GRAVEL PACK DISPLACEMENT LIMITS IN EXTENDED HORIZONTAL OFFSHORE WELLS

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Long horizontal section wells are economical requirements for heavy oil fields in deepwater environments. This article discusses the operational limits for gravel pack displacements such kind of wells, considering the well extension and low fracture gradients encountered in deepwater reservoirs among other hydraulic limits. A parametric study on the variables governing the gravel pack operations indicates that careful hydraulic design and detailed operational procedures can guarantee a successful job. Alternative strategies are proposed to extend hydraulic limits in critical conditions.

Gravel Pack, Hydraulic Limits, Modelling, Stratified Flows

1. Introduction

The new scenario for offshore development in Brazil includes heavy oil fields in deepwaters where 1000m to 2000m horizontal sections are required. Due to the non-consolidated formations found, sand control techniques are required in Campos Basin, offshore Brazil. Sand production results in several surface problems: equipment erosion and sedimentation inside the oil/gas/water separator.

There are many techniques for sand control, such as: slotted liners, expandable screens, pre-packed screens and resined sands, but gravel packing is the most globally spread technique due to the lower cost, if compared with other alternatives and due to the good results obtained to maintain a high productivity index of the wells.

The gravel packing technique consists in filling out the annular space between screen and producer formation, with a sand or ceramic particles with selected grain diameter. The idea is to create a second porous medium with a pore throat diameter smaller than the formation grain diameter and, in this case, fluid would easily flow through the gravel pack while formation particles would not (Fig. 4).

Due to the critical conditions, such as the deep and ultra deepwater and low frac gradients, a lot of precision is required to assure gravel packing success. Most models available in the industry for horizontal gravel pack design are essentially empirical, resulting in imprecise predictions for extrapolated conditions.

These aspects were the main motivators for a research project including theoretical and experimental development. A mechanistic model to calculate the pressure loss during the displacement, including sand injection and alpha/beta waves propagation, taking into account fluid leakage, multi zonal isolation and beta wave pressure reduction optimization was developed. This paper describes a sensibility analysis on the operational parameter, which can be monitored or defined during well design, which can extend the horizontal well length during a gravel pack operation.

2. Brief Description of the Operation

For displacement calculation purposes, the horizontal well gravel pack operation can be divided in three different stages: the injection, the alpha wave propagation and the beta wave propagation.

The injection stage, as highlighted in Fig. (1), consists of pumping a fluid-gravel mixture (red line) through the pipe from the rig until a cross over tool located in the beginning of the open hole, where the flow will be diverted to the open hole annulus. At this moment, there is usually a decrease in the mixture displacement velocity, due to the larger area, resulting that the force which sustains the gravel particles is not high enough to maintain them in suspension. Consequently, the solids begin to sediment in the lower portion of the annulus (Fig. 4), forming a bed that, for a given flow rate, reaches an equilibrium height (h_α). The deposited sand length will propagate till the extremity of the horizontal section, leaving a free channel between the superior wall of the well and the top of the bed. This stage is known as alpha wave propagation and is illustrated in Fig. (2).

When the alpha wave arrives at the extremity of the well, a new step, called the beta wave propagation, begins: since the sand can not flow through the screens, it will start to deposit above the sand deposited in the alpha wave stage, beginning at the extremity of the well and finishing at the crossover tool, traveling in the opposite way. Figure (3) highlights the process.

While during the alpha wave propagation, the fluid flow totally happens through the annular space between the screen and the open hole, in the beta wave the fluid will flow radially through the screen and then axially through the annular gap formed between the screen and the washpipe. Figure (4) shows the cross section of the horizontal wells when equipped with the gravel pack displacement columns.

Three points are relevant for the present study (Fig.3): pump pressure at the rig (P_p), bottom hole pressure (P_b) and casing shoe pressure (P_{cs}). The critical point as at the casing shoe where the pressure is maximum along the whole operation.

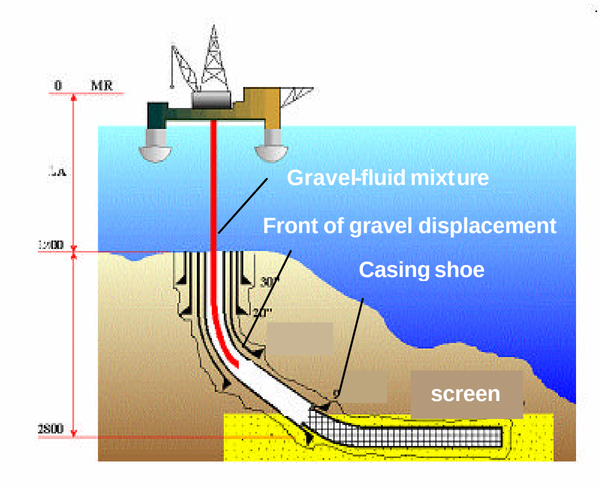

Figure 1. Injection stage.

