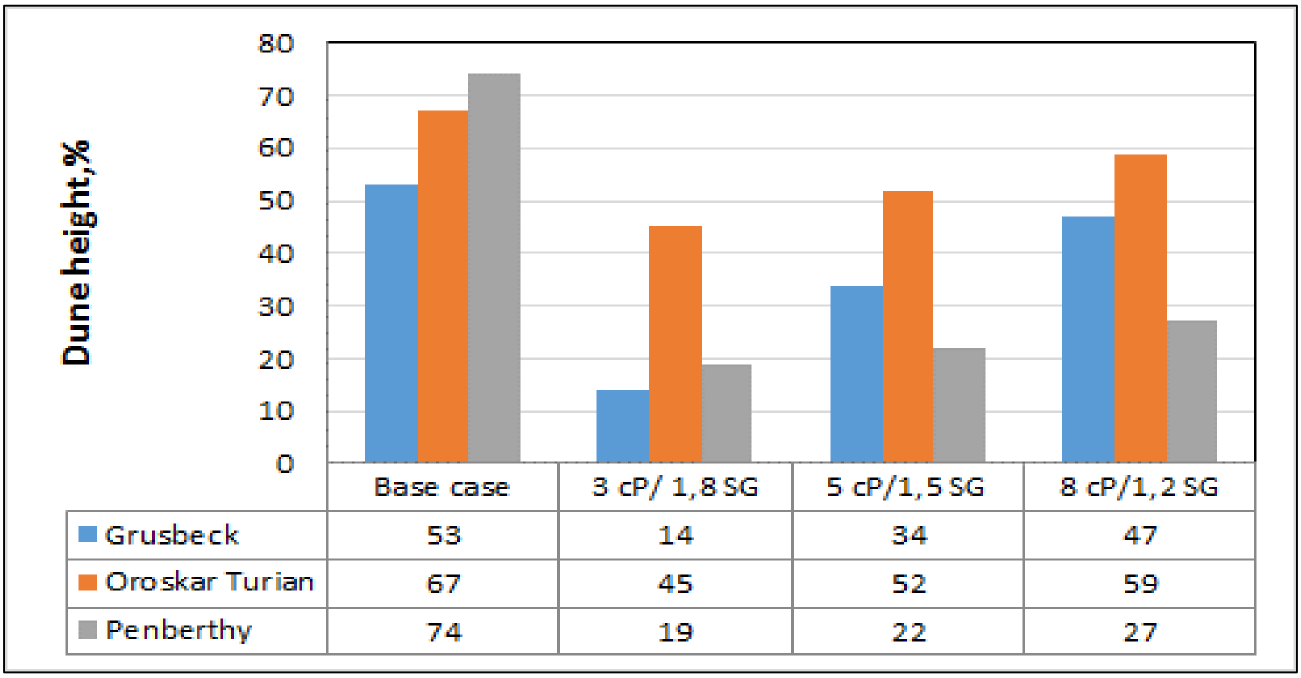
Figure 59 Settling velocities for various viscosity and carrier fluid combinations.

The settling velocities were used as input parameter for the dune height prediction. Figure 60 presents the predicted critical velocity. In this figure the outcome from the three models are compared to each other graphically. Similar figure is presented with the predicted dune height in figure 61.



	Base case	3 cP/ 1,8 SG	5 cP/1,5 SG	8 cP/1,2 SG
🟦 Grusbeck	1,4	0,8	1	1,3
🟧 Oroskar Turian	2	1,2	1,4	1,6
⬜ Penberthy	2,5	0,8	0,9	0,9

Figure 60 Predicted critical velocity for viscosity and carrier fluid SG combinations



	Base case	3 cP/ 1,8 SG	5 cP/1,5 SG	8 cP/1,2 SG
🟦 Grusbeck	53	14	34	47
🟧 Oroskar Turian	67	45	52	59
⬜ Penberthy	74	19	22	27

Figure 61 Predicted dune height for viscosity and carrier fluid SG combinations

Actual velocity with base case parameters and critical velocity from the three models concerning dune height are plotted in figure 59.

Figure 62 and 63 compares the outcome of the simulation with base case parameters, 1,04 SG carrier fluid and 1.3 cP, and the outcome of the simulation with 8 cP and 1,2 SG carrier fluid.

Plots from simulations with 3 cP and 1,8 SG carrier fluid and 5 cP and 1,5 SG fluid are included in the appendix (#14 & #15).

