An Integrated Sand Control Method Evaluation
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This paper was prepared for presentation at the IGPC Oil and Gas Conference and Exhibition held in Kuala Lumpur, Malaysia, 16-21 August 2003.

Abstract
A numerical model has been developed that is able to predict the onset of sand production and evaluate the performance of sand control, should sand production become unavoidable. The simulation of perforation stability was carried out using a two-dimensional, two-phase finite-element model. This is a coupled geomechanical and fluid flow model. The rock was assumed to be heterogeneous and the pores were completely filled with fluid. The deformation condition is considered as plane strain and either the Mohr-Coulomb or Drucker-Prager yield surface was used to designate perforation failure. The model enables the study on the effect of perforation pattern and density on wellbore stability. Simulation runs on a sample model indicated that the lowest pore pressure, the greatest shear stress and major principle stress were found close to the perforation tip. The greatest major principal stress occurred around the center of perforation roof. In other words, the perforation was always surrounded by high stress concentration. In those events when sand production is a certainty, it is necessary to evaluate the performance of sand control methods using a finite-difference flow model was used to calculate the additional pressure drop from the well boundary to the sand control screen. The Forchheimer equation was used in place of the more conservative Darcy equation so that the effect of high-velocity flow to the well performance could be considered. The result of several sample runs indicated firm relationship between total additional pressure drop and the flow rate imposed, where a larger flow rate will cause greater pressure loss. Also, the well productivity showed improvement with more shots per foot. The results suggested that the majority of well pressure drop was caused by the casing-cement tunnel.

Development of numerical model
In an integrated approach to sand production problems, we seek to predict the stress state around the wellbore for different operating conditions, and if sanding is inevitable, the optimum gravel-pack configuration is chosen. The tools involved are a coupled mechanical-fluid flow model and a three-dimensional well productivity model. The essential equations for the two models are given below.

The Perforation Stability Prediction Model
In predicting the perforation stability, the borehole is divided into slices. The number of slices depends on the thickness of each slice and the borehole radius. The deformation condition for every slice is considered to be of plane-strain type and the oil flow is confined within the domain of each slice. The perforation is assumed to be a cylinder with an open end, the other end being semi-spherical. Fig. 1 shows a slice with one perforation cavity. The interactions between slices are considered by taking into account the stress component that act between the slices.

Generally, the perforation stability prediction model is comprised of 2 main elements: flow continuum equation and solid equilibrium equation. The flow continuity equations calculate fluid pressure distribution around perforation, while solid equilibrium equation determine the stress state and rock deformation. According to Lewis and Schrefler (1987), the flow continuity equation is:

- \( \nabla \cdot \left( k_{eff} \nabla (p + \rho gh) \right) + \lambda \frac{\partial p_a}{\partial t} + \lambda_\sigma \frac{\partial p_\sigma}{\partial t} = \frac{\partial q}{\partial t} \)

\( S_e \left( \frac{m}{K_e} \right) \frac{\partial p_a}{\partial t} + \frac{\partial q}{\partial t} = 0 \)

The solid equilibrium equation can be written as:

- \( \int \delta \sigma^T \delta D \, d\Omega + \int \delta \sigma^T \left( \frac{D_e}{3K_e} - m \right) \delta p_a \, d\Omega \)

- \( \int \delta \sigma^T \delta D \, d\Omega = \int \delta \omega^T \frac{db}{dt} \, d\Omega - \int \delta \omega^T \frac{dt}{dt} \, d\Omega = 0 \)

Eq. (1) and (2) are coupled and solved by using the finite-element method (FEM). \( D \) in Eqs. (1) and (2) is the tangential stiffness matrix which is defined by a constitutive model. It can be the tangential elastic stiffness matrix, \( D^t \) for elastic deformation or the tangent elastoplastic modulus matrix \( D^p \) for plastic deformation. Two types of elastoplastic models suitable for the prediction of perforation failure are the Mohr-Coulomb yield surface and the Drucker-Prager yield surface, and both are available in this model (Veeken et al., 1991; Brady, 1994).

Gravel-Pack Well Productivity Model
The governing equation for one-phase flow through a petroleum reservoir in three-dimensional cylindrical coordinates \((r, \theta, z)\) is:

- \( \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda \frac{\partial p}{\partial r} - \gamma \frac{\partial h}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( \delta \theta \lambda \frac{\partial p}{\partial \theta} - \gamma \frac{\partial h}{\partial \theta} \right) = \frac{\partial q}{\partial t} + \frac{\partial p}{\partial t} \)

The governing equation is discretized in space in the directions of \( r, \theta \) and \( z \) for both the oil and water phases. The governing equation is also discretized in time using the forward difference approach. In this work, the distinction between the perforation and the reservoir rock is in their permeability where gravel permeability is used for the gravel-
filled perforations and original permeability for the reservoir.

