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Bibliografia referenciada

ARTOLA F.A.V. e ALVARADO D. **Sensitivity Analysis of Gassmann's Fluid Substituition Equations: Some Implications in Feasibility Studies of Time-lapse Seismic Reservoir Monitoring**. Journal of Applied Geophyscis. 59, 47-62. 2006

BATZLE M. e WANG Z. **Seismic Properties of Pore Fluids**. Geophysics, v. 57, n. 11, p. 1396 - 1408. 1992

BYRNE P.M. e JANZEN W. **A Computer Program for Nonlinear Analysis of Stress and Deformation in Oil Sand Masses**. Soil mechanics series No. 80. Department of Civil Engineering. The University of British Columbia, Vancouver, British Columbia, 1984

BUTLER R.M. **Some Recent Developments in SAGD**. JCPT, v 40, n 1. Jan. 2001

BUTLER R.M., MACNAB G.S., LO H.Y. **Theoretical Studies on the Gravity Drainage of Heavy Oil During *In-situ* Steam Heating**. Canadian Journal of Chemical Engineering. v. 59, n 4, p. 445-460. August. 1981

CARLSON M. **SAGD and Geomechanics**. JCPT v. 42, n. 6, Jun. 2003

CARVAJAL O.C. **Modelagem Sísmica em Arenitos, Efeito da Dispersão da Velocidade e do Tipo de Fluido**. Tese de doutorado. Departamento de Engenharia Civil - Pontifícia Universidade Católica de Rio de Janeiro PUC-Rio, Rio de Janeiro – Brasil, 2008.

CHALATURNYK R.J. e SCOTT D.J. **Geomechanical Response of Heavy Oil Reservoirs to the Steam Assisted Gravity Drainage Process**. SPE Paper 37569. 1997

CLAUDINO C. S., FIGUERÓ W.M., ALVARADO V., MARTINS B.H.M. **Modelagem Sísmica Time-lapse com Base em Simulação de Fluxo de Reservatórios.** Tenth International Congress of the Brazilian Geophysical Society. Nov. 2007

COLLINS P.M. **The False Lucre of Low-Pressure SAGD**. JCPT. Pre-print. 2004

COLLINS P.M., CARLSON M.R., WALTERS D.A., SETTARI A. **Geomechancal and Thermal Reservoir Simulation Demonstrates SAGD Enhancement Due to Shear Dilation.** SPE/ISMR Paper 78237. 2002

DUSSEAULT M. B. **Production Technologies for Development of Heavy Oil**. Aversion1. 2006

EASTWOOD J. **Temperature-Dependent Propagation of P- and S-waves in the Cold Lake Oil Sands: Comparison of Theory and Experiment.** v. 58, n. 6, p. 863-872. 1993

ERTEKIN T., ABOU-KASSEM J.H., KING G. R. **Basic Applied Reservoir Simulation.** SPE Textbook Series. 2001

FALCÃO F. **Efeitos Geomecânicos na Simulação de Reservatórios de Petróleo**. Dissertação de mestrado. Departamento de Engenharia Civil - Pontifícia Universidade Católica de Rio de Janeiro PUC-Rio, Rio de Janeiro – Brasil, 2002.

FIORILLO G. **Exploration and Evaluation of the Orinoco Belt**. PDVSA. 1983

FJAER E., HOLT R, M., HORSRUD P., RAAEN A. M., RISNES, R. **Petroleum Related Rock Mechanics.** Elsevier Science B. V. 2nd Edition, 2008

GASSMANN, F. **Über die Elastizität Poröser Medien. Vierteljahrs der Naturforsch. Ges.** v. 96. 1951.

