A DISCUSSION ON THE PARAMETERS GOVERNING DUNE HEIGHT IN OPEN HOLE GRAVEL PACK OPERATIONS

João Vicente Martins de Magalhães, jvmm@petrobras.com.br
Wellington Campos, wcampos@petrobras.com.br
André Leibsohn Martins, aleibsohn@petrobras.com.br
PETROBRAS S.A., Av. Horácio Macedo, 950, Cidade Universitária, Ilha do Fundão, Rio de Janeiro, cep: 21941-915

Bruno Venturini Loureiro, brunovl@ucl.br
Universidade do Centro Leste, Av. Lourival Nunes, 181, Jardim Limoeiro, Serra, Espírito Santo, cep: 29164-050

Fábio Pereira dos Santos, fabio.santos.engineering@petrobras.com.br
Engineering Simulation and Scientific Software - ESSS, Rua Lauro Muller, 116, sala 1404, Botafogo, Rio de Janeiro, cep: 22290-160

Abstract. *Gravel packing in horizontal wells is a well known technique for sand control in non consolidated reservoirs. The technique consists in filling the horizontal annular space formed by the wellbore and the production screens with a sized sand pack which generates a high permeability porous medium which allows oil flow while traps reservoirs sand fines. Gravel placement is usually performed by pumping a water – sand mixture at a previously established flow rate which will generate a dune deposition (called alpha wave) along the horizontal section. After the dune propagates till the end of the horizontal section, sand starts to deposit above the dune in a backwards movement (beta wave). This article proposes a discussion on the parameters governing dune heights. The idea is that the shear stresses at the dune interface would be responsible for the balance of deposition and entrainment processes. A CFD simulation approach was used to analyze the dune interface shear stresses at concentric and eccentric annular flows. In parallel, a mechanistic model is proposed to capture the influence of sand properties and concentration. The use of this approach provided less conservative results which make possible the open hole gravel pack operations in long horizontal sections, economical requirements for heavy oil field development.*

Keywords*: gravel pack, simulation, computational fluid dynamics, completion, petroleum*

1. INTRODUCTION

The unique conditions found in the Brazilian deepwater fields pushed the industry to develop dedicated technology to guarantee technical feasibility and economicity of such projects. Non consolidated reservoirs require sand control and Campos Basin history have been constructed with gravel packing techniques (Marques et al, 2007) and different technological implementations allowed overcoming hydraulic issues in narrow operational window scenarios.

In cases where a selective completion is required to isolate multiple reservoir zones special care should be taken in gravel pack placement. In such situations, one or more Annular Barreirs Tools (ABTs) are installed along the production screen. Because of the narrower annular section formed in front of each ABTs, different placement dynamics occurs.

The main topic to be developed in this article is to determine how wall shear stresses during horizontal well gravel packing impact in alpha wave dune heights. To accomplish this task we developed a parametric study for comparison flow phenomena in a regular gravel packing operation annular and a narrow annular formed between wellbore walls and ABT.

The mechanisms actuating in the solids deposition in the annulus comprise two different aspects:

- Solids sedimentation: resulting from the density difference between gravel and carrier fluid, solids will tend to settle in the lower portions of the annular section.
- Shear efforts at the dune surface: due to axial flow, the solids deposited will tend to be re-suspended into the flow stream.

Figure1 illustrates the two mechanisms governing bed height. If the flowrate is such that the erosion rate (R_e) is bigger than the deposition rate (R_d), the dune will be eroded. If the opposite occurs, the dune will grow in height. When the two rates are equal, and equilibrium dune height will be achieved. The next step is to analyze which variable governs this balance. Two different criteria are proposed in the literature, both for gravel packing and drilled cuttings transport analysis:

- Critical depositional velocity: this idea, supported by Campos (1995), Ford (1996) and Becker (1991), suggests that there is a critical average flow velocity above which no sedimentation will occur. Once the relation between flow rate and dune height for an open hole gravel packing operation is known, (Martins et *al*. 2005a), the values which provide the same average velocity in the annular section formed between the wellbore walls and the packer OD will guarantee no sedimentation. Because the constant flow rate, equivalent cross sectional areas will provide similar velocities, as illustrated by fig.2.