The IMPES (Implicit Pressure Explicit Saturation) method is used to combine the governing equations for the oil and water phases. The difference equations are written for each grid block and the resulting system of equations is collected and expressed in matrix form. The matrix is solved using the iterative Gauss-Seidel method for the pressure at the innermost part of the perforation, i.e., \( p_{i} \). It should be noted that perforation here refers to the part of the perforation outside the casing. The pressure drop across this zone is the difference between the reservoir pressure, \( p_{r} \), and \( p_{i} \).

**High-velocity flow effects**

As the flow velocity increases, deviations from Darcy’s Law are observed. In this study, the Forchheimer equation is used in place of Darcy’s Law in the modeling equations. The Forchheimer equation is given as

\[
\nu = -\frac{k \frac{dp}{dx} \delta}{\mu} \quad \ldots\ldots (4)
\]

where

\[
\delta = \frac{1}{\left(1 + \frac{\beta \rho k}{\mu} \right)^{1/2}} \quad \ldots\ldots (5)
\]

The symbol \( \delta \) is a turbulence correction factor, which is introduced into the governing equation that is Eq. 3. Another parameter important in high-velocity flow is the high-velocity coefficient \( \beta \) as found in Eq. 5. Among the numerous correlations available in the literature, the Brown (1984) correlation is popular and is used in this work. The Brown (1984) correlation gives \( \beta \) as a function of permeability, that is

\[
\beta = \frac{1.47 \times 10^{7}}{k^{0.55}} \quad \ldots\ldots (6)
\]

**Pressure drop in the casing-cement tunnel**

In this work, the perforation is divided into two sections. The first is the perforation in the formation outside the casing, which has been discussed in the previous section. The second is a shorter tunnel in the both the casing and the cement. Due to its relatively small size, the flow regime in this tunnel is regarded as linear. The equation for linear one-dimensional flow through a perforation is given by Sauclier (1974) as

\[
\Delta p_{pf} = 0.888 \frac{L \rho q B}{k A} + 9.1 \times 10^{-12} \beta L (q B)^{2} \quad \ldots\ldots (7)
\]

The first term on the right side gives the pressure drop due to Darcy flow and the second term represents the additional pressure drop due to high-velocity flow. The parameter \( \beta \) is the same high-velocity coefficient as presented in Eq. 5.

**Result and discussion**

The applicability of the perforation prediction model is demonstrated by running a sample case. This sample model was run for 495.01 second. Five slices were used to construct a perforation. Relevant data of the sample model are given in Table 1. While Table 2 shows the formation volume factor for the oil in the sample model.

Fig. 2 and Fig. 3 shows the pore pressure distribution at nodal points along the perforation roof for \( q = 0.01328 \) m³/D/perf and \( q = 0.02655 \) m³/D/perf. When the production rate is increased the pore pressure is decreased due to more oil withdrawal and rock compaction. The difference in pore pressure between the sand face and the wellbore outer boundary is very small for both production rates because the model is small. Both figures indicate that along the perforation roof, pore pressure is very low and the lowest pore pressure is at the zone close to the perforation tip.

Fig. 4 shows the stress distribution at Gauss point along the perforation roof for 2 different production rates (0.01328 m³/D/perforation and 0.02655 m³/D/perforation). From this figure, for both production rates, the greatest shear stress and minor principle stress were always located at the perforation roof. On the other hand, the major principle stress was highest around the center of perforation roof. This figure also suggests that the perforation was always surrounded by high stress concentration. If the production rate is increased, the stresses along the perforation roof will also increase. This is because a higher production rate will induce larger displacements that cause increase in stress.

As with the wellbore stability model earlier, a case study is performed using the well productivity model. A fictitious model is constructed based on the design of a typical well installed with an inside-casing gravel pack. The model has a cylindrical shape with a hole at the center. For simplicity, the model is assumed to contain only oil. The model is delineated on the outside, top and bottom by no-flow boundaries. The hole at the center of the model acts as the wellbore. The number of grids used is 5 in the radial (r), 12 in the angular (θ) and 12 in the vertical (z) directions, respectively, giving a total of 720 grids blocks. Both cases of openhole and perforation flow were considered. The basic condition of a drawdown test is simulated with the flow rate being kept constant. The duration of all simulation runs was 1 hr. (3600s), which is approximately the time required to reach pseudo-steady state. The additional pressure drop due to gravel-packed perforations outside the casing for a particular perforated case, \( \Delta p_{pm} \), is obtained by subtracting the pressure at the opening of the perforation (perforated case) from the pressure at the same position for the openhole case. For the subsequent linear flow through the casing-cement tunnel, the additional pressure drop, \( \Delta p_{pm} \), is calculated directly from Eq. 5. The total additional pressure drop is the sum of the two.