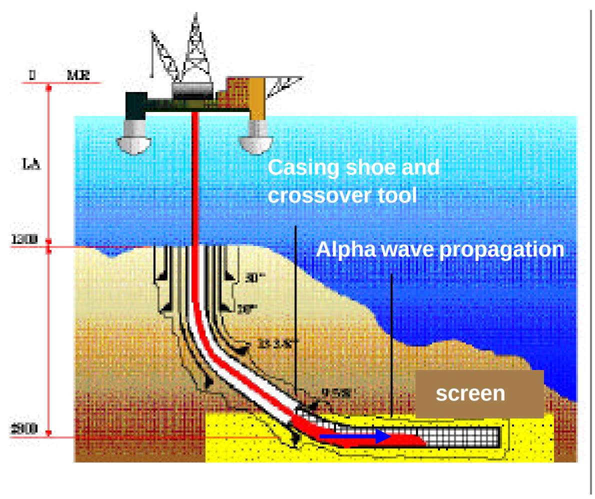

Figure 2. Alpha wave stage.

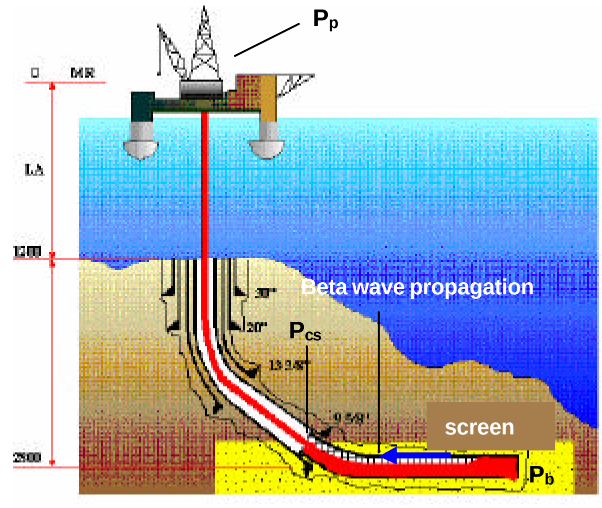

Figure 3. Beta wave stage.

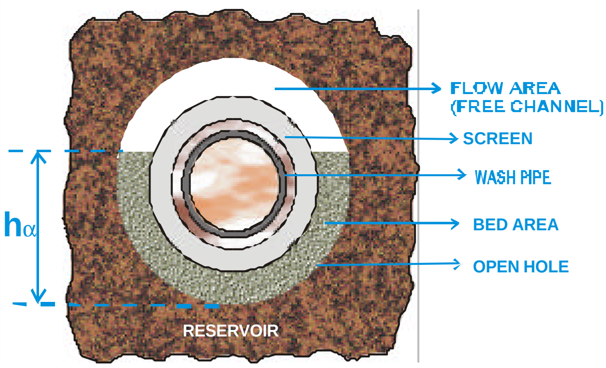

Figure 4. Cross section.

3. Theoretical Model and Software Development

The proposed model consists on the following steps: pressure propagation during string injection, alpha wave height calculation, pressure propagation during alpha wave displacement and pressure propagation during beta wave displacement. In order to predict alpha wave deposition heights, a two layer model was adopted. The present model is an extension, for horizontal gravel packing applications, of the model proposed by Martins (1990) for drilled cuttings transport analysis. Whole theoretical model for alpha wave height calculation as well as the friction losses calculation can be seen in more details in Martins et al. (2003).

The proposed modeling was implemented in a computer code for use in projects and during the gravel pack operations. This code was written in PASCAL language using DELPHI™ 6.0 environment.

Computer Simulator Input Data:

- Open hole diameter and length
- Rathole diameter and length
- Sea level and casing shoe measured depth
- Casing internal diameter
- Screen Diameters (OD and ID)
- Wash pipe and gravel diameters
- Well path
- Injection and return flow rates
- Particle and fluid densities
- Frac gradient

4. Defining the Operational Window

In order to achieve a successful gravel pack operation, different hydraulic limits should be respected. Dynamic pressures during the operation should be between a window formed by the pore pressure and the fracture pressure. If the wellbore pressure, at any time, is below the pore pressure, there will be influx of formation fluid to the well. On the of the hand if the wellbore pressure is greater than the formation fracture pressure, there will be influx of drilling fluid to the formation, possibly generating damage. Figures 5 and 6 shows typical shallow waters and deepwaters pore and frac pressure profiles. Operational windows are normally much narrower at deepwater environments were the formations are poorly consolidated and, consequently, present low frac pressures.