GOODMAN R. **Introduction to Rock Mechanics.** Ed. J. Wiley. Nova Iorque. 412p., 1999

GUTIERREZ M. e LEWIS R.W. **The Role of Geomechanics in Reservoir Simulation**. SPE Paper 47392. 1996

FUNG L.S.-K., BUCHANAN L., WAN R.G. **Coupled Geomechanical-Thermal Simulation for Deformaing Heavy-Oil Reservoirs.** JCPT v. 33, n. 4, April 1994

HATCHELL P.J., KAWAR R.S., SAVITSKI A.A. **Integrating 4D Seismic, Geomechanics and Reservoir Simulation in the Valhall Oil Field.** EAGE 67th Conference & Exhibition — Madrid, Spain, 13 - 16 June 2005

IBAÑEZ J.P. **Modelagem Constitutive para Solos com Ênfase em Solos Não Saturados**. Dissertação de mestrado. Departamento de Engenharia Civil -

Pontifícia Universidade Católica de Rio de Janeiro PUC-Rio, Rio de Janeiro – Brasil, 2003.

ITO Y. **Discussion of “When Is It Important to Consider Geomechanics in SAGD Operations?** JCPT. Discussion Paper. 2004

ITO Y. e SUZUKI S. **Numerical Simulation of the SAGD Process in the Hangistone Oil Sands Reservoir.** JCPT. v.38, n. 9, September 1996

KUMAR D. **A Tutorial on Gassmann Fluid Substitution: Formulation, Algorithm and Matlab Code**. Geohorizons. v. 11, n. 1, January 2006

LUMLEY D., BEHRENS R., WANG Z**. Assesing the Technical Risk of 4-D Seismic Project**. The Leading Edge. N. 63. 1287-1291. 1997

LI P. e CHALATURNYK R.J. **Discussion on SAGD and Geomechanics**. JCPT. v. 42. n.9. September 2003

LI P. e CHALATURNYK R.J. **History Match of the UTF Phase . A Project with Coupled Reservoir Geomechanical Simulation.** JCPT. v. 48. n.1. January 2009

LI P. e CHALATURNYK R.J. **Permeability Variations Associated with Shearing and Isotropic Unloading During SAGD Process.** JCPT. n. 45 n. 1, January 2006

LI P. e CHALATURNYK R.J. **When Is It Important to Consider Geomechanics in SAGD Operations?**. JCPT. v. 43, n. 4. April 2004

LI P., CHAN M., FROEHLICH W. **Steam Injection Pressure and the SAGD Ramp-up Process**. JCPT. v. 48, n. 1. January 2009

LI P., CHALATURNYK R.J., TAN T.B. **Coupled Reservoir Geomechanical Simulations for the SAGD Process.** JCPT v.45, n. 1, January 2006

MAVKO G., MUKERJI T., DVORKIN J. **The Rock Physics Handbook**. Tool for seismic analysis in porous media. Cambridge University Press. Cambridge University Press. Nova Iorque. 1998.

MENDOZA H.A., FINOL J.J., BUTLER R.M. **SAGD, Pilot Test in Venezuela.** SPE Paper 53687. 1999

MINKOFF S.E., STONE C.M., BRYANT S., PESZYNSKA M. **Coupled Geomechanics and Flow Simulation for Time-lapse Seismic Modeling. Geophysics**, v 69, n. 1 p. 200–211, 1999

NACCACHE P.F. **A Fully-Implicit Thermal Reservoir Simulator.** SPE Paper 37985. 1997

RODRIGUES L.G., CUNHA L.B., CHALATURNIK R.J. **Incorporating Geomechanics into Petroleum Reservoir Simulation.** SPE Paper 107952. 2007

RØSTE T. **Monitoring Overburden and Reservoir Changes from Prestack Time-lapse Seismic Data – Application to Chalk Fields.** 167p. Ph. D Dissertation. Department of Petroleum engineering and Applied geophysics. Norwegian university of Science and Technology. 2007

SAMIER P. E de Gennaro S. **A Practical Iterative Scheme for Coupling Geomechanics with Reservoir Simulation**. SPE paper 107077. 2007

SASAKI K., AKIBAYASHI S., YAZAWA N., DOAN Q.T., FAROUQ A.S.M. **Experimental Modeling of the SAGD Process – Enhancing SAGD Performance with the Periodic Stimulation of the Horizontal Producer**. SPE Paper 69742 2001

