An Integrated Simulation Model For Sand Control Evaluation

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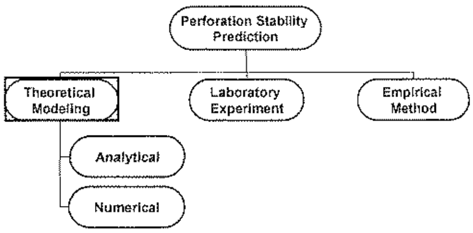
Presentation Outline

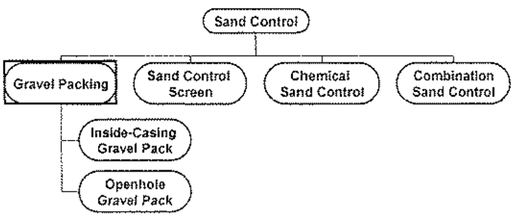
Introduction

- Sand production is the production of load-bearing solids together with the petroleum flow stream.
- An integrated simulation model assess sand production problem by
  - Prediction of perforation stability
  - Selection of optimum gravel-pack configuration for sand control (if sanding is inevitable)

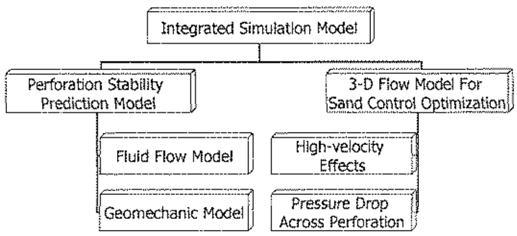
Perforation Stability Prediction Techniques



Sand Control Techniques



Integrated Simulation Model



Perforation Stability Prediction Model

- The model is developed in pseudo 3-D and 2-p (oil & water)
- FEM is used to develop the model
- The model provides stress state and pore pressure distribution around perforation
- Plane strain & non-linear deformation is assumed
- The model includes Mohr-Coulomb and Drucker-Prager yield surface to detect rock failure

Perforation Stability Prediction Model (continued)

- Governing equations:
  - Flow continuity model

$$-\nabla^T\left\{k\frac{k_{r l}}{\mu_l B_l}\nabla(p_l+\rho_l g h)\right\}+\lambda_A\frac{\partial p_o}{\partial t}+\lambda_B\frac{\partial p_w}{\partial t}+\frac{S_l}{B_l}\left(m^T-\frac{m^T D_T}{3K_s}\right)\frac{\partial \varepsilon}{\partial t}=0$$

  - Solid equilibrium model

$$\int_\Omega \delta\varepsilon^T D_T\frac{\partial \varepsilon}{\partial t}d\Omega+\int_\Omega \delta\varepsilon^T\left(\frac{D_T m}{3K_s}-m\right)\overline{SO}\frac{\partial p_o}{\partial t}d\Omega+\int_\Omega \delta\varepsilon^T\left(\frac{D_T m}{3K_s}-m\right)\overline{SW}\frac{\partial p_w}{\partial t}d\Omega$$

$$-\int_\Omega \delta\varepsilon^T D_T\frac{\partial \varepsilon_o}{\partial t}d\Omega-\int_\Omega \delta u^T\frac{db}{dt}d\Omega-\int_\Gamma \delta u^T\frac{d\hat{t}}{dt}d\Gamma=0$$

Perforation Stability Prediction Model (continued)

- Governing equations:
  - Mohr-Coulomb yield surface

$$F=\left(\sqrt{3}\cos\theta_0-\sin\theta_0\sin\phi\right)q-3p\sin\phi-3c\cos\phi=0$$

  - Drucker-Prager yield surface

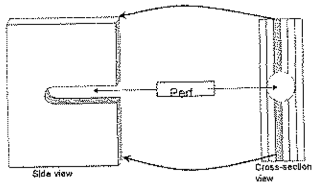
$$F=-3\alpha p+\frac{1}{\sqrt{3}}q-k'=0$$

  - Quantity of sand produced

$$S_c(t)=\pi(1+\alpha)(\phi_y-\phi_h)r_p^{\frac{2\alpha}{1+\alpha}}\left(R^{\frac{2}{1+\alpha}}-r_p^{\frac{2}{1+\alpha}}\right)$$

Perforation Stability Prediction Model (continued)

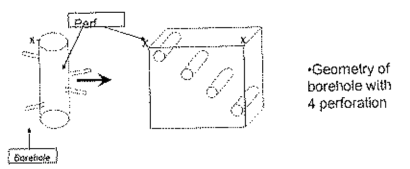
- Model geometry



•The geometry of single perforation

Perforation Stability Prediction Model (continued)