Another important issue is to guarantee that the operation will be run at a minimum flow rate which avoids premature screen out of the rat hole: normally there is a short section (around 10 m) of open hole with a larger diameter than the whole open hole section. This short section is called rat hole and results from the drilling of the previous phase of the well (normally with 12 ¼ in diameter) which is not cased. Since a larger diameter open hole section is exposed, if the flow rate is too low, alpha waves formed may be high enough to block sand passage to the open hole, generating immediately a beta wave in the rat hole, according to Marques (2004). The consequence is that the pressure at the casing shoe will immediately increase and the operation will have to be aborted without packing the open hole. Figure 7 shows a scheme of the process.

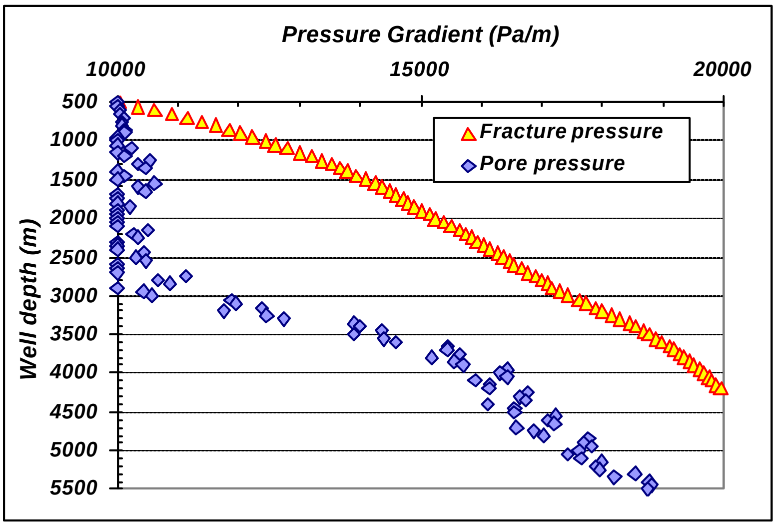

Figure 5. Wide pressure window for shallow waters

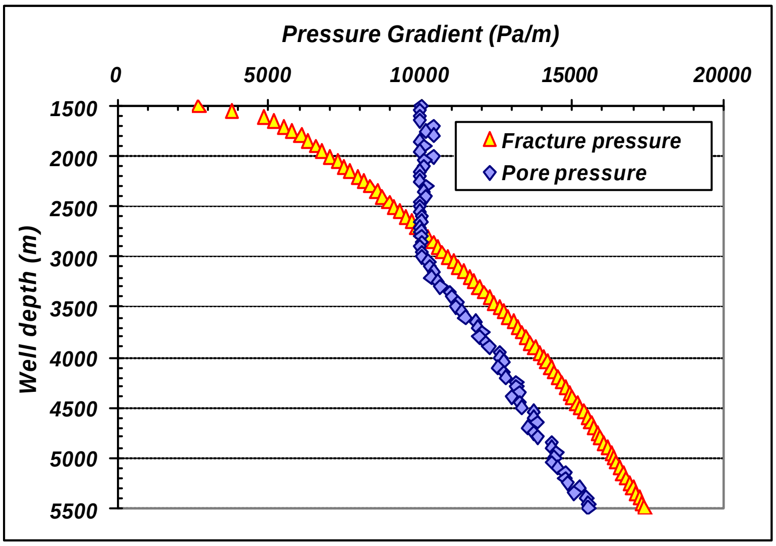

Figure 6. Narrow pressure window for deepwaters

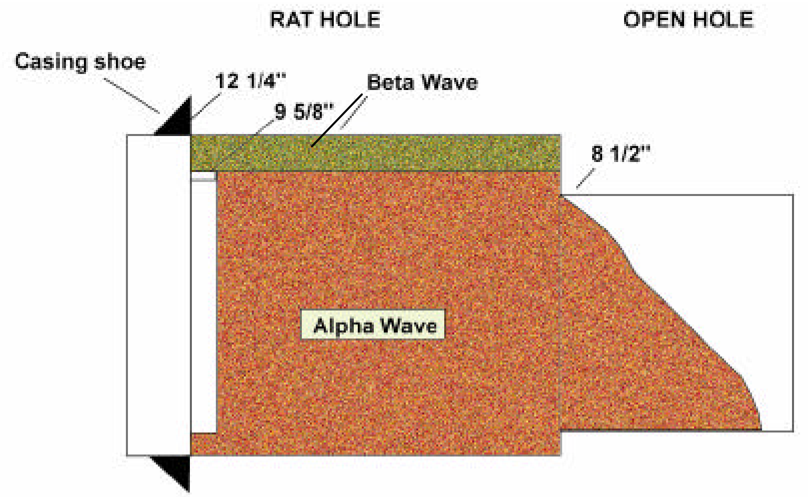

Figure 7. Rat hole scheme

With the input data, the computer program previously mentioned can predict alpha wave heights in the open hole and rat hole sections, besides pressure propagation during injection/alpha wave/beta wave stages with displacement time. These results generate outputs in two different ways:

- Defining the operational flow rate window for a given operation based on minimum flow rate required to avoid premature screen out in the rat hole and maximum flow rate which does not lead to a formation fracture (Fig. 8). Normally fluid density is designed to generate wellbore pressures in static conditions higher than pore pressures.
- Once optimum flow rate is chosen inside operational window (between maximum and minimum flow rate), predicting the pressure propagation with displacement time (Fig. 9).

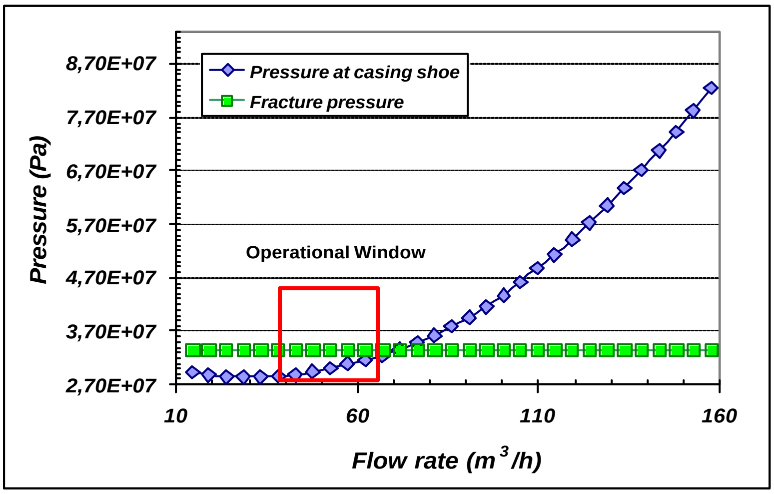

Figure 8. Defining operational window

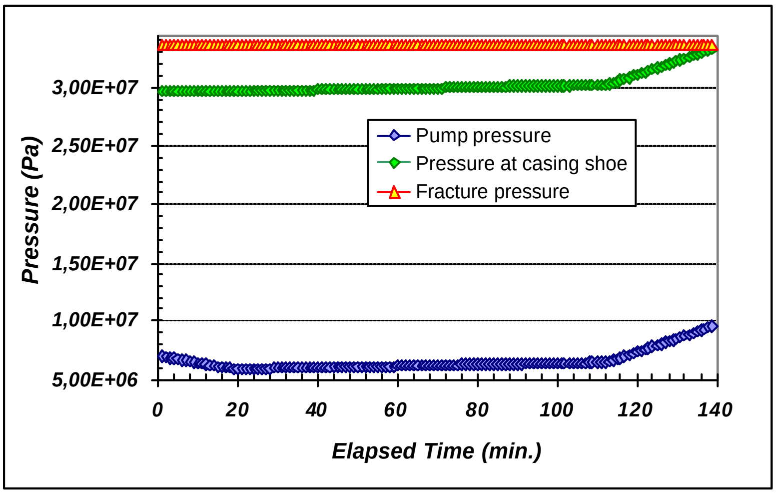

Figure 9. Pressure propagation

5. Sensitivity Analysis

This item details a sensitivity analysis on the impact of several important parameters on the maximum horizontal well extension which is possible to be gravel packed for a given frac gradient. The following geometric configurations were adopted:

Configuration #1: Open hole diameter = 21.60 cm
External screen diameter = 16.60 cm
Internal screen diameter = 12.34 cm

Configuration #2: Open hole diameter = 24.13 in
External screen diameter = 18.56 cm
Internal screen diameter = 13.89 cm

Configuration #3: Open hole diameter = 31.11 cm
External screen diameter = 23.94 cm
Internal screen diameter = 17.91 cm

The following parameters were considered as a base case:

- Water depth: 1200 and 1800m
- Kick Off Point: 1450 and 2000m (for 1200 and 1800 m water depth, respectively). This is the depth where the well starts to be inclined
- Angle Build-up rate: 3.18^o/100 m and 7.2^o/100 m (when changed water depth)
- Reservoir depth: 3250 and 3850m
- Fluid density: 1.20 g/cm^3
- Gravel concentration: 0.12 g/cm^3
- Gravel Type: sand 20/40 mesh
- Open BOP configuration (friction losses between the sea floor and the rig are negligible).

All plots in the next items represent the maximum dynamic pressures reached at the end of beta wave placement which will not to fracture the formation.