- Critical interfacial shear stress: other authors like Sanchez (1997) and Martins (2008) claim that the equilibrium of deposition and erosion rates are governed by local properties at or in the vicinity of the dune surface. In this case the average (or maximum) shear stress would govern the process and similar stresses at both regions would define the required flow rate to avoid gravel deposition around the barriers (fig.3).

2. CASE STUDY

Horizontal wells usualy are drilled with 8 ½" bits (where often a ½ inch hole enlargement is used as a safety criterion) or, less frequently, with 9 ½" bits. Fig.4 details expected dune heights as function of the flow rate, based on predictions of the model proposed by Martins et al (2005b). There is no increasing influence of the wellbore diameter in the dune height with the increase of flow rate (for small flow rates the effects are negligible).The results were obtained for 6.16 inches OD concentric screens, 20/40 sand mesh, pumped at 1 ppa concentration.

3. DEFINING MINIMUM FLOW RATE

3.1. Critical Depositional Velocity Method

In this method, the areas above the dune and around the ABT should be the same. Figure 5 associates, based on geometric derivations, the area above the dune with dune height for the 3 well diameters in study.
Now the following steps were performed to define the minimum flow rate required to avoid sedimentation around the ABT:

1. Select an ABT diameter;
2. Calculate the annular cross sectional area formed by the open hole and the ABT;
3. For the calculated area estimate dune height using fig.5;
4. With the calculated dune height, estimate the flow rate using fig.4 (or equivalent, for different sand properties, fluid properties and concentration).

Figure 6 is a generalized chart, based on the critical deposition velocity concept and valid for the conditions which generated fig.4. Results consistently indicate that, for a given openhole diameter, the minimum flow rate required to avoid sedimentation around the ABT decreases with the increase of ABT diameters. In the same way, a same ABT would require larger pump rates at larger wellbores.

3.2. Critical Shear Stress at the Dune Interface Method

This method consists in assuming that no deposition around the ABT will happen when the shear stresses at the dune surface are equal to the shear stresses at the wellbore walls in front of the ABTs. Since the shear stress will vary along the position at the dune surface, an average value will be considered. Since this method requires evaluation of local properties some kind of numerical simulation will be required, and will be presented further. The following steps are proposed to calculate the required flow rate:

1. Define the pump rate for the gravel pack operation;
2. Estimate dune height, according to fig.4;
3. Evaluate shear stress profile at the dune surface using numerical simulation (CFD);
4. Calculate an average shear stress at the dune surface;
5. For a given ABT, use a recursive method to define the required flow rate to avoid sedimentation (which generates shear stresses at the wellbore walls similar to the average shear stress at the dune surface.
6. Determine critical flow rate (Q) using eq. 1.
7. If the critical flow rate is smaller or equal to the value defined in item 1, the design is OK. If not, this value should be discarded. Other design criteria, concerning the lower limit of the operational window should be checked.

Equation (1) defines the required flow rate,

$$Q = \overline{V}A = \frac{\pi\left(D_W{}^2 - OD_{ABT}{}^2\right)}{4}\left(\frac{\tau}{0.0395\rho^{3/4}\left(\dfrac{\mu}{D_{W-ABT}}\right)^{1/4}}\right)^{4/7} \qquad (1)$$

Where D_W is the wellbore diameter, OD_{ABT} is the ABT outside diameter, τ is the shear stress at the wellbore walls, μ is the fluid viscosity and $D_{w\text{-}ABT}$ is the annular hydraulic diameter. Derivation of Eq. (1) is detailed in Appendix 1.
The numerical solution for the prediction of shear stresses at the dune surface was developed using a comercial computational fluid dynamics package (Fluent 6.2), based on the finite volumes method. The simulations were based on water flowing that occur through a partially obstructed annular section. Since the flow rates tested implied both in a partially and in a totally covered screen, the geometry considered the three possbilities illustrated in the fig.7 for the 9" well. Each simulation required a singular geometry construction, starting from the values of flow rate and dune height provided by fig. 4. Table 1 details the simulations performed. The total annular length considered in all simulations was 6 m. Radial flow through the screens was neglected. Figure 8 shows different views of the 3D geometry built for CFD simulations.

Each mesh was built for each geometry considering uniform spacing. The meshes were constituted by 80 cells in the wellbore walls (tangential direction), 80 cells in the dune surface (radial direction) and 1000 cells along the annulus length (axial direction). Fig.8 illustrates similar shear stresses results at dune surface for two different meshes.