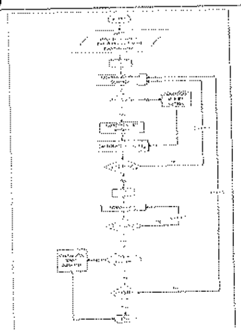
- Model geometry



•Geometry of borehole with 4 perforation

Perforation Stability Prediction Model (continued)

- Flow chart



3-D Flow Model

- The model is 3-D cylindrical flow model
- The model developed using finite different method
- The model provides pressure drop for
  - Gravel packed perforations in formation rock
  - Casing-cement tunnel
  - Annular gravel pack
- The pressure drop due to velocity effect was calculated using Forchheimer equation

3-D Flow Model (continued)

- Governing equation
  - 3-D flow continuity equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\delta_r\lambda R\left(\frac{\partial P}{\partial r}-\gamma\frac{\partial h}{\partial r}\right)\right]+\frac{1}{r^2}\frac{\partial}{\partial \theta}\left[\delta_\theta\lambda\theta\left(\frac{\partial P}{\partial \theta}-\gamma\frac{\partial h}{\partial \theta}\right)\right]+\frac{\partial}{\partial z}\left[\delta_z\lambda Z\left(\frac{\partial P}{\partial z}-\gamma\frac{\partial h}{\partial z}\right)\right]$$
$$=\Psi\frac{\partial P}{\partial t}+q$$

  - Velocity effect (Forchheimer equation)

$$u=-\delta\frac{k}{\mu}\frac{dp}{dx} \quad \text{and} \quad \delta=\frac{1}{\left(1+\frac{\beta\rho k}{\mu}|u|\right)}$$

3-D Flow Model (continued)

- Pressure drop across perforation
  - Pressure drop across perforation (outside casing)

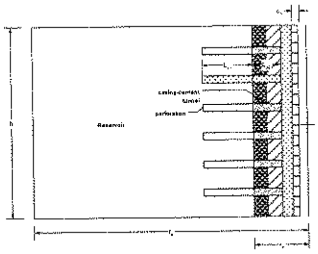
$$\Delta P_1 = P_r - P_p$$

  - Pressure drop in the casing-cement perforation tunnel (Saucier's equation)

$$\Delta P_2 = 0.888\frac{L\mu q}{kA}+9.1\times10^{-13}\beta L\rho\left(\frac{q}{A}\right)^2$$

3-D Flow Model (continued)

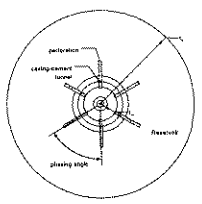
- Model geometry



•Well model (side view)

3-D Flow Model (continued)

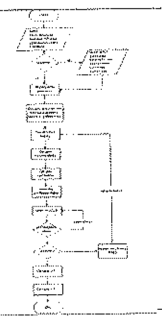
- Model geometry



•Well model (top view)

3-D Flow Model (continued)

- Flow chart



Validation of Results

Perforation stability prediction model

- The model was verified using laboratory experiment data
- Good match was achieved between predicted and experiment result for wellbore pressure, water cut, mean effective stress and quantity of sand produced
- Main findings: rock failure normally occur at perforation entrance and perforation tip

Validation of Results

Perforation stability prediction model

Input Data

Young's modulus	= 1.1204E+09 Pa
Poisson's ratio	= 0.3
Permeability	= 3.6516E-07 m^2 (370 mD)
Porosity	= 0.26
Initial pore pressure	= 8.8942E+06 Pa (1290 psi)
Initial water saturation	= 0.535
Oil viscosity	= 1.5E-03 Pa·s (1.5 cp)
Oil density	= 0.85E+03 kg/m^3
Water viscosity	= 1.0E-03 Pa·s (1.0 cp)
Water density	= 1.0E+03 kg/m^3
Overburden stress	= 3.4474E+07 Pa (5000 psi)
Horizontal stress	= 2.4132E+07 Pa (3500 psi)
Wellbore diameter	= 0.12065 m (4.75 in)
Reservoir radius	= 0.2936 m (0.9633 ft)
Reservoir thickness	= 0.4084 m (1.34 ft)
Perforation length	= 0.11176 m (4.4 in)
Perforation diameter	= 0.01905 m (0.75 in)
Number of perforation	= 8
Phasing angle	= 90°

Validation of Results (continued)

Perforation stability prediction model

Input Data

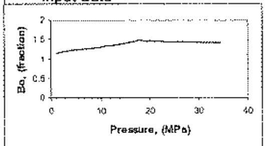
Time (sec)	Production (STB/D)	Injection (STB/D)
1 – 12400	93.5	88.8
12400 – 18218	97.5	92.6
18218 – 25648	154.7	147.0
25648 - 30466	248.0	235.6