SCHØTT C.R., BERTRAND-BIRAN V., HANSEN H.J., KOUTSABELOULIS N., WESTENG K. **Time-lapse Inversion Modeling of the South Arne Field.** First Break. v. 26, May 2008

SETTARI A. E MOURITS F.M. **A Coupled Reservoir Geomechanical Simulation System.** SPE Paper 50939. 1998

SCHLUMBERGER OILFIELD SERVICES**. TERRATEK Report.** Houston. United State. 2006

TEREZ I. **Horizontal Wells in Thermal Applications for Displacement and Gravity Drainage**. SPE Paper 78974 2002

THEUNE U., SCHMITT D.R., ROKOSH D. **Feasibility Study of Time-lapse Seismic Monitoring for Heavy Oil Reservoir Development – The Rock-Physical Basis**. SEG Annual Convention. Extended Abstract. 2003

TORTIKE, W.S. e FAROUQ ALI S.M. **Reservoir Simulation Integrated with Geomechanics.** JCPT. v. 32, n. 5, May 1993

TRAN D., NGHIEM L., BUCHANAN L. **An Overview of Iterative Coupling Between Geomechanical Deformation and Reservoir Flow.** SPE/PS-CIM/CHOA Paper 97879. 2005

TRAN D., SETTARI A., NGHIEM L. **New Iterative Coupling Between a Reservoir Simulator and Geomechanics Module.** SPE paper 88989. 2004

VÁSQUEZ H. A.R, SÁNCHEZ M.S., CONSULTORES VVA., MCLENNAN J., GUO Q., PORTILLO F., POQUIOMA W., MENDOZA H. **Mechanical and Thermal Properties of Unconsolidated Sands and Its Applications to the Heavy oil SAGD Project in the Tia Juana Field, Venezuela.** SPE Paper 54009, 1999

VAZIRI H. **Non-linear Temperature and Consolidation Analysis of Gassy soils**. Ph.D. Dissertation. Department of Civil Engineering. The University of British Columbia, Vancouver, British Columbia, 1986

VASQUEZ G.F. e DILLON, L.D. **Módulos Adiabáticos e Isotérmicos de Óleos Brutos. 3° Congresso Internacional da Sociedade Brasileira de Geofísca**. Rio de Janeiro, 1993

VIDAL S., LONGUEMARE P., HUGUET F., MECHLER P. **Reservoir Parameters Quantification from Seismic Monitoring Integrating Geomechanics.** Geophysics, v. 69, n. 1, p. 200–211, 2002

VINSOME P.K.W. e WESTERVELD J. **A Simple Method for Predicting Cap and Base Rock Losses in Thermal Reservoir Simulators**. JCPT, July-September 1980, 87-90

WAN R.G., CHAN D.H., KOSAR K.M. **A Constitutive Model for the Effective Stress-Strain Behaviour of Oil Sands.** JCPT. v. 30, n.4 1991

WANG Z. **Wave Velocities in Hydrocarbons and Hydrocarbon Saturated Rocks – With Applications to EOR Monitoring.** Ph.D. Dissertation. Department of Geophysics. Stanford University 1998

WANG Z. e NUR AMOS. **Effect of Temperature on Wave Velocities in Sands and Sandstone with heavy hydrocarbons.** Rock physics Project, Stanford University. 1986

ZHANG W., YOUN S., DOAN Q. **Understanding Reservoir Architectures and Steam-Chamber Growth at Christina Lake, by Using 4D Seismic and Crosswell Seismic Imaging.** SPE Paper 97808. 2007.