Turbulent flow was considered by adoption of the standard k-ε model, despite of flow anisotropy. Pressure-velocity coupling was performed through the SIMPLE (Patankar 1980) method and the discretization of momentum and turbulence equations was performed through the First Order Upwind method.

As boundary conditions, the following assumptions were made: no wall slip, no surface rugosity. Mass flow rate provided in the inlet and fully established flow at the outlet. Local variables were collected at a cross section located at 5.5 m from the entrance, where inlet effects were not anylonger felt as illustrated in fig. 10.

The next figures represent the flow rate requirements as a function of ABT diameters, based on the critical shear stress hypothesis. Figures 11, 12 and 13 represent the 8 ½", 9" and 9 ½" wells respectivelly. The results for the critical deposition velocity criteria are also plotted for comparison purposes. The following procedure illustrates how to use the figures.

- On the figure13 (9 ½ in openhole) choose a 6 bpm flow rate for gravel pack pumping
- Follow the horizontal dashed line until it intersects the circular points curve, referent to the numerical simulation of shear stresses at the dune interface at 6 BPM.
- The x-axis coordinate for this intersection represents the minimum ABT diameter where no deposit will occur at this pump rate. In this case an 8.4 in ABT diameter is obtained against 8.7 in from the critical deposition velocity concept.

A relevant remark is to question the uncertainty associated to the relation between flow rate and dune height illustrated by fig.4. Although generated by a mechanistic model, results were calibrated by experimental data (Martins et al, 2005a) generated in a reduced scale flow loop (5.92 in X 4.45 in – annular formed by wellbore and screens). Consequently, uncertainties associated to flow rate control and dune height measurements are expected. Figure 14 illustrates the impact of a 5% uncertainty (positive and negative) of dune height or of flow rates values on shear stress predictions. The error bars denote the impact of dune height fluctuations while the "x" characters identify the flow rate uncertainties. The errors in dune height propagate more expressively on shear stress due to the 3.75 power relationship between hydraulic diameter and shear stress (against a 1.75 power relation between flow rate and shear stress). Therefore, an uncertainty analysis should be associated to fig.4 and consequently to the results obtained in figs. 11, 12 and 13.

4. FINAL REMARKS

This article proposes a local and phisically meaningful criteria to determine conditions which avoid depostion of sand in annular solid/liquid flows. The relevant parameters calculations were only possible via a robust 3D Computational Fluid Dynamics Simulation (CFD).

The application of the critical shear stress methodology for open hole gravel packs design in multizone completion projects indicates less conservative results which can make possible operations in critical operational windows scenarios.

The current results are limited to simplified turbulence modeling (k-ε model). The introduction of advanced turbulence models, such as Reynolds Stress, may capture the anisotropic effectes related to flow through the obstructed annulus. Besides, experimental validation (with screens equipped with ECPs) will add reliability to this design methodology.

5. ACKNOWLEDGEMENTS

The authors would like to thank Petrobras and Faculdade do Centro Leste for the permission to publish this paper and ESSS for the cluster simulations support

6. REFERENCES

Becker, T.E., Azar, J.J., Okrajni, S.S. 1991. "Correlations of Mud Rheological Properties with Cuttings-Transport Performance in Directional Drilling". *SPE Drill & Compl* **1**(6): 16-24. SPE-19535-PA. DOI: 10.2118/19535-PA.

Campos, W. 1995. "Mechanistic Modeling of Cuttings Transport in Directional Wells", PhD dissertation, Tulsa U., Tulsa, Oklahoma.

Ford, J.T., Goo, E., Oyeneyin, M.B., Peden, J.M., Larrucia, M.B., Parker, D. "A New MTV Computer Package for Hole-Cleaning Design and Analysis". *SPE Drill & Compl* **11**(3): 168-172. SPE-26217-PA. DOI: 10.2118/26217-PA Heriot-Watt U.

Machado, F.A. et al. 2001. "Seletive Completion with Open Hole Gravel Pack Sub-horizontal Well: An Inedited Experience at the World". Presented at 4th Petrobras Well Engineering Seminar, Rio de Janeiro, Brazil.

Marques, L. *et al*. 2007. "The 200th Openhole Gravel-Packing Operation in Campos Basin: A Milestone in the History of Petrobras Completion Pratices in Ultradeep Waters". Paper SPE presented at the 2007 SPE European Formation Damage Conference, Scheveningen, The Netherlands. SPE 106364-MS. DOI: 10.2118/106364-MS.