Effect of Wellbore Diameter

Figure 10, shows the effect of 3 diferent wellbore diameters (configurations). Results indicate that, for gravel pack displacement purposes, the larger the diameter the longer will be the achievable packing length. Of course wellbore diameter affects other important operations such as drilling and running the screen (Martins et al. 2004). Anyway, since gravel packing is the most critical operation among all the drilling and completion hydraulically related ones, larger diameter wells can be an interesting alternative.

Effect of Water Depth

Figure 11, shows the water depth effect for the geometric configuration 1. For a similar frac gradient it would be easier to extend the horizontal section at shallow waters. Normally, the frac gradients decrease with the increase of water depth due to the decreasing sediment thickness. So, deepwater wells are normally much more critical than shallow water wells and the analysis for a given frac gradient does not express operational reality.

Effect of Reservoir Depth

Figure 12, shows the effect of reservoir depth for the geometric configuration 1. In this case, it seems easier to gravel pack the long section for, for the same frac gradient, in the deeper reservoir. The frac gradient is defined as the frac pressure divided by the sediment thickness and, for the deeper reservoir, the same frac gradient meas a larger frac pressure. Normally this fact reflects the operational reality since the deeper the sediment layer the more competent will be the formation. For the case study at 38.2 m^3/h (4 bpm) pump rate, an increase in 600m reservoir depth resulted in about 200m extension of the maximum horizontal well length.