Apêndice A
Arquivo de entrada para o cálculo da substituição de fluidos

Adaptado do código desenvolvido por Kummar (2006)

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Dados de entrada:
% rho_o = densidade do óleo (API)
% rho_g = densidade específica do gás (API)
% T = Temperatura (oC)
% P = Pressão (psi)
% phi = porosidade (fração)
% VSH = volume de folhelho (fração)
% isw = SWT: saturação inicial de água (fração)
% tsw = saturação final de água
% vp = velocidade de onda P apartir de perfil (ft/s)
% vs = velocidade de onda S apartir de perfil (ft/s)
% rho = densidade total apartir de perfil (gm/cc)
% Dados de saída:
% vp_sat = velocidade de onda P depois da substituição de fluidos(ft/s)
% vs_sat = velocidade de onda S depois da substituição de fluidos(ft/s)
% rho_sat = densidade depois da substituição de fluidos (gm/cc)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
API_o = 10;
rhoi_g = 1.2;
Ti = xlsread('tempi_3D.xls');
Ti = (5/9)*(Ti-32);
Pi = xlsread('pressi_3D.xls');
T = xlsread('CASE1_DIR1_42_STEP108_T.xls');
T = (5/9)*(T-32);
P = xlsread('CASE1_DIR1_42_STEP108_P.xls');
S = 0.0
phi = 0.32;
vsh = 0.03632;
isg = 0.088;
isw = 0.164;
tsw = xlsread('CASE1_DIR1_42_STEP108_Sw.xls');
tsg = xlsread('CASE1_DIR1_42_STEP108_Sg.xls');
ifluid = 1;
fluid = 2;
vp = 8397.0;
vs = 3759.0;
rho = 2.065 ;
%
% Parâmetros fixos (e.g., Mavko et al., 1998)
%
```

```
k_clay = 20.9;
k_qtz = 36.6;
rho_clay = 2.58;
rho_qtz = 2.65;
%
% Conversões
%
div_mill = 1/1000000;
fs2kms = 0.000305;
kms2fs = 3280.84;
v_clay = vsh*0.70;
v_qtz= 1-v_clay;
ish = 1-isw-isg;
tsh = 1-tsw-tsg;
rhoi_o = 141.5/(API_o+131.5);

Pi = Pi*6.894757*0.001;
P = P*6.894757*0.001;
S = S*div_mill;
vp = vp*fs2kms;
vs = vs*fs2kms;
%
GORi = 2.03*rhoi_g*(0.006894757*Pi.*exp(0.02878*API_o-0.00377*Ti)).^1.205;
GOR = 2.03*rhoi_g*(0.006894757*P.*exp(0.02878*API_o-0.00377*T)).^1.205;
%
% Passo 1: Propriedades da matriz
%
k_voigt = v_clay*k_clay + v_qtz*k_qtz;
k_reuss = 1/(v_clay/k_clay + v_qtz/k_qtz);
k_matrix = 0.5*(k_voigt + k_reuss);
rho_matrix = v_clay*rho_clay+v_qtz*rho_qtz;
%
% Passo 2: Propriedades da salmoura
%
w(1,1) = 1402.85; w(1,3) = 3.437*10^(-3);
w(2,1) = 4.871; w(2,3) = 1.739*10^(-4);
w(3,1) = -0.04783; w(3,3) = -2.135*10^(-6);
w(4,1) = 1.487*10^(-4); w(4,3) = -1.455*10^(-8);
w(5,1) = -2.197*10^(-7); w(5,3) = 5.230*10^(-11);
w(1,2) = 1.524; w(1,4) = -1.197*10^(-5);
w(2,2) = -0.0111; w(2,4) = -1.628*10^(-6);
w(3,2) = 2.747*10^(-4); w(3,4) = 1.237*10^(-8);
w(4,2) = -6.503*10^(-7); w(4,4) = 1.327*10^(-10);
w(5,2) = 7.987*10^(-10); w(5,4) = -4.614*10^(-13);
sumi = 0;
for i=1:5
   for j=1:4
      sumi = sumi+w(i,j).*Ti.^(i-1).*Pi.^(j-1);
   end
end
vi_water = sumi;

sum = 0;
for i=1:5
   for j=1:4
```

```
        sum = sum+w(i,j).*T.^(i-1).*P.^(j-1);
    end
end
v_water = sum;