Martins, F.F., Campos, W., Miranda, A.V.M. 2008."Cuttings Bed Removal in na Eccentric Annulus Considering The Critical Shear Stress Criterion", 12th Brazilian Congress of Termal Engineering and Sciences, 0-14 November, Belo Horizonte, Brazil.

(a) Martins, A.L., de Magalhães, J.V.M., Calderon, A., Mathis, S.P., Trujillo, C., Nguyen, H.T. 2005. "Experimental and Theoretical Simulation of Gravel Pack Displacement in Extended Horizontal Offshore Wells", *SPE Drill & Compl* **20**(2): 141-146. SPE 86509-PA. DOI: 10.2118/86509-PA.

(b) Martins, A.L., Magalhães, J.V.M. and Calderon, A. 2005. "A Mechanistic Model for Horizontal Gravel Pack Displacement". SPE J. **10** (3): 229-237. SPE-82247-PA. DOI: 10.2118/82247-PA.

Patankar, S.V. 1980. *Numerical Heat Transfer and Fluid Flows*, Hemisphere Publishing Corporation, New York.

Pinto, A.C.C. *et al.* 2001. "Marlim Complex Development: A Reservoir Engineering Overview". Paper presented at the 2001 SPE Latin American and Caribbean Petroleum Engineering Conference, Buenos Aires, Argentina. SPE 69438.

Pinto, H.L.C.P. *et al.* 2006. "Integrated Multizone Low-Cost Intelligent Completion for Mature Fields". Paper presented at the 2006 Intelligent Energy Conference and Exhibition, Amsterdam, The Netherlands. SPE 99948.

Ritchie, B., *et al*. "Challenges in Completing Long Horizontal Wells Selectively". Paper presented at the 2008 SPE Asia Pacific Oil & Gas Conference & Exhibition, Perth, Australia. SPE 116541-MS. DOI: 10.2118/116541-MS.

Robinson, M. 2003. "Intelligent Well Completions". *J. Pet Tech*. **55** (8): 57-59.SPE 80993-MS. DOI: 10.2118/80993-MS.

Sanchez, R.A. 1997. "Modeling of Drilled Cuttings Bed Erosion in Highly Inclined Wells", MSc dissertation, Tulsa U., Tulsa, Oklahoma.

Trindade, W.L. and Branco, C.C.M, 2005. "The Offshore Heavy Oil Development Challenges in Brazil". Paper presented at the 2005 SPE Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, Brazil. SPE 97381-MS. DOI: 10.2118/97381-MS.

5. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

Appendix A – Derivation of a shear stress and velocity relationship for annular flow

Shear stress and velocity are correlated by a dimensionless friction factor as follows:

$$\tau = f\,\frac{\rho v^2}{8} \qquad \text{(A-1)}$$

The friction factor can be estimated by a Blasius proposal:

$$f = 0.316\,\mathrm{Re}_h^{-1/4} \qquad \text{(A-2)}$$

Substituting Eq (A1-2) in (A1-1):

$$\tau = \left(0.316\,\mathrm{Re}_h^{-1/4}\right)\frac{\rho v^2}{8} \qquad \text{(A-3)}$$

Where the Reynolds number is defined by:

$$\mathrm{Re}_h = \frac{\rho v D_h}{\mu} \qquad \text{(A-4)}$$

Substituting Eq (A1-4) in (A1-3):

$$\tau = \left[0.316\left(\frac{\rho v D_h}{\mu}\right)^{-1/4}\right]\frac{\rho v^2}{8} \qquad \text{(A-5)}$$

or:

$$\tau = 0.0395\,\rho^{3/4}\left(\frac{\mu}{D_h}\right)^{1/4} v^{7/4} \qquad \text{(A-6)}$$

and, consequently:

$$v^{7/4} = \frac{\tau}{0.0395\,\rho^{3/4}\left(\frac{\mu}{D_h}\right)^{1/4}} \qquad \text{(A-7)}$$

Substituting $D_h = D_0 - D_i$ in Eq (A1-7):

$$v^{7/4} = \frac{\tau}{0.0395\,\rho^{3/4}\left[\frac{\mu}{(D_0 - D_i)}\right]^{1/4}} \qquad \text{(A-8)}$$

Table 1 - Pumping Flow for each wellbore diameter. Symbol "x" denotes the cases studied, and the symbol "0" denotes the cases do not studied.