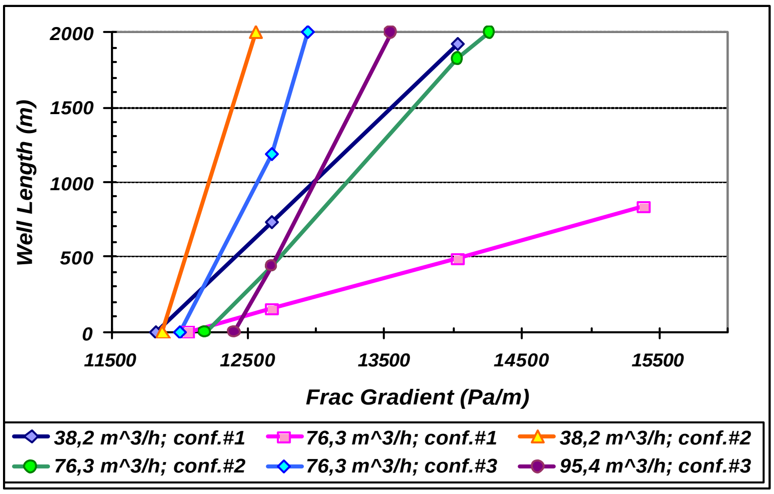

Figure 10. Effect of Wellbore diameter

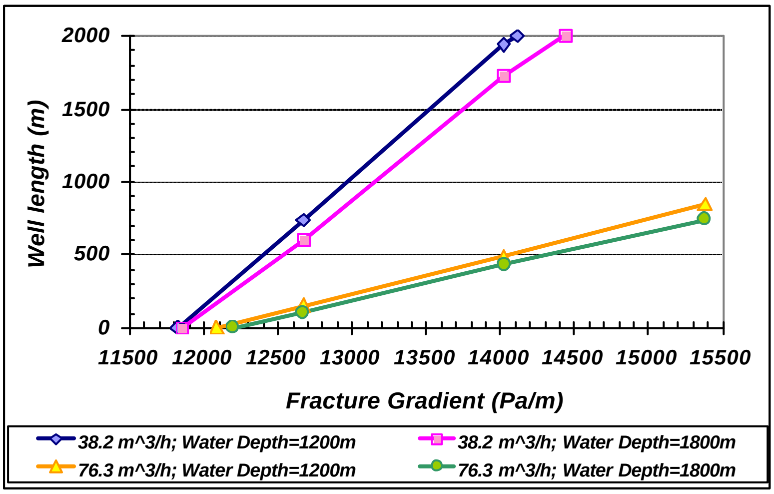

Figure 11. Effect of water depth

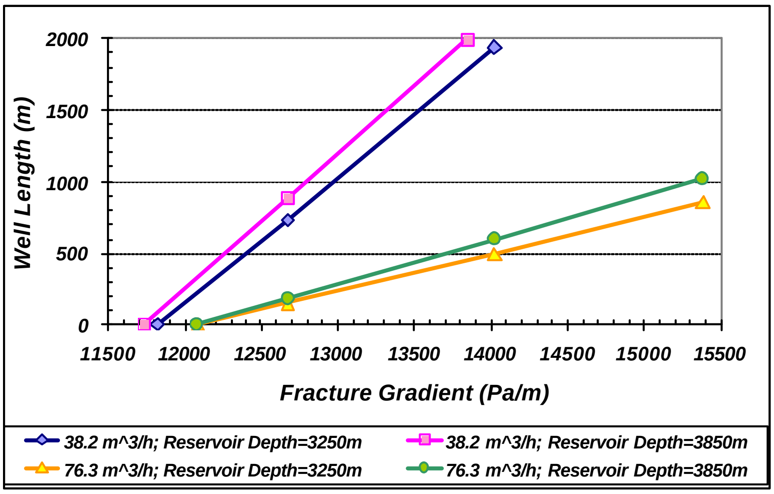

Figure 12. Effect of reservoir depth

6. Extending Hydraulic Limits

The previous item details the effect of important parameters (hole diameter, reservoir and water depths) on the hydraulic limits for successful gravel packing. Such properties, however, are normally defined (although some discussion can be made on well diameter). In the next item are discussed some strategies which may be performed in order to extend hydraulic limits while gravel packing.

6.1 Fluid Density

Normally the fluid density is designed in a way that the hydrostatic pressure generated is higher than the pore pressure and lower than frac pressure. Once the operational window gets narrower, dynamic pressures will certainly overcome frac pressures. One possible alternative is to reduce the fluid weight to levels which guarantee the total gravel pack displacement in the extended well. Figure 13 shows the effect of weight reduction on the extension of the horizontal well section limits. Among the strategies proposed in this article, the reduction of fluid density is a very effective but risky strategy, since at an eventual pump stop, wellbore static pressure may be too low and formation fluid influx may occur.

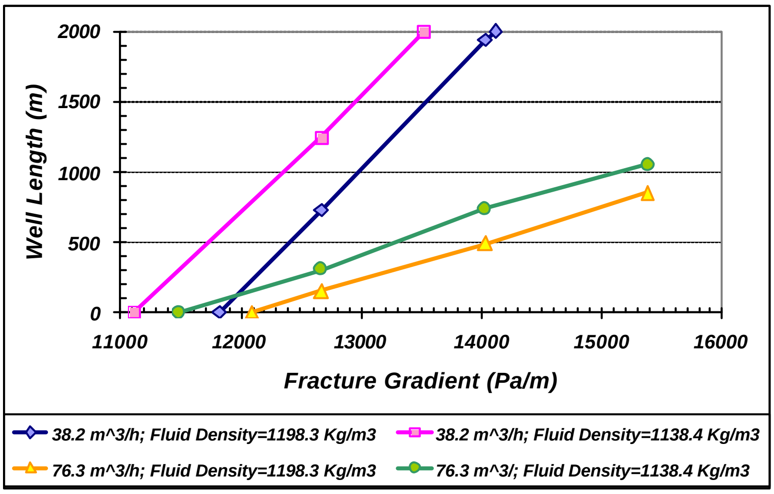

Figure 13. Fluid weight reduction

6.2 Open BOP Configuration

The BOP (Blow out preventer) is an equipment installed at the sea floor which allows the control of unexpected gas influx. Normally the gravel pack operation would be conducted with the closed BOP configuration.

The return flow is diverted, at the sea floor, to two pipelines (called kill and choke lines) usually with 7.62 cm diameter which conduct the fluid back to the rig floor. The flow through these sections results in expressive friction losses, specially at deepwaters, where their length is large. In the limit situation, when low frac pressure is found, an alternative is to open the BOP, and allow the return flow through the riser (normally a 50.8 cm pipe), where friction losses are negligible. This strategy has been used, in the last years, to permit gravel packing in deep and ultradeep water environments. Fig. 14 shows the impact of opening the BOP on the hydraulic limits extension. Note that, using open BOP configuration is possible to extend well length in 400 m.

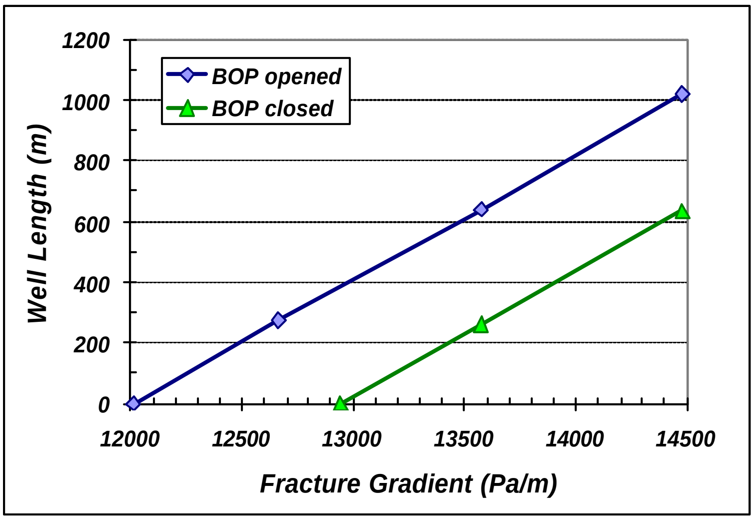

Figure 14. BOP configurations

6.3 Low Friction Loss Cross Over Tools

One point of expressive localized friction loses is the crossover tool, string element which diverts the downward flow from the interior of the string to the annulus and the upward flow in the opposite direction. The service companies invest in different tool designs in order to optimize operational issues and minimize friction losses through the restrictions which divert flow. Table 1 shows different friction loss – flow rate behavior for two commercial tools, while Fig. 15 shows its impact on the hydraulic limits extension. Note that, using tool #1 is possible to extend well length in about 50 m.