Sw	Pc (Pa)
0.44	29819.95
0.45	29556.50
0.50	28512.86
0.55	27570.53
0.60	26709.27
0.65	26020.26
0.70	25544.03
0.72	25432.58

Validation of Results (continued)

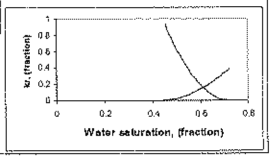
Perforation stability prediction model

Input Data



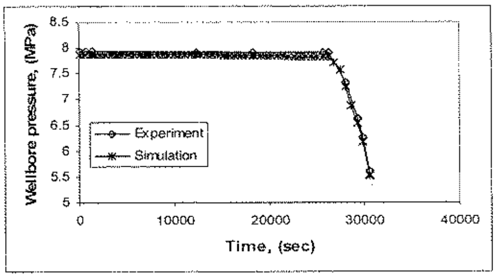
•Oil formation volume factor data

•Relative permeability data



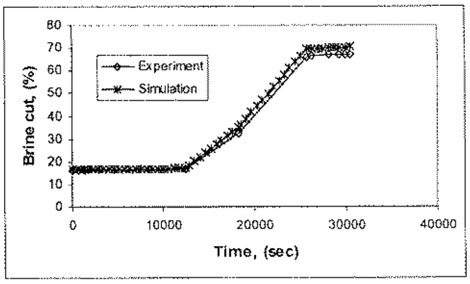
Validation of Results (continued)

Perforation stability prediction model



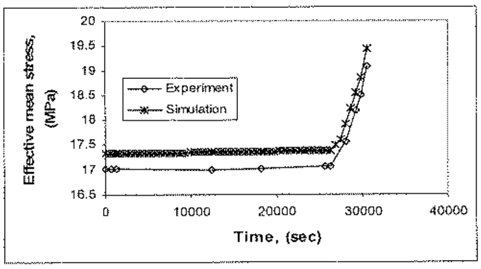
Validation of Results (continued)

Perforation stability prediction model



Validation of Results (continued)

Perforation stability prediction model



Validation of Results (continued)

Perforation stability prediction model

	Experiment	Mohr-Coulomb	Drucker-Prager
Wellbore pressure at failure	4.8714 MPa	5.5158 MPa	6.1778 MPa
Effective mean stress at failure	19.488 MPa	19.449 MPa	18.861 MPa

	Experiment	Simulation
Sand quantity	2251 g	1619 g

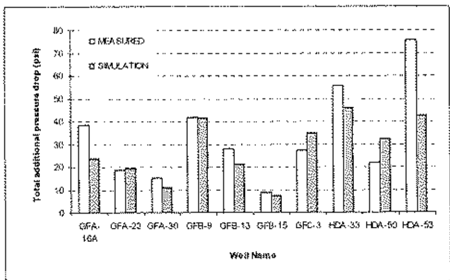
Validation of Results (continued)

3-D flow model

- The results were verified using actual well data (10 wells)
- Good match was achieved between predicted and actual well pressure drops (>70% match)
- Main findings
  - Major pressure drop (82-96%) along casing-cement tunnel
  - 4-18% pressure drop along perforation in formation rock
  - 0.005-1.12% pressure drop in annular gravel pack

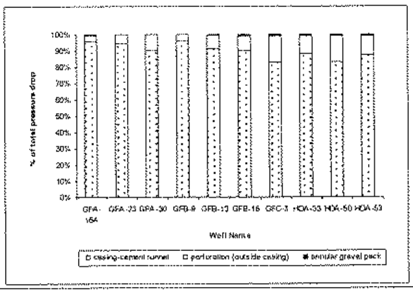
Validation of Results (continued)

3-D flow model



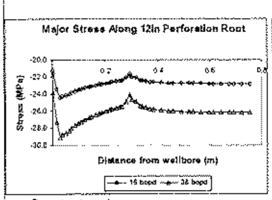
Validation of Results (continued)

3-D flow model

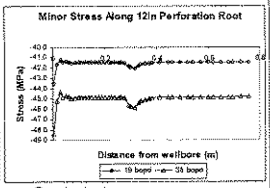


Case Study

- Effect of flow rate on stress distribution



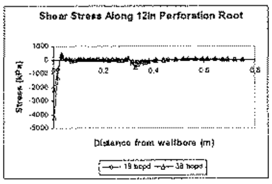
•Greatest major principle stress occur along perforation root



•Greatest minor principle stress occur at perforation entrance and perforation tip

CASE STUDY (CONTINUED)

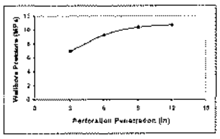
- Effect of flow rate on stress distribution



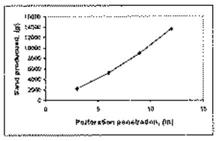
- Greatest shear stress occur at perforation entrance and perforation tip