The total additional pressure drop in a gravel-packed well is shown in Fig. 5 for different perforation densities and flow rates. As expected, the total additional pressure drop decreased with more shots per foot. This is consistent with earlier studies of productivity of perforated wells (Locke, 1961; McLeod, 1983), which suggested better productivity with higher shot densities. Also, the total additional pressure drop was found to increase with flow rate. The effect of flow rate on total pressure drop was greater for lower shot densities. This is most probably due to high-velocity flow that is more...
Fig. 6 shows the contribution of gravel-packed perforations outside the casing and the casing-cement tunnels to the total additional pressure drop. For all flow rates and shot densities studied, most of the pressure drop occurred in the casing-cement tunnels. The pressure drop in casing-cement tunnels accounted for 89-95% of the total additional pressure drop. This is especially the case in high-permeability reservoirs, where the combined effect of perforation and well geometry will be small compared to the casing-cement tunnels. In gravel-packed wells in such reservoirs, it is likely that the total pressure drop will be dominated by pressure losses in the casing-cement tunnels. However, in low permeability reservoirs, or reservoirs that experience severe damage (due to drilling fluids invasion, crushed zone etc.), the effect of gravel-packed perforation outside the casing may contribute more to the total pressure drop. As can be seen in Fig. 6, the contribution of perforations outside the casing increased with increasing shot density, which is true for all the flow rates studied.

Conclusion

Based on the results presented thus far, the following conclusions are drawn:

1. The perforation stability prediction model is able to determine the pressure distribution and stress state for the rock around the perforation. With these information, perforation failure can be predicted by using one of the two failure criterions given.

2. An increase in flow rate will cause higher stresses to exist around perforation, and thus increase the likelihood of perforation failure.

3. The well productivity model can be used to determine the productivity of gravel-packed wells under different operating conditions.

4. The productivity of gravel-packed wells is improved with increasing perforation densities; higher flow rates will cause greater pressure loss and thus impair well productivity.

5. The majority of well pressure drop is due to pressure loss in the casing-cement tunnel.

Acknowledgments

The authors wish to thank the Ministry of Science, Technology and the Environment, Malaysia for providing the necessary funding that made this study possible.

Nomenclature

\[
\begin{align*}
\text{cm} & = \frac{(1-\phi)}{K_s} T \, \text{m}^3 \text{D}_t \text{m} \\
\text{SO} & = S_o - p_o \, S_w + p_w \, S_w' \\
\text{SW} & = S_w + p_o \, S_w' - p_w \, S_w' \\
\left( \frac{1}{B_o} \right) & \text{ - slope of } \left( \frac{1}{B_w} \right) \text{ versus } p_w \text{ curve}
\end{align*}
\]