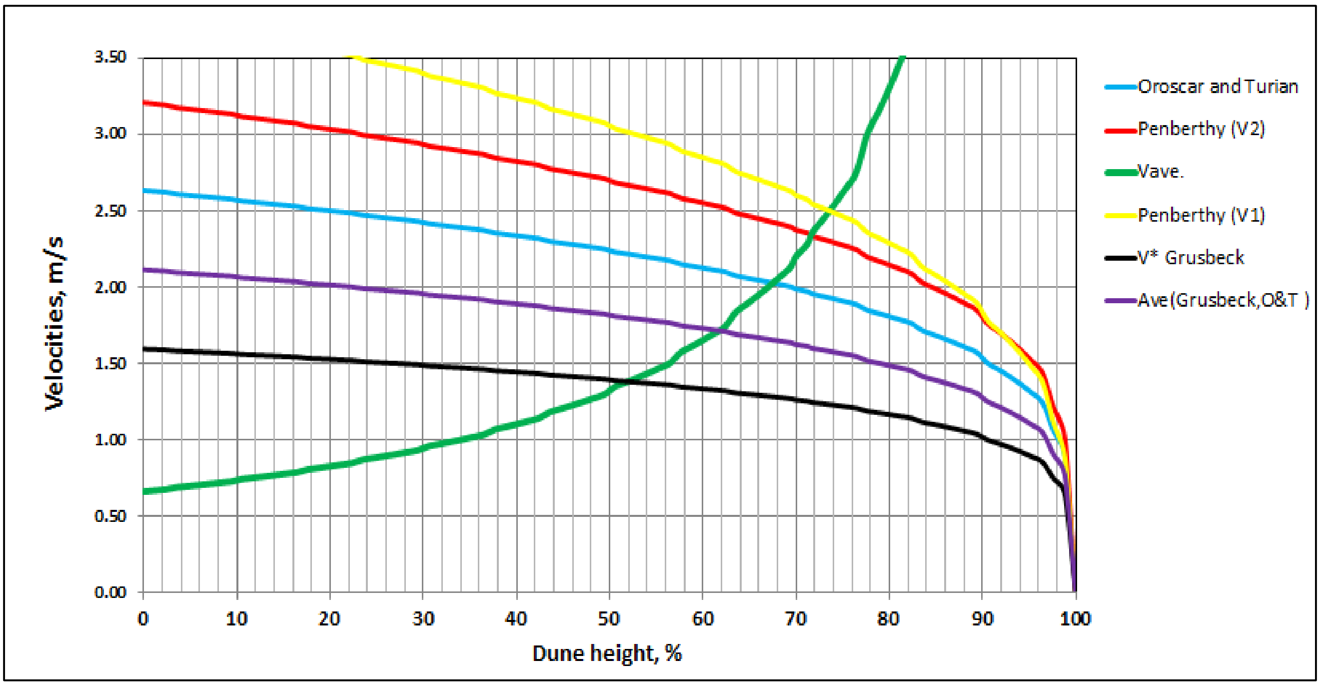


Figure 62 Plot from simulation with base case parameters

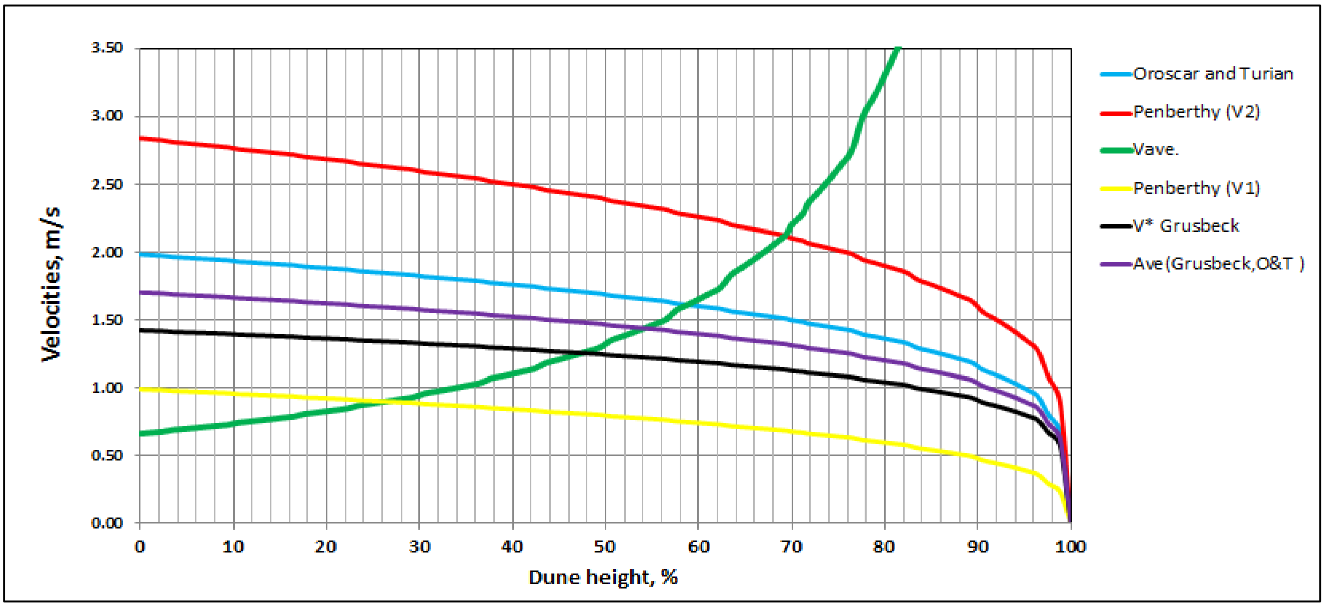


Figure 63 Plot from simulation with 1,2 SG and 8 cP viscosity carrier fluid

5 Discussion

The objective of this evaluation was to review and compare the outcome from three numerical gravel pack models to each other and evaluate which model is more sensitive to certain parameters and which is not. Several simulations has been done. During simulation the effect of single and combined effect on bed height deposition were analysed. Both the effect of single change and combined change is evaluated.

Alpha wave dune height is critical during job design and in the afterward execution of gravel placement. Excessive alpha dune height is the cause of many unwanted premature screen outs. Several mathematical models to calculate critical settling velocity has been published. Some of the most commonly used models in the industry are the ‘Penberthy’, ‘Gruesbeck’ and ‘Oroscar and Turian’. These are the three models reviewed in this thesis.

When comparing the outcome of the three models concerning change in density of carrier fluid the Gruesbeck model is most sensitive with regards to dune height. The Gruesbeck model estimates 84,9% decrease in dune height when changing from 1, 04 SG to 1,8 SG carrier fluid. Settling velocity is not part of the Penberthy model hence a change in carrier fluid density gives a smaller change in dune height prediction.

When it comes to the effect of gravel concentration in the three models,the Penberthy model is not affected by this parameter as gravel concentration is not part of the equation. Gruesbeck and Oroscar and Turian estimates a slight increase in dune height when the gravel concentration is increased from 36,4 kg/m3 to 120 kg/m3, an increase of 9,4% and 6% respectively. A concern with the Oroscar & Turian and Gruesbeck et al’s model is when c (gravel concentration) goes to zero, the critical velocity also approaches zero. However it has been shown that the critical velocity reaches a steady, non-zero value when the slurry is diluted (Mantz, 1977 [20]).

If the carrier fluid is viscosified from 1,3 cP to 10 cP the Gruesbeck model is not affected by this. Oroscar and Turian is estimating a slight decrease of dune height while the Penberthy, which is most sensitive to viscosity, estimates an increase of 60 % on the alpha dune height.

None of the models are very affected by a change in gravel size. When increasing the gravel size from 625 micron (20/40 us mesh) to 900 micron the settling velocity increases by 43%

while the outcome of the simulations from the three models are quite similar. The size of the gravel for the gravel pack is chosen based on sand screen opening and the size of the formation sand. 20/40 us mesh gravel is very commonly used but if there is a need for sandscreens with bigger openings and a bigger gravel is required, the change in alpha wave is minor according to these three models.

The Gruesbeck model is most sensitive to an increase in injection rate, it predicts a reduced alpha dune height of 38% while ‘Oroscar and Turian’ and ‘Penberthy’ estimates a decrease of 24 % and 15% respectively. In this simulation, the pump rate was increased from 600 lpm to 1200 lpm.

On the combined parameter change, it is not easy to make a clear conclusion on the sensitivity of each model. When changing two parameters it makes the picture more complicated as the two changes can move the prediction in one direction or the two changes can work against each other that again results in minor changes to the prediction.

When increasing rate and gravel concentration from 900 lpm and 60 kg/m3 to 1200 lpm and 120 kg/m3 the Gruesbeck model estimates a decrease of dune height from 60 % to 61 % which is more than the estimates from the other two models. This confirms the sensitivity to flowrate for the Gruesbeck model. This is also the case when changing the injection rate and carrier fluid density, the Gruesbeck is most sensitive.

When the carrier fluid density is changed from 1.04 SG to 1.8 SG the settling velocity decreases with 44,8%. This alone should result in a significantly lower alpha dune. When the injection rate is reduced to 800 lpm, compared with base case 1000 lpm, this again should give a higher alpha dune, so these two changes works in opposite directions. In this scenario Gruesbeck predicts a significantly lower dune than the two other models especially in the simulation with 800 lpm and 1.8 SG carrier fluid.

In the last simulation where viscosity and carrier fluid density is altered, the Gruesbeck model is most sensitive. This is due to the high sensitivity to carrier fluid density for this model. The Penberthy model also show some sensitivity to these combined changes which is due to the high sensitivity to viscosity for this model.