v1i = 1170-9.6*Ti+0.055*Ti.*Ti-8.5*10^(-5)*Ti.*Ti.*Ti+2.6*Pi-0.0029*Ti....
    *Pi-0.0476*Pi.*Pi;
vi_brine = vi_water+S*v1i+S^1.5*(780-10*Pi+0.16*Pi.*Pi)-1820*S*S;
r1i = 489*Pi-2*Ti.*Pi+0.016*Ti.*Ti.*Pi-1.3*10^(-5)*Ti.*Ti.*Ti....
    *Pi-0.333*Pi.*Pi-0.002*Ti.*Pi.*Pi;
rhoi_water=1+10^(-6)*(-80*Ti-3.3*Ti.*Ti+0.00175*Ti.*Ti.*Ti+r1i);
r2i = 300*Pi-2400*Pi.*S+Ti.*(80+3*Ti-3300*S-13*Pi+47*Pi.*S);
rhoi_brine = rhoi_water+0.668*S+0.44*S*S+10^(-6)*S*r2i;
ki_brine = rhoi_brine.*vi_brine.*vi_brine*div_mill;
%
% Passo 3: Propriedades iniciais do hidrocarboneto
%
if ifluid == 1
    B0i = 0.972+0.00038*(2.495*GORi*sqrt(rhoi_g/rhoi_o)+Ti+17.8).^1.175;
    rhoi_ps = rhoi_o./((1+0.001*GORi).*B0i);
    rhoi_s = (rhoi_o+0.0012*GORi*rhoi_g)./B0i;
    r1i = rhoi_s+(0.00277*Pi-1.71*0.0000001*Pi.*Pi.*Pi)....
        *(rhoi_s-1.15).^2+3.49*0.0001*Pi;
    rhoi_hyc = r1i./(0.972+3.81*0.0001*(Ti+17.78).^1.175);
    vi = 2096*sqrt(rhoi_ps./(2.6-rhoi_ps))-3.7*Ti+4.64*Pi+0.0115*...
        (sqrt(18.33./rhoi_ps-16.97)-1).*Ti.*Pi;
    ki_hyc = rhoi_hyc.*vi.*vi*div_mill;
    R = 8.314;
    Tai = Ti+273.15;
    Ppri = Pi./(4.892-0.4048*rhoi_g);
    Tpri = Tai./(94.72+170.75*rhoi_g);
    E1i = exp(-Ppri.^1.2./Tpri.*(0.45+8*(0.56-1./Tpri).^2));
    Ei = 0.109*(3.85-Tpri).^2.*E1i;
    Z1i = 0.03+0.00527*(3.5-Tpri).^3;
    Zi = Z1i.*Ppri+0.642*Tpri-0.007*Tpri.^4-0.52+Ei;
    rho_hyc_g_i = 28.8*rhoi_g*P./(Zi*R.*Tai);
    dz_dp_i=Z1i+0.109.*(3.85-Tpri).^2.*E1i.*(-1.2*Ppri.^0.2./Tpri.*...
        (0.45+8*(0.56-1./Tpri).^2));
    yoi = 0.85+5.6./(Ppri+2)+27.1./(Ppri+3.5).^2-8.7*exp(-0.65*(Ppri+1));
    k_hyg_i = Pi.*yoi./1000*1.0./(1-Ppri./Zi.*dz_dp_i);
end
%
% Passo 4: Propriedades do fluido
%
ki_fl = 1./(isw./ki_brine+ish./ki_hyc+isg./k_hyg_i);
rhoi_fl = isw.*rhoi_brine+ish.*rhoi_hyc+isg.*rho_hyc_g_i;
%
% Passo 5: Módulo original in-situ (rocha saturada in-situ)
%
dens_poros = 0;
if dens_poros == 1
    rho = phi*rhoi_fl + (1-phi)*rho_matrix;
end
k_sat = rho*(vp*vp-vs*vs*4/3);
g = rho*vs*vs;
```

