CATO-2 Deliverable WP3.07-D07

Software development as part of WP3.07 (Permanent Geophysical Monitoring)

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1 Executive Summary (restricted)

As part of the PhD work done in this work package, software has been developed to address issues related to 3D geophysical monitoring of CO_2 storage. The focus has been on the seismic and the EM technique.

One PhD focusses on seismic wave propagation effects in partly saturated media, and software has been developed that simulates seismic responses for such media. As part of the CATO2 work, this PhD has developed a new effective model which turned out to give good results for weak-frame and/or highly permeable rocks where conventional effective models fail. The software developed determines responses using this new effective model, next to exact solutions and other effective models. The responses simulate fluid-pressure and stress measurements.

The other PhD focusses on the integration of seismic and EM techniques. As part of this, both a seismic and an EM code has been developed that uses the same approach to calculate the their responses. The responses are for 3D media heterogeneous in the vertical direction only and the responses are for stress and particle velocities. A fast and robust analytically based seismic forward modelling code is introduced that uses a more stable reflection formalism than used in the past. So, these codes are very suitable for an integrated inversion approach.

The software is available for CATO2 members on request:
for the poroelastic modelling: a.kudarova@tudelft.nl ;
for the EM and seismic modelling: a.m.schaller@tudelft.nl.
General requests: g.g.drijkoningen@tudelft.nl .

Distribution List

(this section shows the initial distribution list)

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Document Change Record

(this section shows the historical versions, with a short description of the updates)

Version	Nr of pages	Short description of change	Pages
See header	1 - xx	First version	

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2 Applicable/Reference documents and Abbreviations

2.1 Applicable Documents

(Applicable Documents, including their version, are the “legal” basis to the work performed)

	Title	**Doc nr**	**Version**
AD-01d	Toezegging CATO-2b	FES10036GXDU	2010.08.05
AD-01f	Besluit wijziging project CATO2b	FES1003AQ1FU	2010.09.21
AD-02a	Consortium Agreement	CATO-2-CA	2009.09.07
AD-02b	CATO-2 Consortium Agreement	CATO-2-CA	2010.09.09
AD-03i	Program Plan 2014b	CATO2-WP0.A-D03	2014.10.16

2.2 Reference Documents

(Reference Documents are referred to in the document)

	Title	**Doc nr**	**Version**
RD-01			

2.3 Abbreviations

(this refers to abbreviations used in this document)

EM	Electro-Magnetic

3 Background and software

As part of the CATO2 PhD work of Ms. Kudarova, an effective poroelastic model is proposed that describes seismic attenuation and dispersion in periodically layered media. In this model, the layers represent mesoscopic-scale heterogeneities (larger than the grain and pore sizes but smaller than the wavelength) that can occur both in fluid and solid properties. The proposed effective medium is poroelastic, contrary to previously introduced models that lead to effective viscoelastic media (see, e.g., Vogelaar *et al.* 2007). The novelty lies in the application of the pressure continuity boundary conditions instead of no-flow conditions at the outer edges of the elementary cell. The approach results in effective Biot elastic moduli and effective porosity that can be used to obtain responses of heterogeneous media in a computationally fast manner (Kudarova *et al.* 2013a). The model is validated by the exact solution obtained with the use of Floquet's theory (Floquet 1883). Predictions of the new effective poroelastic model are more accurate than the predictions of the corresponding effective viscoelastic model when the Biot critical frequency is of the same order as the frequency of excitation, and for materials with weak frame. This is the case for media such as weak sandstones, weakly consolidated and unconsolidated sandy sediments. The reason for the improved accuracy for materials with low Biot critical frequency is the inclusion of the Biot global flow mechanism which is not accounted for in the effective viscoelastic media. At frequencies significantly below the Biot critical frequency and for well-consolidated porous rocks, the predictions of the new model are in agreement with previous solutions.

As part of this new effective model, software has been developed that calculates fluid-pressure and particle-velocity responses:

- Exact ones using Biot equations for poro-elastic media (Floquet 1883)
- Conventional effective models based on Vogelaar *et al.* (2007)
- New effective model as described in Kudarova *et al.* (2013a).