6 Summary and conclusion

As shown in Chapter 5, several particle studies are presented. From the simulation result it can be observed that:

- The simulations show that the Gruesbeck model is very sensitive to changes in the density of carrier fluid.
- The simulations show that the Penberthy model is very sensitive to viscosity of the carrier fluid.
- None of the models are very affected by a change in gravel size.
- It is observed that the Gruesbeck model predicts lowest critical velocity and alpha dune in all simulations except when carrier fluid viscosity is 5 cP and 10 cP.
- From combined effect simulation, it was observed that different parameters shows positive synergy and also negative synergy when it comes to dune height deposit.
- Only the Gruesbeck model is affected by a change in settling velocity for the gravel.

As one increase the carrier fluid density from 1.04 SG to 1.8 SG, the alpha dune prediction for the Gruesbeck model goes from 53% to 26% even though injection rate is decreased to 800 lpm at 1.8 SG. The weight of the carrier fluid can usually not be changed due to well control issue so in this case one need to consider to drop the rate even more in order to increase alpha dune height. When considering decreasing the injection rate it is important to take into consideration critical velocity in drill pipe. The absolute lower limit for injection rate is when gravel starts to settle out in drill pipe. If gravel starts to settle out in drillpipe it will jeopardize the job therefore it needs to be avoided.

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List of symboles

C_D= Drag coefficient

C_μ= sorting factor or uniformity coefficient

d_{40} = formation sand diameter, 40 percentile

d_{90} = formation sand diameter, 90 percentile

D = Diameter

F = Force

g = Gravitational acceleration

PV = Plastic viscosity

YP = Yield point

u / V = Velocity

r = Radius

Q = Rate

ρ = Density

τ = shear stress

γ = shear rate

μ = viscosity

μ_α = Apparent viscosity

Abbreviations

OH = Open hole

POOH = Pull out of hole

ID = Inner dimeter

OD = Outer diameter

lpm = liters per minute, (l/min)

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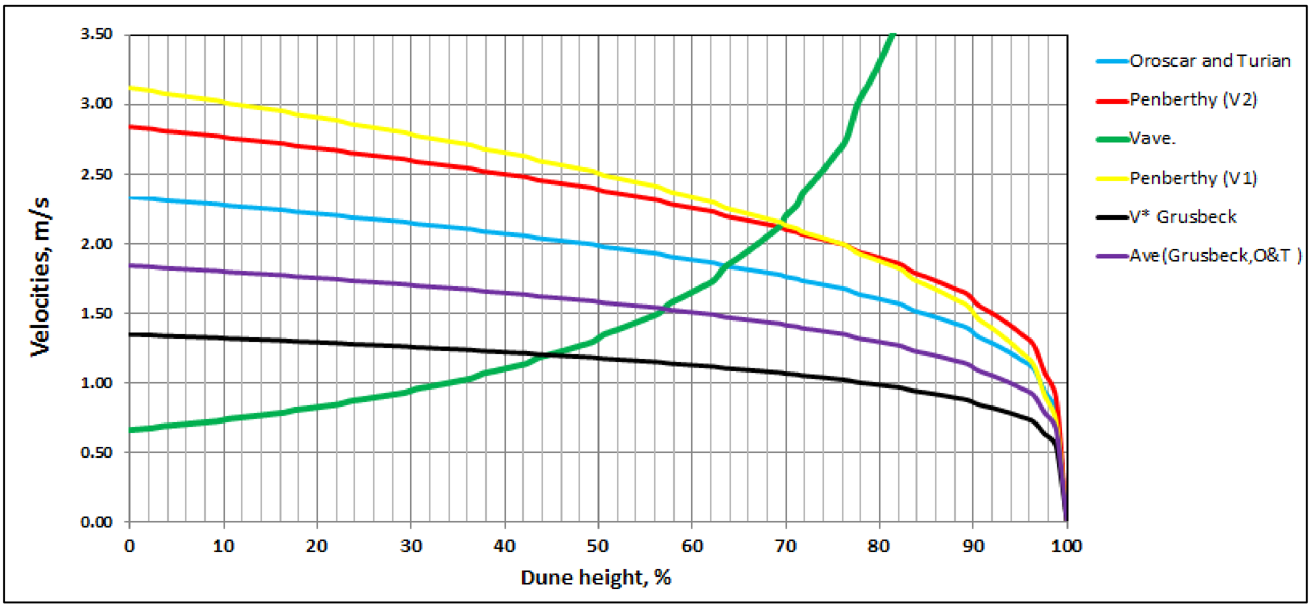
Appendix

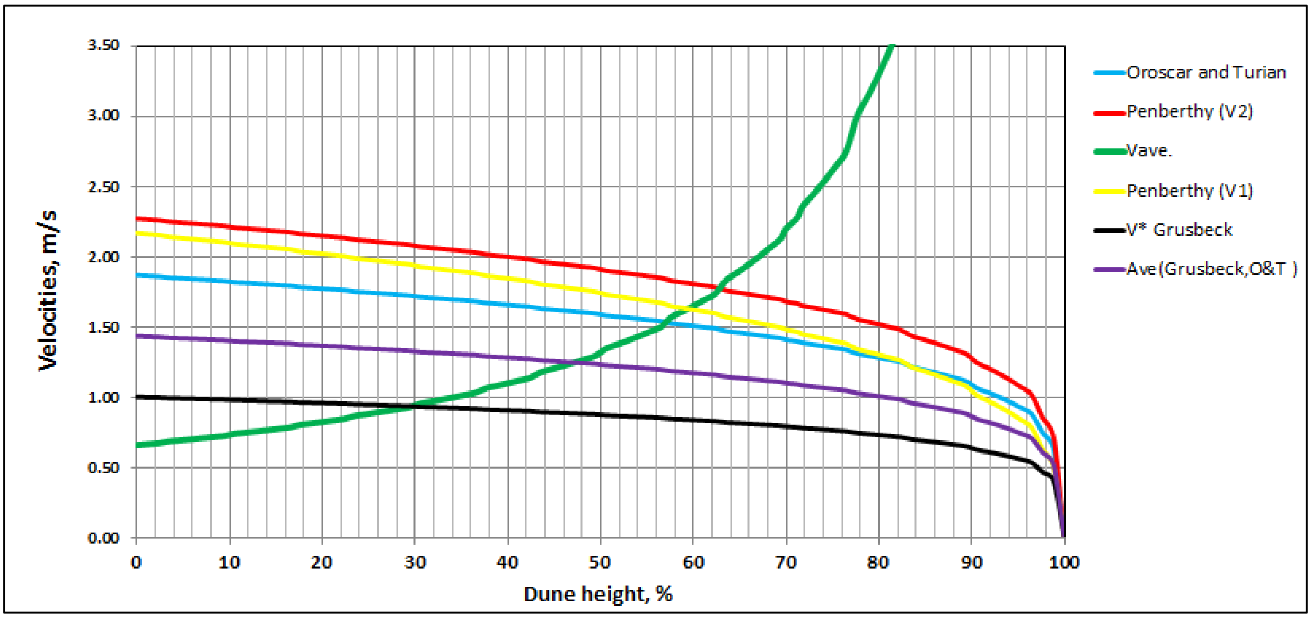
Single parameter change

1.