\[
\begin{align*}
\frac{1}{B_o} & \text{ - slope of } \frac{1}{B_w} \text{ versus } p_w \text{ curve} \\
\frac{B}{B_w} & \text{ - formation volume factor} \\
b & \text{ - body force} \\
\text{D}_t & \text{ - tangent matrix} \\
g & \text{ - gravity} \\
h & \text{ - the head above some arbitrary datum} \\
k & \text{ - absolute permeability matrix of the medium} \\
\text{k}_r & \text{ - relative permeability function} \\
\text{k}_s & \text{ - bulk modulus of solid phase} \\
m & \text{ - for normal stress components is unity and for shear stress components is zero} \\
p & \text{ - fluid pressure} \\
q & \text{ - production rate} \\
S & \text{ - fluid saturation} \\
S_w & \text{ - slope of the capillary curve} \\
t & \text{ - time level} \\
\hat{t} & \text{ - boundary traction} \\
\delta & \text{ - virtual displacement} \\
\varepsilon & \text{ - total strain of rock skeleton} \\
\varepsilon_o & \text{ - autogeneous strain} \\
\phi & \text{ - porosity} \\
\lambda & \text{ - } \lambda_o \text{ or } \lambda_{sw} \\
\lambda_{so} & = \frac{\phi}{B_o} \frac{S_o}{B_w} + \phi S_w' \left( \frac{1}{B_o} \right) + \frac{S_w}{B_w} C_m \frac{SO}{SO} \\
\lambda_{so} & = \frac{\phi}{B_w} \frac{S_o}{B_w} + \phi S_w' \left( \frac{1}{B_o} \right) \frac{S_w}{B_w} C_m \frac{SO}{SO} \\
\lambda_{sw} & = \frac{\phi}{B_o} \frac{S_o}{B_o} + \phi S_w' \left( \frac{1}{B_o} \right) + \frac{S_w}{B_w} C_m \frac{EW}{SW} \\
\lambda_{sw} & = \frac{\phi}{B_w} \frac{S_o}{B_w} + \phi S_w' \left( \frac{1}{B_w} \right) + \frac{S_w}{B_w} C_m \frac{EW}{SW} \\
\mu & \text{ - dynamic viscosity} \\
\rho & \text{ - density} \\
\Gamma & \text{ - boundary} \\
\Omega & \text{ - domain} \\
u & \text{ - fluid velocity} \\
\hat{\delta} & \text{ - turbulence factor} \\
\Psi & \frac{\hat{\delta}}{B} \text{ - dimensionless} \\
\beta & \text{ - high-velocity \beta coefficient} \\
L & \text{ - length of casing-cement tunnel} \\
A & \text{ - flow area of perforation tunnel} \\
o & \text{ - oil phase} \\
w & \text{ - water phase}
\end{align*}
\]

Superscript

T - matrix transpose
References

Appendices

Table 1: Data for perforation stability prediction model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Model outer radius</td>
<td>1.524 m</td>
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<tr>
<td>Wellbore radius</td>
<td>0.1524 m</td>
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<tr>
<td>Model height</td>
<td>0.3048 m</td>
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<tr>
<td>Young's modulus</td>
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<tr>
<td>Initial pressure</td>
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<tr>
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<td>2.2x10^-3 Pa.s</td>
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<tr>
<td>Oil density</td>
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<tr>
<td>Perforation length</td>
<td>0.1921 m</td>
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<tr>
<td>Perforation diameter</td>
<td>0.0536 m</td>
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Table 2: Formation volume factor for perforation stability prediction model

<table>
<thead>
<tr>
<th>Pressure (MPa)</th>
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<tbody>
<tr>
<td>8.2737</td>
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<td>1.2363</td>
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<td>16.5474</td>
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<td>17.9264</td>
<td>1.2228</td>
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Table 3: Data for gravel-packed well productivity model

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<tr>
<td>Wellbore radius</td>
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<td>Model height</td>
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<tr>
<td>Porosity</td>
<td>35%</td>
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<tr>
<td>Perforation length</td>
<td>0.1130 m</td>
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<tr>
<td>Perforation diameter</td>
<td>0.0254 m</td>
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<tr>
<td>Perforation density</td>
<td>Openhole, 4 SPF, 6 SPF and 12 SPF</td>
</tr>
<tr>
<td>Phasing angle</td>
<td>90° (4 SPF), 60° (6 SPF) and 30° (12 SPF)</td>
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<tr>
<td>Gravel permeability</td>
<td>1.8111x10^-7 m²</td>
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<tr>
<td>formation permeability</td>
<td>4.9350x10^-7 m²</td>
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<tr>
<td>Initial pressure</td>
<td>1.3790x10^7 Pa</td>
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<tr>
<td>Oil viscosity</td>
<td>6.50×10^3 Pa.s</td>
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<tr>
<td>Oil density</td>
<td>782.20 kg/m³</td>
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<tr>
<td>Flow rates</td>
<td>794.94 m³/D, 1589.87 m³/D and 3179.75 m³/D</td>
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Table 4: Formation volume factor for gravel-packed well productivity model

<table>
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<th>Pressure (Pa)</th>
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<td>1.17×10^7</td>
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<td>1.14×10^7</td>
<td>1.543</td>
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<tr>
<td>1.10×10^7</td>
<td>1.540</td>
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Figure 1: Perforation model

Figure 2: Pore pressure distribution along perforation roof ($q = 0.01328 \text{ m}^3/\text{D/ perf}$)

Figure 3: Pore pressure distribution along perforation roof ($q = 0.02655 \text{ m}^3/\text{D/ perf}$)

Figure 4: Stress distribution along perforation roof.

Figure 5: The effect of perforation density and flow rate on total additional pressure drop

Figure 6: The contribution of gravel-packed perforation (beyond casing) and casing-cement tunnel on total additional pressure drop