The program is written in Fortran 90 and is called `poroelastic_layered_exacteff.f90`. It makes use of the IMSL (International Mathematics and Statistics Library) numerical library. A periodically layered half-space is considered, and the input data used in the program is: physical properties of the constituent layers, configuration (thicknesses of the layers), properties of the source function (Ricker wavelet) located at the top pf the half-space and location of the receiver. The output of the program is: frequency-domain and time-domain responses at a given location of the receiver and dispersion characteristics (phase velocity and attenuation). All the output is calculated for the exact solution and two models, as described above.

As part of the PhD work of Ms. Kudarova, an effective model is derived for periodically layered poroelastic media, where layers represent mesoscopic-scale heterogeneities that are larger than the pore and grain sizes but smaller than the wavelength (Kudarova *et al.* 2013b). Each layer is homogeneous, described by Biot's equations of poroelasticity. The proposed model has only real-valued frequency-independent effective coefficients determined analytically exclusively by the physical parameters of the layers. It serves as an alternative to the existing models with frequency-dependent effective elastic properties (see, e.g., Vogelaar *et al.* 2007). Homogenization is based on asymptotic expansions with multiple spatial scales and results in equations of motion containing higher-order derivatives. It is valid for wavelengths much larger than the period of the system. This approach, being widely used in elasticity, is extended to poroelasticity in this work. The exact analytical solution, obtained by the application of Floquet's theory (Floquet 1883) to poroelastic composites, is used to validate the model.

As part of this new frequency-independent effective model, software has been developed that calculates phase velocity and attenuation for the:

- Exact ones using Biot's equations for poro-elastic media (Floquet 1883)
- New effective model as described in Kudarova *et al.* (2013b).

The program is written in Fortran 90 and is called `poroelastic_layered_asymptotic.f90`. It makes use of the IMSL numerical library. The input data in the program is: physical properties of the constituent layers and configuration (thicknesses of the layers). The output of the program contains dispersion characteristics (phase velocity and attenuation) of the effective model and the exact solution.

Finally as part of the PhD work of Ms. Kudarova, a method is proposed to obtain effective parameters used in Biot's theory in order to capture attenuation effects in initially heterogeneous medium, based on wave propagation in porous media with spherical inclusions which represent mesoscopic-scale heterogeneities (Kudarova *et al.* 2014). These effective parameters characterize an equivalent homogeneous porous medium. We compare the obtained results with the model of White (1975) and its extension by Dutta and Ode (1979), elaborated further by Vogelaar *et al.* 2010. We show that our model has a wider applicability than White's model and its extensions: next to the mesoscopic-scale attenuation mechanism, it also takes into account the global flow attenuation mechanism. The model can be used as a benchmark for more complicated problems in 3D, and for predictions of seismic attenuation in porous media with inclusions.

As part of this new effective model with spherical inclusions, software has been developed that calculates phase velocity and attenuation for the:

- Exact ones using Biot's equations for poro-elastic media (Floquet 1883)
- Conventional effective model from White (1975)
- New effective model as described in Kudarova *et al.* (2014).

The program is written in Fortran 90 and is called `poroelastic_spher_eff.f90`. It makes use of the IMSL numerical library. The input data in the program is: physical properties of the constituent layers and geometry (thicknesses of the layers). The output of the program contains dispersion characteristics (phase velocity and attenuation) of the effective models (see above).

As part of the PhD work of Mr. Schaller, cooperation has taken place within the Applied Geophysics group to calculate the 3D EM responses for vertically heterogeneous models (Hunziker *et al.* 2014). This includes the possibility for anisotropic diffusive fields of the VTI type, i.e., Vertical Transverse Isotropy, which is nowadays included in the interpretation and inversion of EM fields. What is also included is the calculation of the gradients of the EM field with respect to the EM-related parameters of the medium, such as thickness of the layers, their EM properties electric permittivity and magnetic permeability, and saturation (e.g., CO_2).

The main program is written in C, and almost all the subroutines are written in Fortran90. The main program is called `emmod.c`. It makes use of the numerical library FFTlib. The input data in the program are: physical EM properties of the constituent layers, geometry and some general parameters like sampling time, etc. The output is the EM response (electric and magnetic fields) to that configuration.