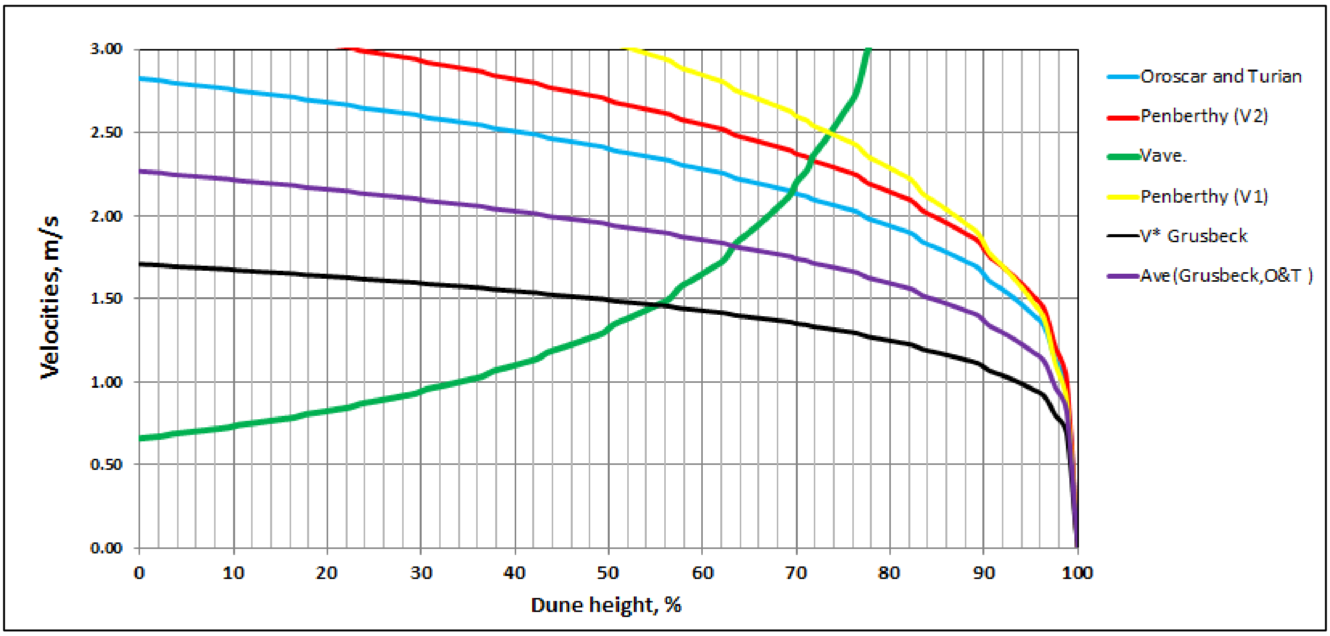
Simulation outcome with 1.2 SG carrier fluid

2.



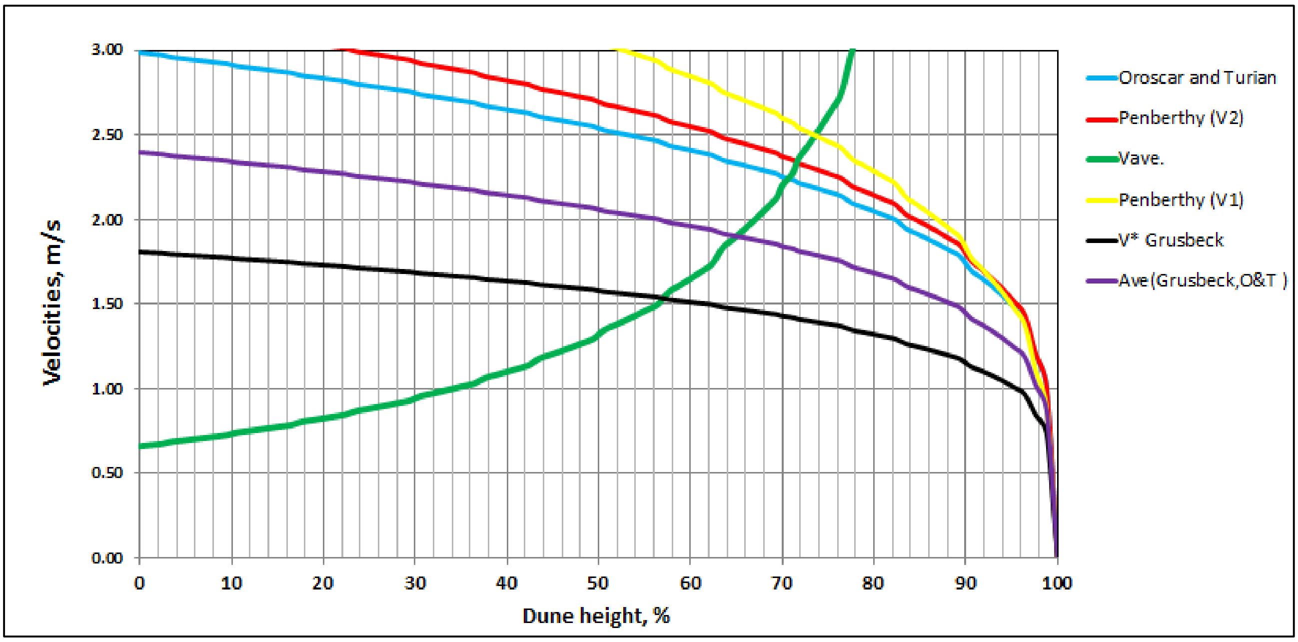
Simulation outcome with 1.5 SG carrier fluid

3.



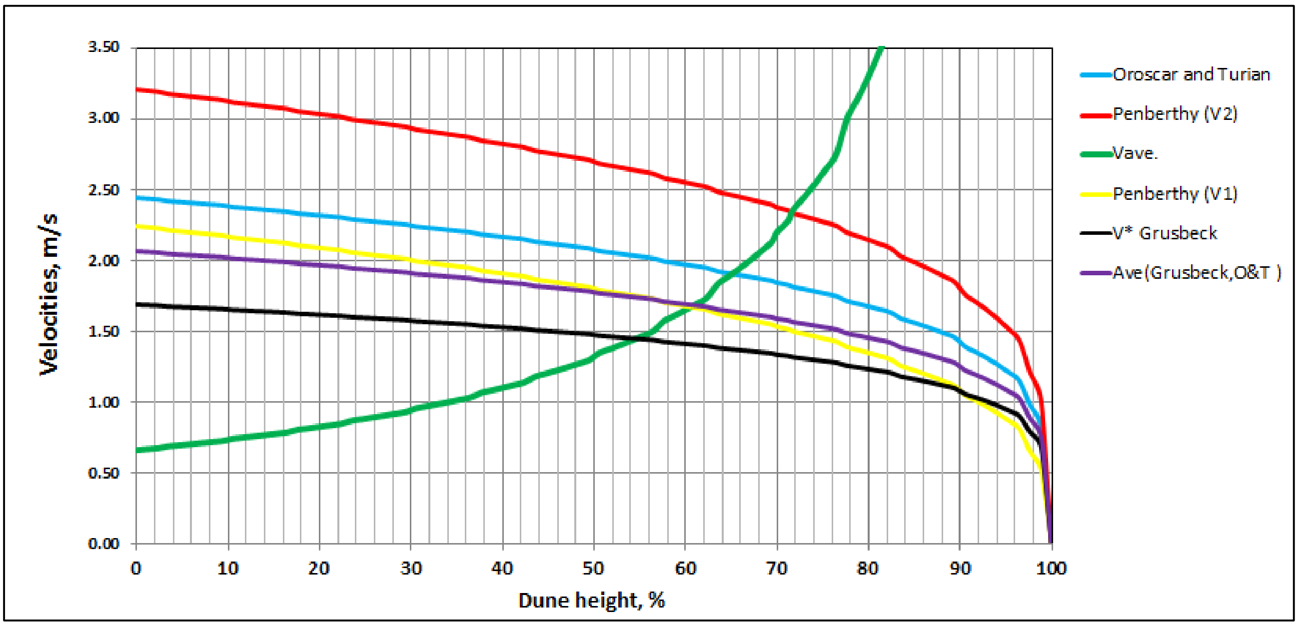
Outcome from simulation with 60 kg/m^3 gravel concentration