```
%
% Passo 6: Propriedades do arcabouço
%
k1 = k_sat*(phi*k_matrix./ki_fl+1-phi)-k_matrix;
k2 = phi*k_matrix./ki_fl+k_sat/k_matrix-1-phi;
k_frame = k1./k2;
%
% Passo 7: Seleção do tipo de fluido de saída
%
if fluid == 1

elseif fluid == 2

   B0 = 0.972+0.00038*(2.495*GOR*sqrt(rhoi_g/rhoi_o)+T+17.8).^1.175;
   rho_ps = rhoi_o./((1+0.001*GOR).*B0);
   rho_s = (rhoi_o+0.0012*GOR*rhoi_g)./B0;
   r1 = rho_s+(0.00277*P-1.71*0.0000001*P.*P.*P).*(rho_s-1.15).^2+...
      3.49*0.0001*P;
   rho_hyc = r1./(0.972+3.81*0.0001*(T+17.78).^1.175);
   v = 2096*sqrt(rho_ps./(2.6-rho_ps))-3.7*T+4.64*P+0.0115*...
      (sqrt(18.33./rho_ps-16.97)-1).*T.*P;
   k_hyc = rho_hyc.*v.*v*div_mill;
   R = 8.314;
   Ta = T+273.15;
   Ppr = P./(4.892-0.4048*rhoi_g);
   Tpr = Ta./(94.72+170.75*rhoi_g);
   E1 = exp(-Ppr.^1.2./Tpr.*(0.45+8*(0.56-1./Tpr).^2));
   E = 0.109*(3.85-Tpr).^2.*E1;
   Z1 = 0.03+0.00527*(3.5-Tpr).^3;
   Z = Z1.*Ppr+0.642*Tpr-0.007*Tpr.^4-0.52+E;
   rho_hyc_g = 28.8*rhoi_g*P./(Z*R.*Ta);
   dz_dp=Z1+0.109.*(3.85-Tpr).^2.*E1.*(-1.2*Ppr.^0.2./Tpr.*(0.45+8*...
      (0.56-1./Tpr).^2));
   yo = 0.85+5.6./(Ppr+2)+27.1./(Ppr+3.5).^2-8.7*exp(-0.65*(Ppr+1));
   % Salmoura
   v11 = 1170-9.6*T+0.055*T.*T-8.5*10^(-5)*T.*T.*T+2.6*P-0.0029*T.*...
      P-0.0476*P.*P;
   v1_brine = v_water+S*v11+S^1.5*(780-10*P+0.16*P.*P)-1820*S*S;
   r11 = 489*P-2*T.*P+0.016*T.*T.*P-1.3*10^(-5)*T.*T.*T.*P-0.333*P.*...
      P-0.002*T.*P.*P;
   rho1_water=1+10^(-6)*(-80*T-3.3*T.*T+0.00175*T.*T.*T+r11);
   r21 = 300*P-2400*P.*S+T.*(80+3*T-3300*S-13*P+47*P.*S);
   rho1_brine = rho1_water+0.668*S+0.44*S*S+10^(-6)*S*r21;
   k_brine = rho1_brine.*v1_brine.*v1_brine*div_mill;

   k_hyg = P.*yo./1000*1.0./(1-Ppr./Z.*dz_dp);
end
%
% Passo 8: Propriedades do fluido (saturação final) e densidade
% da rocha saturada
%
k_fl = 1./(tsw./k_brine + tsh./k_hyc + tsg./k_hyg);
rho_fl = tsw.*rho1_brine + tsh.*rho_hyc + tsg.*rho_hyc_g;
rho_sat = phi*rho_fl+(1-phi)*rho_matrix;
%
```

```
% Passo 9: Módulo total da rocha saturada
%
k1 = phi./k_fl+(1-phi)/k_matrix-k_frame/(k_matrix*k_matrix);
k_sat_new = k_frame + ((1-k_frame./k_matrix).^2)./k1;
%
% Passo 10: Velocidade sísmica depois da substituição de fluidos
%
vp_sat = sqrt((k_sat_new+g*4/3)./rho_sat)*1000;
vs_sat = sqrt(g./rho_sat)*1000;
AI = vp_sat.*rho_sat;
```