Flow [bpm]	Studied Cases		
Q	**8.5 in**	**9.0 in**	**9.5 in**
2	X	X	X
4	X	X	X
6	O	X	X
8	O	O	X

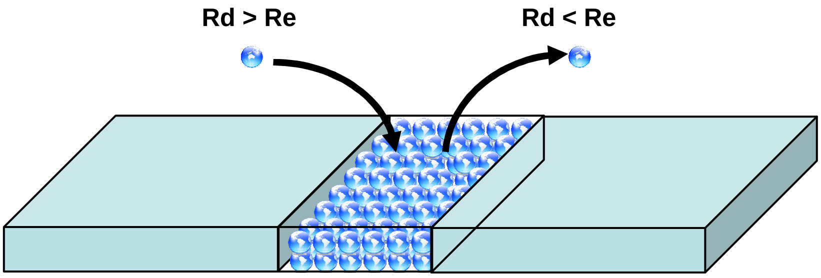

Figure 1: Two mechanisms that govern bed height (difference between deposition rate and erosion rate)

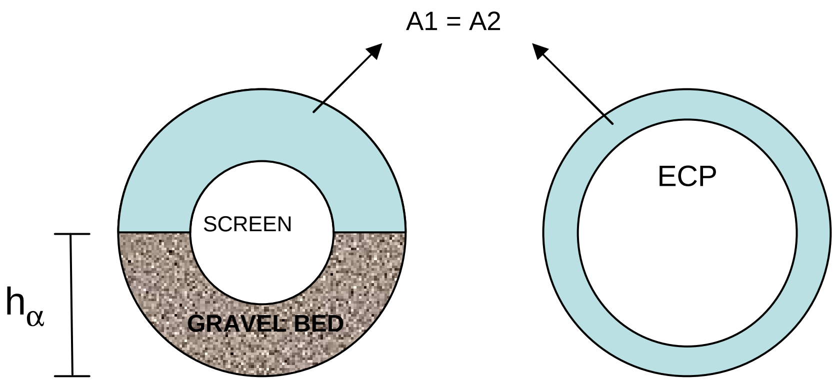

Figure 2: Critical depositional velocity criterion

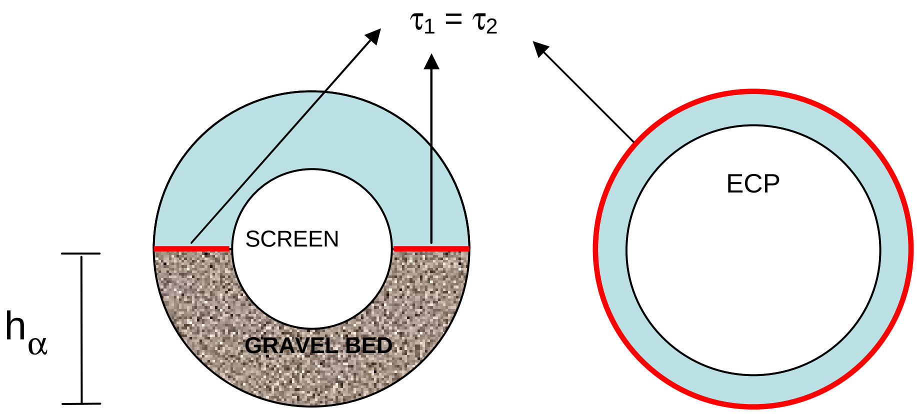

Figure 3: Critical interfacial shear stress criterion

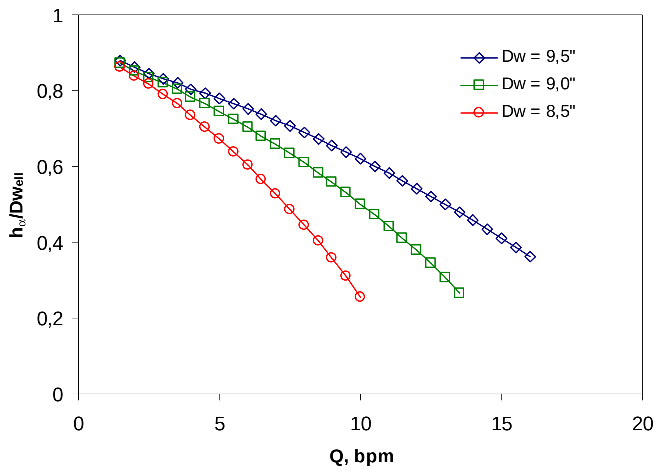

Figure 4: Relative Dune height versus flow rate. From (Martins 2005b).