4.



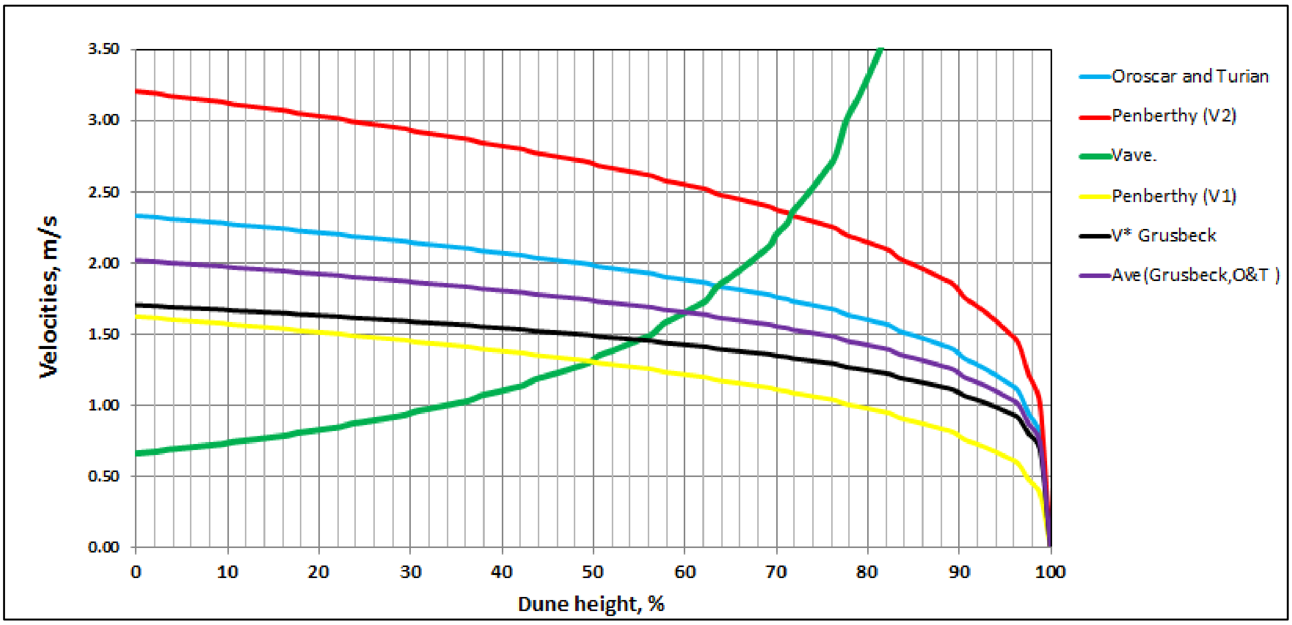
Outcome from simulation with 90 kg/m^3 gravel concentration

5.



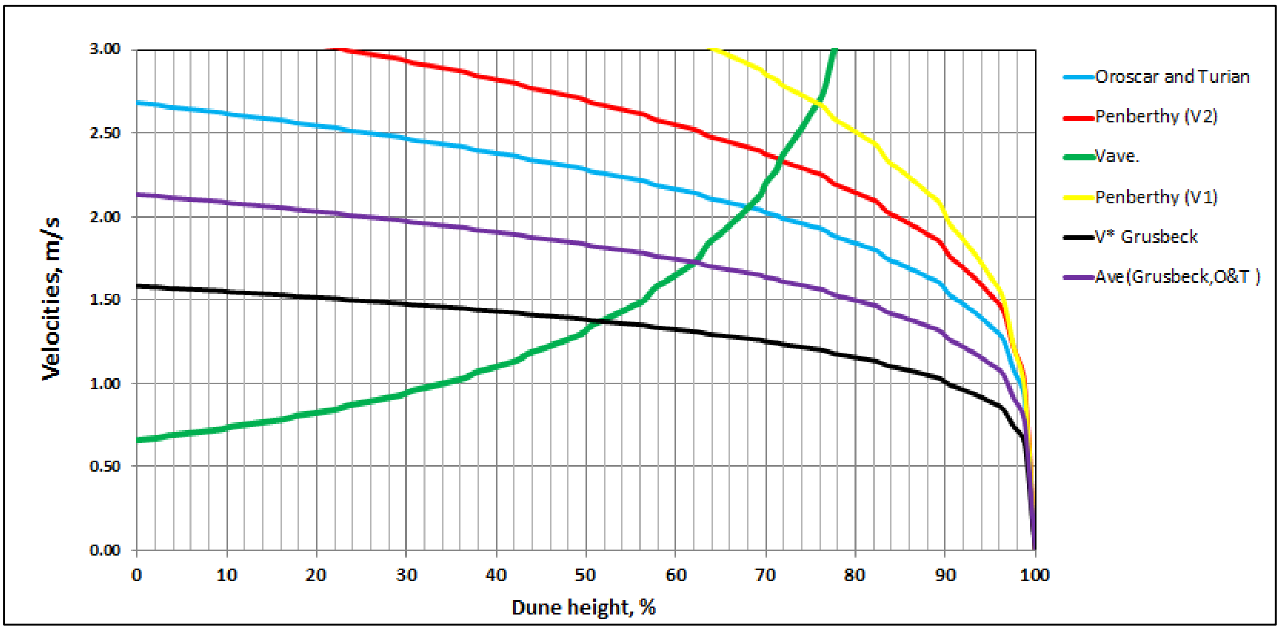
Outcome from simulation with 3 cP carrier fluid

6.