CASE STUDY (CONTINUED)

- Effect of perforation penetration on perforation stability



- Increased in perforation length increase wellbore pressure at failure or reduce the stability



- Greater perforation penetration induced greater sand produced

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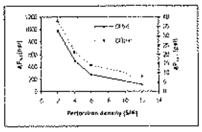
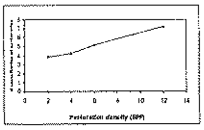
CASE STUDY (CONTINUED)

- Effect of shot density on pressure drop



- Pressure drop decreases with increasing shot density
- The improvement is more pronounced at lower pressure drops



- The contribution of perforations in the formation rock rises with more number of perforations

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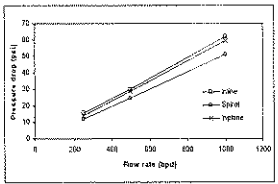
CASE STUDY (CONTINUED)

- Effect of perforating pattern on pressure drop



- The spiral gives the lowest pressure drop, followed by inplane, and inline pattern

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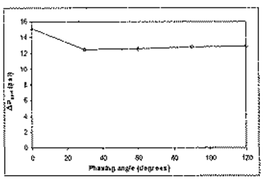
CASE STUDY (CONTINUED)

- Effect of phasing angle on pressure drop



- lowest pressure drop achieved at 30° phasing
- 0° phasing (inline) results in greatest pressure drop
- Phasing angle between 30 and 120° generally give lower pressure drop

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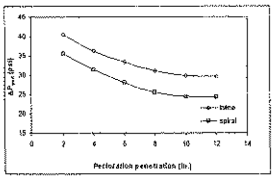
CASE STUDY (CONTINUED)

- Effect of perforation penetration on pressure drop



- Greater perforation lengths result in less pressure drop and better productivity

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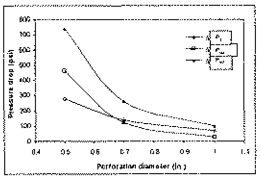
CASE STUDY (CONTINUED)

Effect of perforation diameter on pressure drop

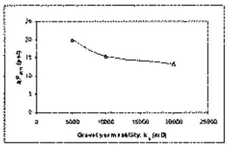


•Significant increase of high-velocity pressure drop with smaller perforation diameter

•The effect of perforation diameter is greater than that of perforation length

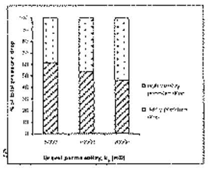
CASE STUDY (CONTINUED)

Effect of gravel permeability on pressure drop



•Significant increase of high-velocity pressure drop with smaller perforation diameter

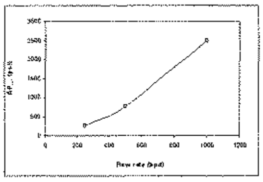
•The effect of perforation diameter is greater than that of perforation length



•High-velocity pressure becoming more dominant at higher gravel permeabilities

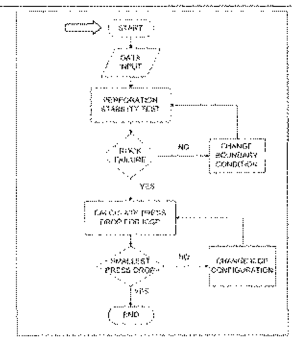
CASE STUDY (CONTINUED)

Effect of flow rate on pressure drop



•Exponential increase of pressure drop with flow rate

Work Flow for INTEGRATED SIMULATION MODEL



CONCLUSIONS

- A good match was obtained between simulated and experiment result by the perforation stability prediction model
- The greatest major principle stress always occur along perforation tunnel
- The greatest minor principle stress and shear stress are located at perforation entrance and perforation tip
- High stress concentration around perforation only extend to 4 in from perforation tip regardless the flow rate value
- Compromise have to make in selection of perforation length to obtain the highest productivity and the stable perforation
- Monitoring of flow rate is required to prevent excessive pressure drop.

CONCLUSIONS (CONTINUED)

- 3-D flow model shows the good match between predicted and actual pressure drops for the wells investigated
- Major pressure drop occur in the casing-cement tunnel (82-96%), with the rest caused by the effect of perforations outside casing (4-18%) and the annular gravel pack (0.005-1.12%)
- The following parameters are ranked in order of importance: (i) flow rate (ii) shot density (iii) perforation diameter (iv) gravel permeability (v) perforation length (vi) phasing angle (vii) perforation pattern
- Due to difficulties in controlling flow rate, perforation length and diameter, good selection of shot density and pattern with suitable phasing angle are important
- Gravel permeability can be maximized through good gravel-packing practices and is crucial to better well productivity.

THANK YOU

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