Also as part of the PhD work of Mr. Schaller, code has been developed to model stress and particle-velocity measurements for integrated seismic and EM. For this integration, a seismic equivalent of the EM program has been made. Since the approach, definitions and conventions are the same, it is very easy to use seismic and EM in an integrated approach. For inversion, fast and robust forward modelling codes are necessary. During an inversion process an initial forward model is generally updated during each iteration resulting in a large number of forward calculations that have to be carried out. Therefore computation time can be very important. The widely used existing codes, such as the code introduced by Kennett (1983), have stability problems due to a reflection formalism based on propagation matrices. Previous extensive tests (within the university) have highlighted this. We introduce a fast and robust analytically based seismic forward modelling code that uses a more stable reflection formalism. The modelling code can deal with all kinds of 1D horizontally layered media and models elastic wave propagation. The seismic responses are with respect to the (seismic) parameters of the medium, such as thickness of the layers, their seismic properties as seismic P- and S-wave velocities and mass density, and saturation.

The main program is written in C, and most of the subroutines are written in Fortran90. The main program is called `elmod.c`. Also, this program makes use of FFTlib. The input and output data is similar to the one for emmod, but then its elasto-dynamical equivalent: physical elasto-dynamic properties of the constituent layers, geometry and some general parameters like sampling time, etc. The output are the seismic responses (stresses and particle-velocity fields) to that configuration.

4 Articles on which software is based

Wave propagation in periodically layered porous media (normal to the layering):

The software for the exact solution using Biot equations for poro-elastic media is based on the article:

Floquet, G., 1883. Sur les équations différentielles linéaires à coefficients périodiques. *Ann. Sci. Ec. Normale Super.,* vol. **2,** 47–88.

The software for the conventional visco-elastic effective model is based on the article:

Vogelaar, B. & Smeulders, D., 2007. Extension of White's layered model to the full frequency range, *Geophys. Prospect.,* vol. **55,** 685–695.

The software for the new effective poro-elastic is based on the article:

Kudarova, A.M., K.N. van Dalen and G.G. Drijkoningen, 2013a. Effective poroelastic model for one-dimensional wave propagation in periodically layered media, *Geophysical Journal International*, vol. **195**, pp.1337-1350. http://dx.doi.org/10.1093/gji/ggt315

The software for the gradient model for poro-elastic media is based on the article:

Kudarova, A.M., K.N. van Dalen and G.G. Drijkoningen, 2013b. Higher-order homogenization for one-dimensional wave propagation in poroelastic composites, *Proceedings of the 5th Biot Conference on Poromechanics*, p. 1766-1771. July 10-12, 2013, Vienna, Austria. http://dx.doi.org/10.1061/9780784412992.209. Publisher: Vienna University of Technology.

Effective models with spherical inclusions:

The software for conventional effective models with spherical inclusions is based on the article:

White, J. E., 1975, Computed seismic speeds and attenuation in rocks with partial gas saturation: *Geophysics*, Vol. **40**, 224–232.

Dutta, N. C., and H. Odé, 1979, Attenuation and dispersion of compressional waves in fluid filled porous rocks with partial gas saturation (White model) — Part I: Biot theory: *Geophysics*, Vol **44**, 1777–1788.

Vogelaar, B., Smeulders D, Harris, J., 2010. Exact expression for the effective acoustics of patchy-saturated rocks. *Geophysics*, Vol. **75**, N87–N96.

The software for the new poro-elastic effective model with spherical inclusions is based on the article:

Asiya Kudarova, A., , Dalen, K.v., and Guy Drijkoningen, G.G., 2014. Seismic wave propagation in porous media with spherical inclusions: extension of White's model, *SEG Technical Program Abstracts 2014*, 84th Conference of the Society of Exploration Geophysicists (SEG), 26 – 31 October 2014, Denver, Colorado, 4637-4642. (http://dx.doi.org/10.1190/segam2014-1243.1)

Forward modelling seismic and EM responses, using the same approach and using gradients (for inversion)

The software for 3D EM wave propagation in layered media is based on the article:

Hunziker, J., Thorbecke, J., and Slob, E., 2014, The electromagnetic response in a layered VTI medium: A new look at an old problem: accepted for *Geophysics* (software and algorithms section)

The software for 3D seismic wave propagation in layered media is used in the article:

Schaller, A., J. Hunziker, E.C. Slob and G.G. Drijkoningen, 2015. Joint 1D inversion of seismic and EM data, *Geophysics,* (to be submitted)