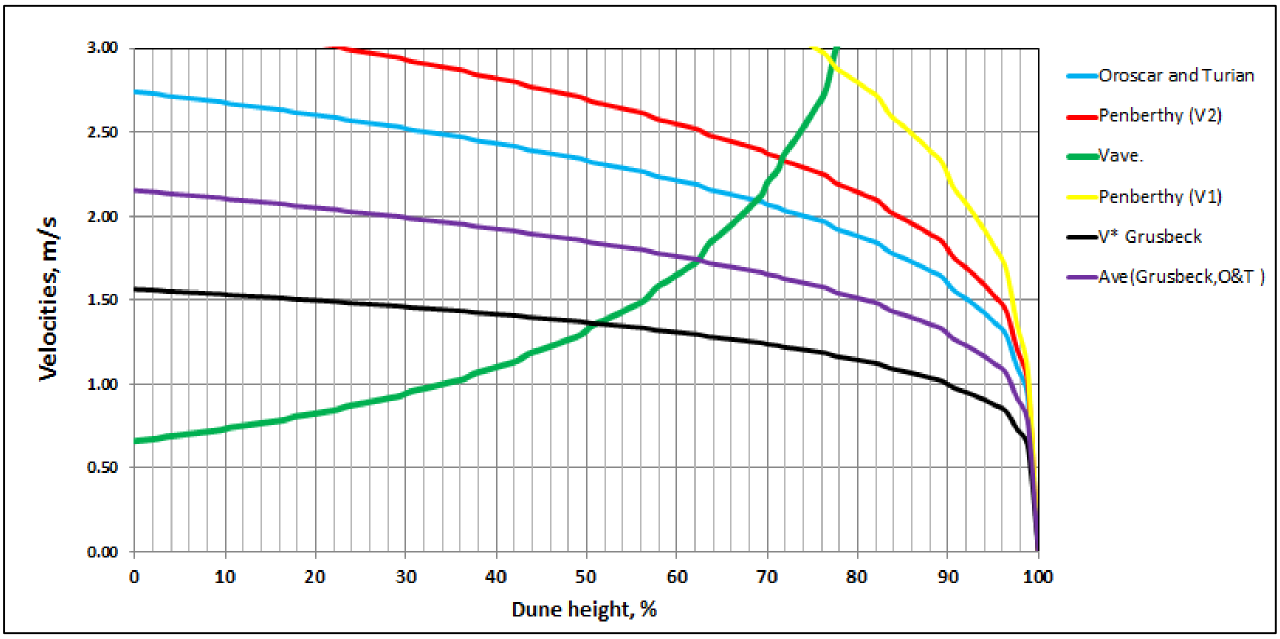
Outcome from simulation with 5 cP carrier fluid

7.



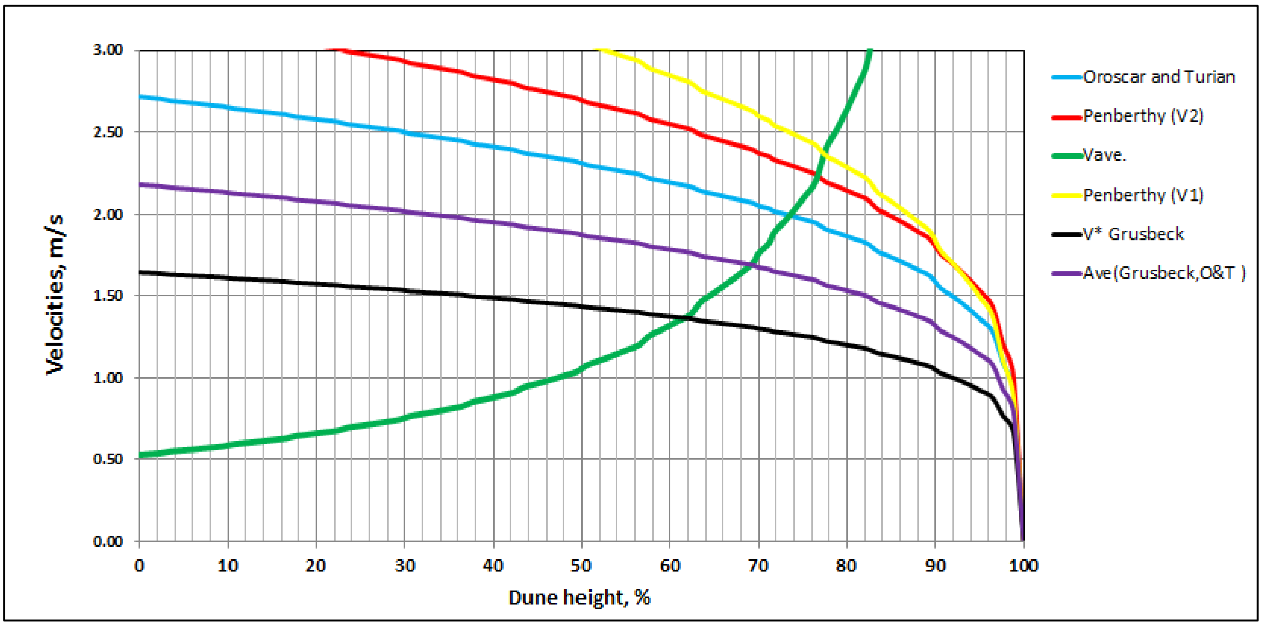
Outcome from simulation with 700 micron gravel size

8.



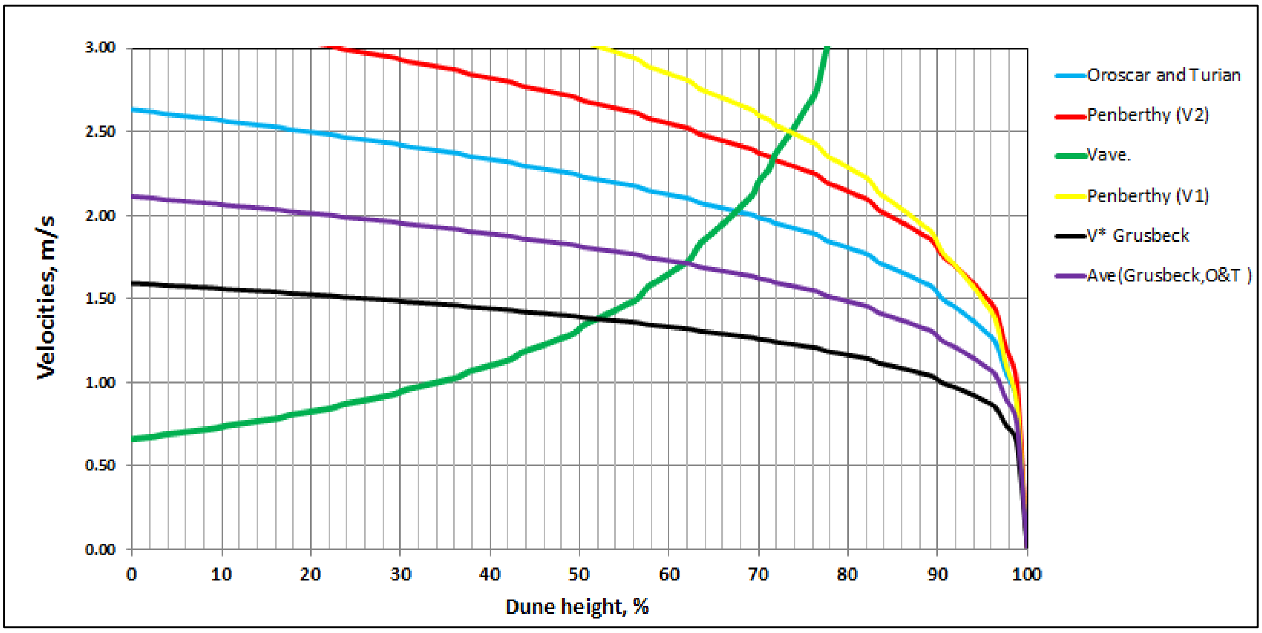
Outcome from simulation with 800 micron gravel size

9.