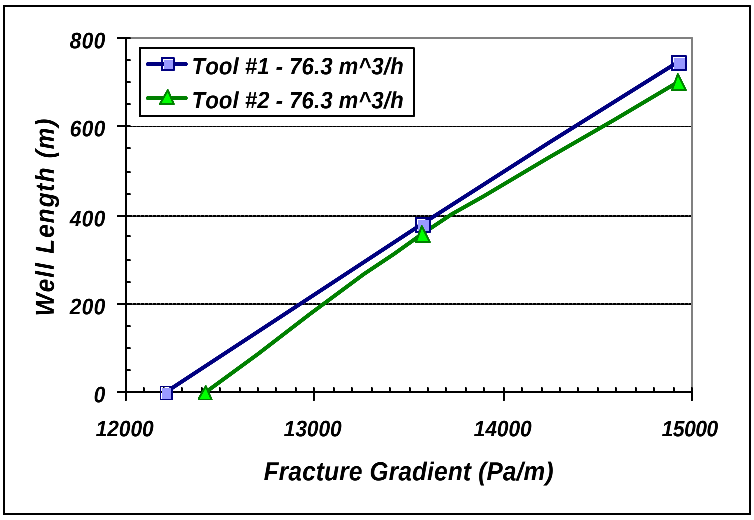

Figure 15. Comparison between two different tools

Table 1: Friction loss tool testing

Tool #1		Tool #2	
Pump rate (m^3/h)	Pressure (pa)	Pump rate (m^3/h)	Pressure (pa)
38,16	2,83E+05	19,08	1,03E+05
47,70	6,48E+05	28,62	2,07E+05
57,24	9,72E+05	38,16	4,55E+05
66,77	1,00E+06	47,70	5,93E+05
76,31	1,07E+06	57,24	9,38E+05
****	****	66,77	1,19E+06

6.4 Zero Rat Hole Configuration

As previously stated, the rat hole is a critical issue in the operational window definition. Several efforts are being spent by the casing design community to make possible a zero rat hole well. In this case, the lower operational limit would be loosened and an extended well operation could be run with lower flow rates. Fig. 16 illustrates the gain in well extension limits when pumping the base case at 33.4 m^3/h (zero rat hole) when compared to 57.2 m^3/h (with the rat hole). An additional issue to be addressed when pumping at low flow rates is the tendency of alpha wave deposition inside the work string.

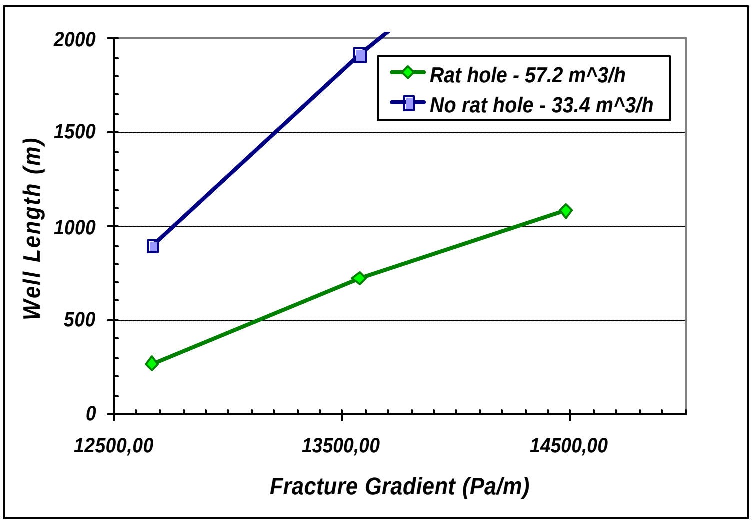

Figure 16. Rat hole comparison

6.5 Use of Drag Reducers

Drag reducers are polymeric additives added to a fluid in order to reduce friction losses during pumping. Turbulence suppression (Lumley 1967 and 1977) and decrease of kinetic energy transport (Virk 1975) are possible mechanisms for the phenomenon. According to Virk, efficient drag reducers can minimize friction losses up to 80% in clear solutions and up to 20% in solid suspensions. During the displacement of the gravel pack friction losses are generated both by the solids suspension (at the downward flow through the string and at the annular flow through the open hole/screen section) and by clear solution (at the annular flow through the screen/wash pipe section and at all the return flow through the wash pipe, casing annulus and kill/choke lines or riser annulus in case of open BOP configuration. Figure 17 illustrates the impact of drag reducers efficiency from 10 to 50% on the hydraulic limits extension.