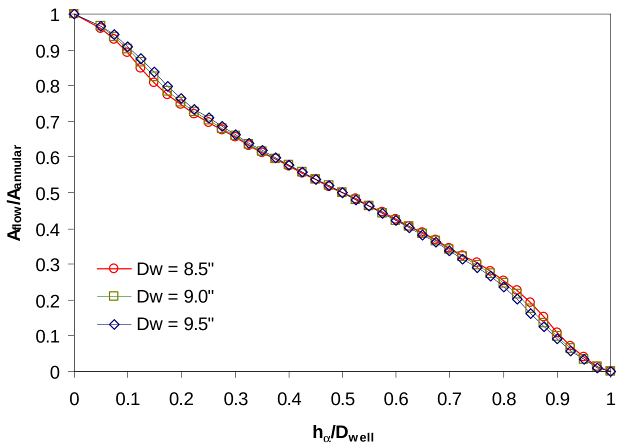

Figure 5: Relative flow area versus relative dune height.

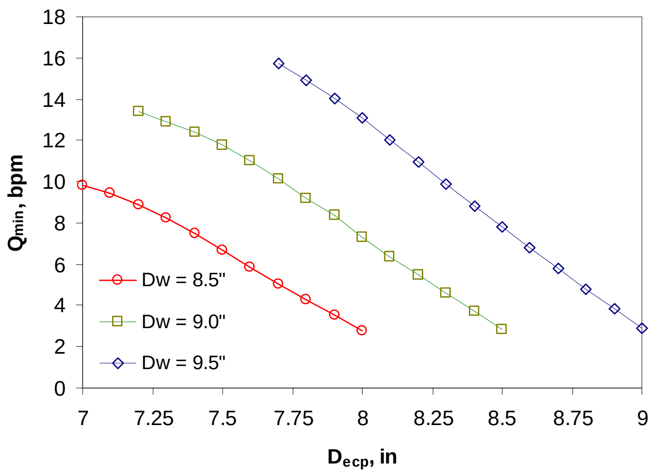

Figure 6: Minimum flow rate required to avoid sedimentation around the ECP considering the critical depositional velocity concept.

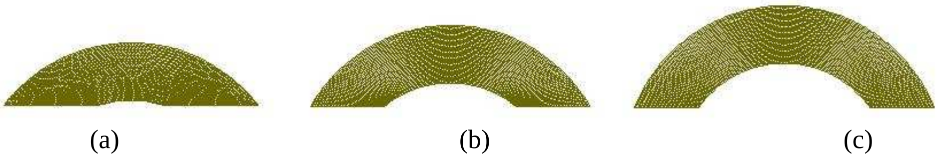

Figure 7: Examples of transversal geometry for well diameter equal to 9 in. (a) 4 bpm; (b) 6 bpm; (c) 8 bpm.

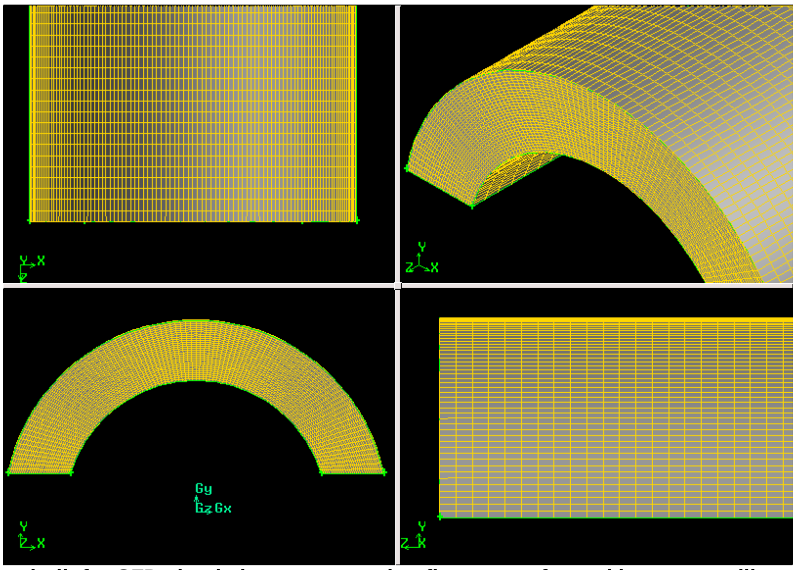

Figure 8: 3D geometry built for CFD simulations representing flow space formed between wellbore, ECP and the dune.