Outcome from simulation with 800 lpm injection rate

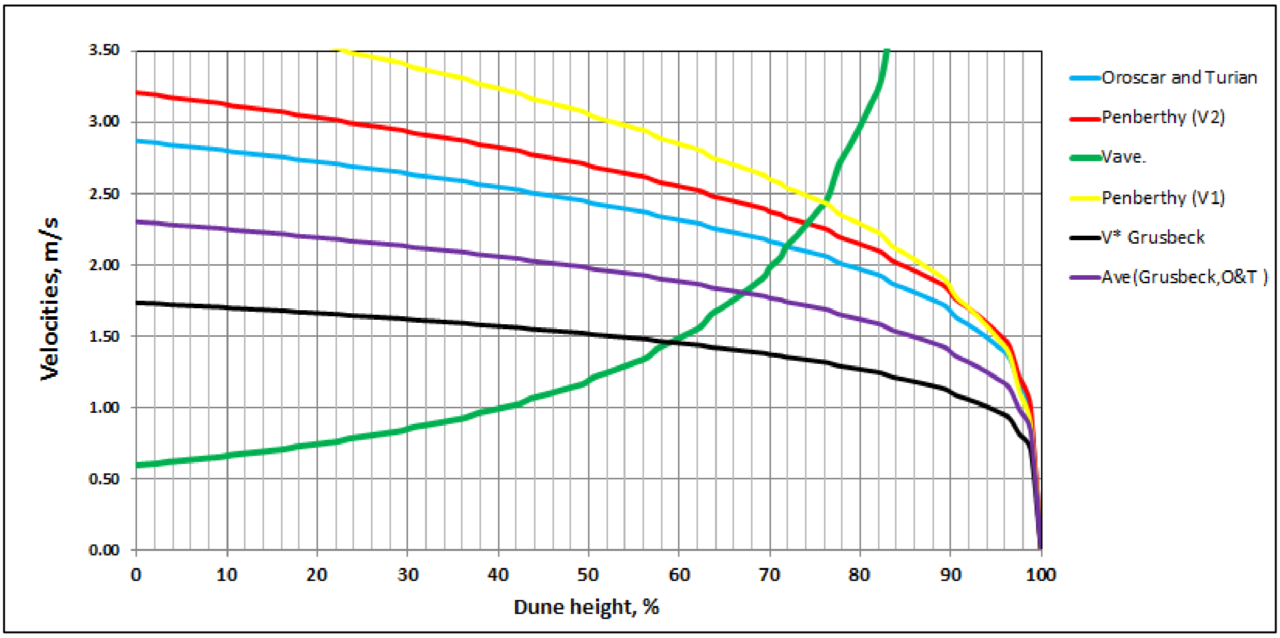
10.



Outcome from simulation with base case parameters, 1000 lpm.

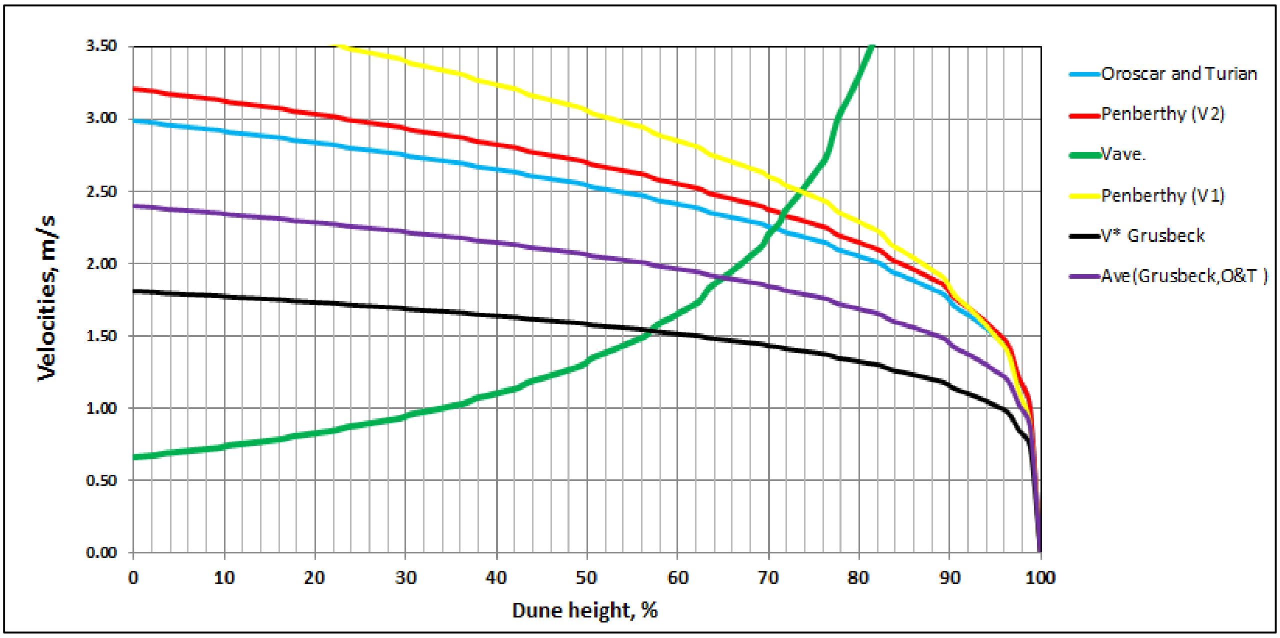
Combined parameter change

11.