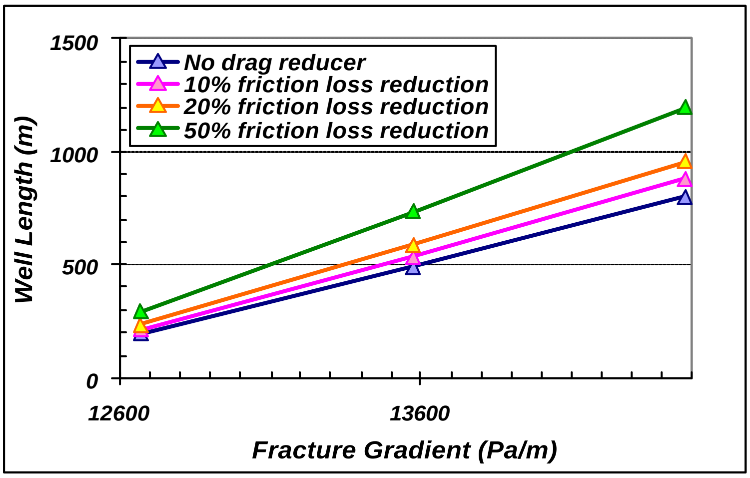

Figure 17. Drag reducers action

6.6 Large Alpha Wave Design

During horizontal open hole gravel packing displacement, the beta wave phase is critical since it generates abrupt pressure increases due to the divergence of annular flow from the open hole/screen section to the narrow annular screen/wash pipe section. A last alternative to make possible open hole gravel packing at extended horizontal wells would be to design a large alpha wave which would cover the screen without significant pressure increase. The beta wave stage would be initiated and performed until frac pressure limits allow. By this point, the operation would be interrupted and when the pressure is alleviated, the non consolidated formation would collapse on the top of the alpha wave at the regions which the beta wave could not be placed. Theoretically the formation sand would not reach the screen since the operation was designed for total screen coverage by the alpha wave. Certainly this is a risky strategy, but it can allow annular packing in extreme cases, where all the other alternatives were not applicable or would not create an operational window. Figure 18 shows the hydraulic limits extension gain for the large alpha wave strategy, when compared to the normal alpha/beta wave approach.

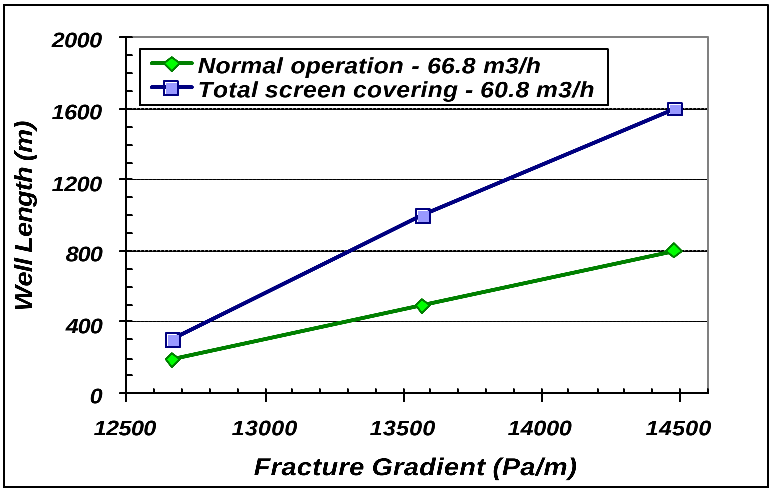

Figure 18. Operational chart

7. Final Remarks

Open hole gravel packs in long horizontal wells are critical operations, specially in deepwater environments. The strategies proposed in this work consist on effective alternatives to extented hydraulic limits and achieve success in critical operations. Some of the alternatives (such as reducing mud weights, zero rat hole configuration and considering large alpha wave displacement) are associated with reasonable risk and should be considered in situations where no other alternative was successful. Other alternatives (such as drag reducers, low friction loss tools and open BOP configurations) are less risky and should be considered whenever necessary. Each operation depends a lot on the specific data of each area and well configuration and should require a singular solution even when compared with a quasi-similar well. Besides, different alternatives are also proposed by the industry, such as flow divergence valves (Coronado 2001) and alternate path technology (Hurst 2004). Generalized well design strategies are not recommended for such complex operations.

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