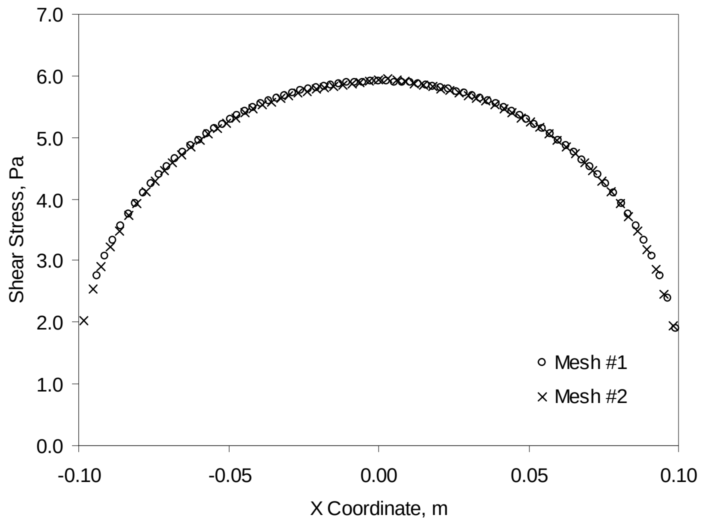

Figure 9: Shear stress on the dune surface for 2 different meshes in the cross section. Mesh #1: 80 cells for dune and wellbore. Mesh #1: 70 cells for dune and wellbore.

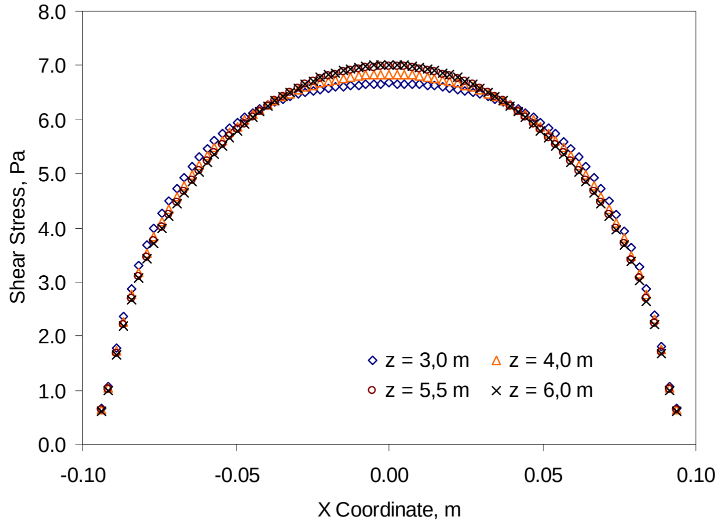

Figure 10: Effects of developing flow in wall shear along the dune surface.

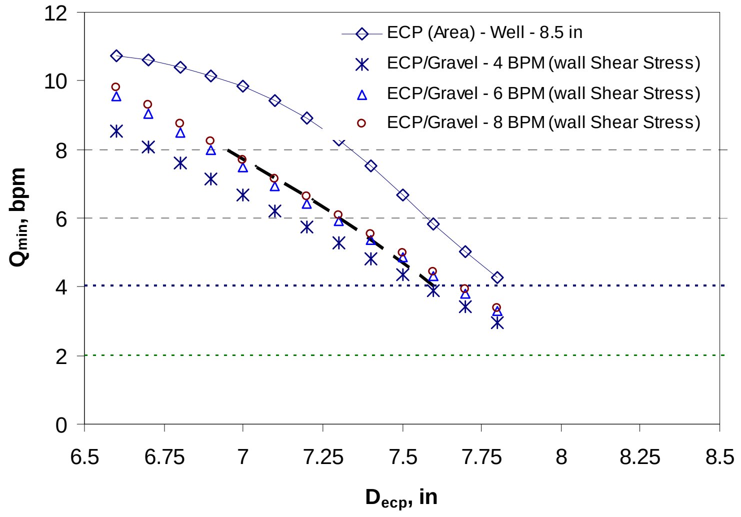

Figure 11: Determining the range of ECP diameters from the criteria of equal areas and interfacial shear stress. D_w = 8.5 in.