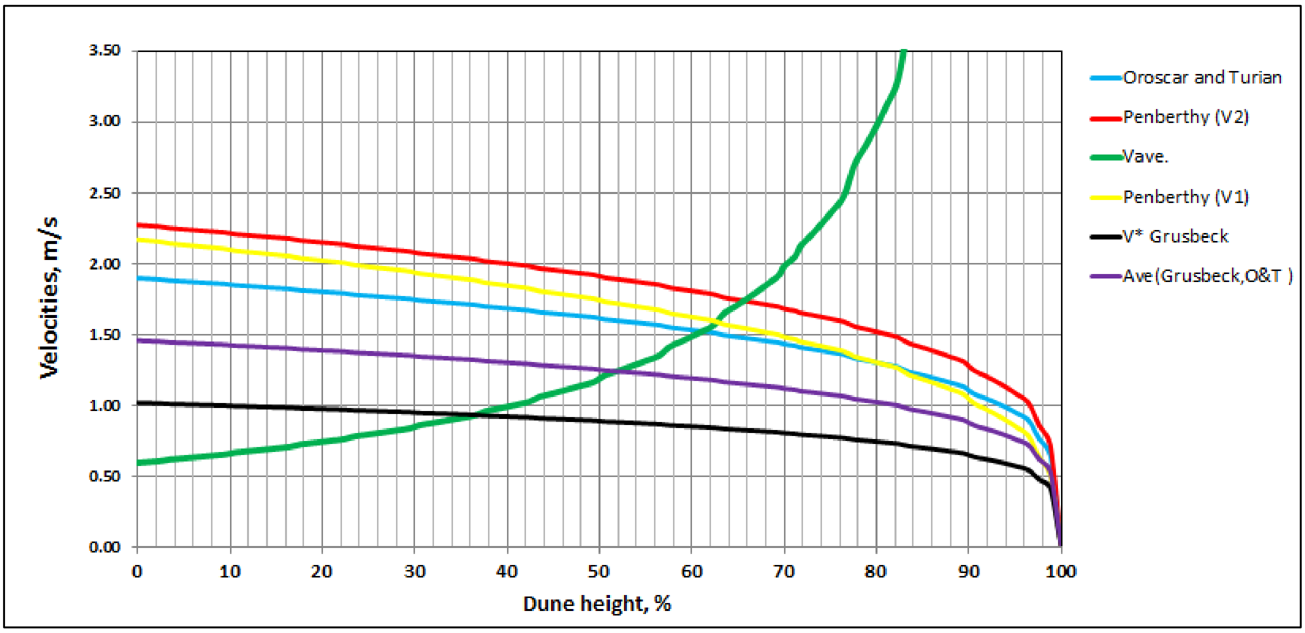
Outcome from simulation with 900 lpm and 60 kg/m^3 gravel concentration

12.



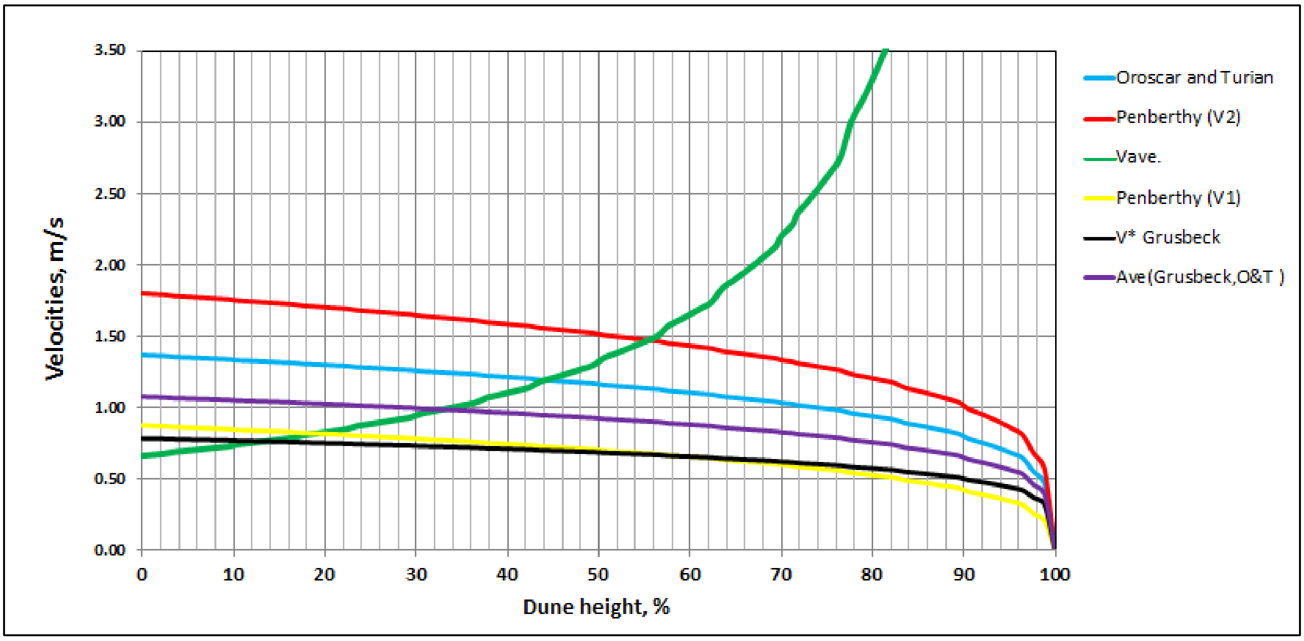
Outcome from simulation with 1100 lpm and 90 kg/m^3 gravel concentration.

13.



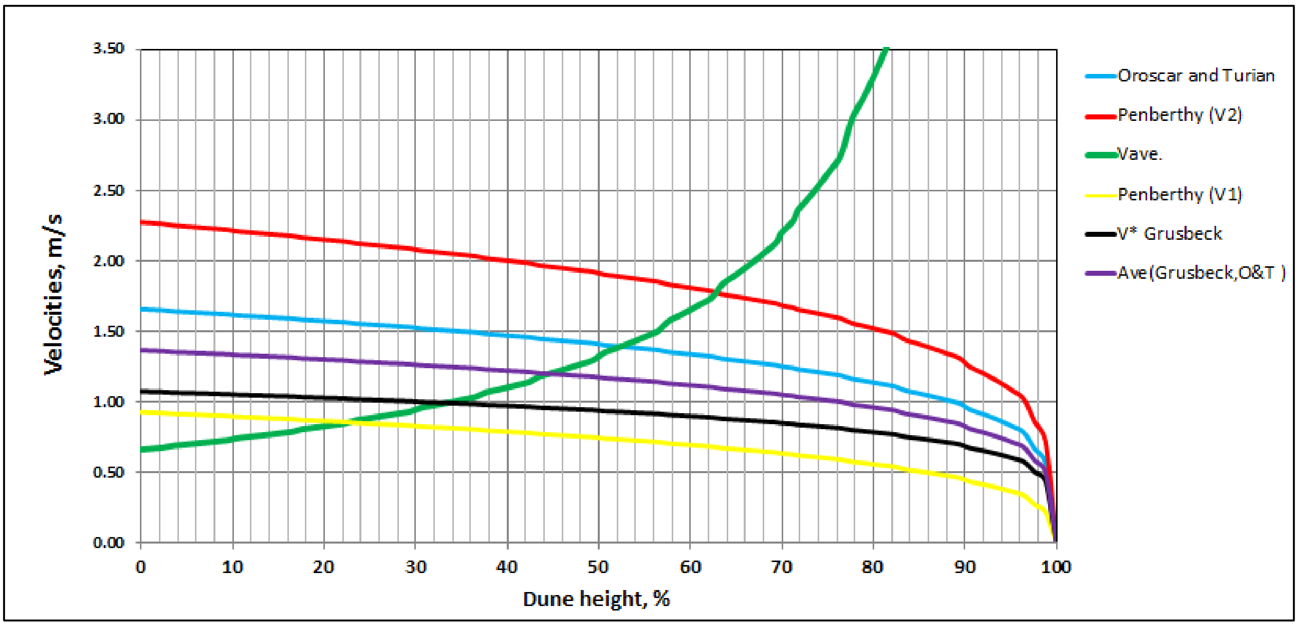
Outcome from simulation with 900 lpm and 1.5 SG carrier fluid

14.



Outcome from simulation with 3 cP and 1.8 SG carrier fluid.

15.



Outcome from simulation with 5 cP and 1.5 SG carrier fluid.