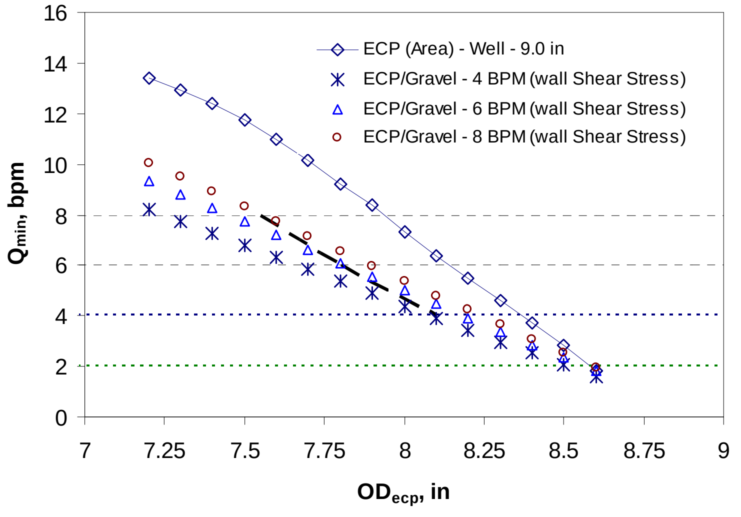

Figure 12: Determining the range of ECP diameters from the criteria of equal areas and interfacial shear stress. D_w = 9.0 in.

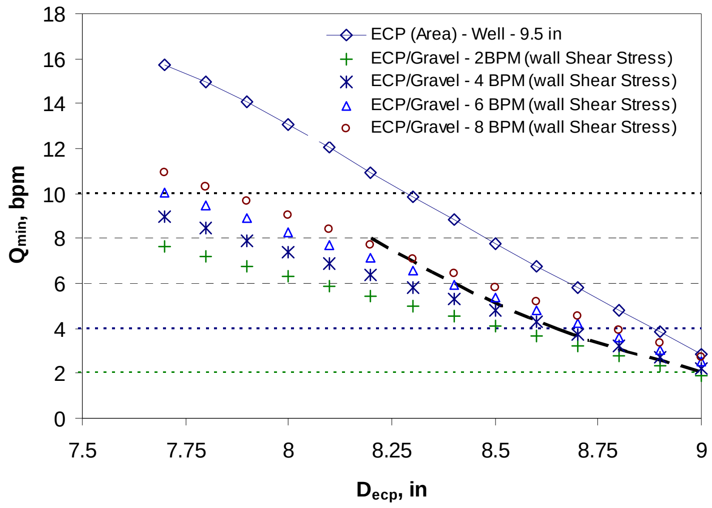

Figure 13: Determining the range of ECP diameters from the criteria of equal areas and interfacial shear stress. D_w = 9.5 in.

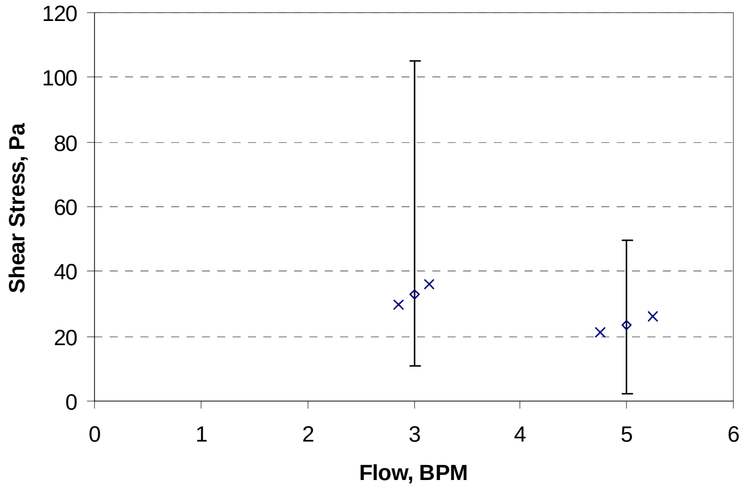

Figure 14: Influence of measurement uncertainty of dune height and flow rate on shear stress.