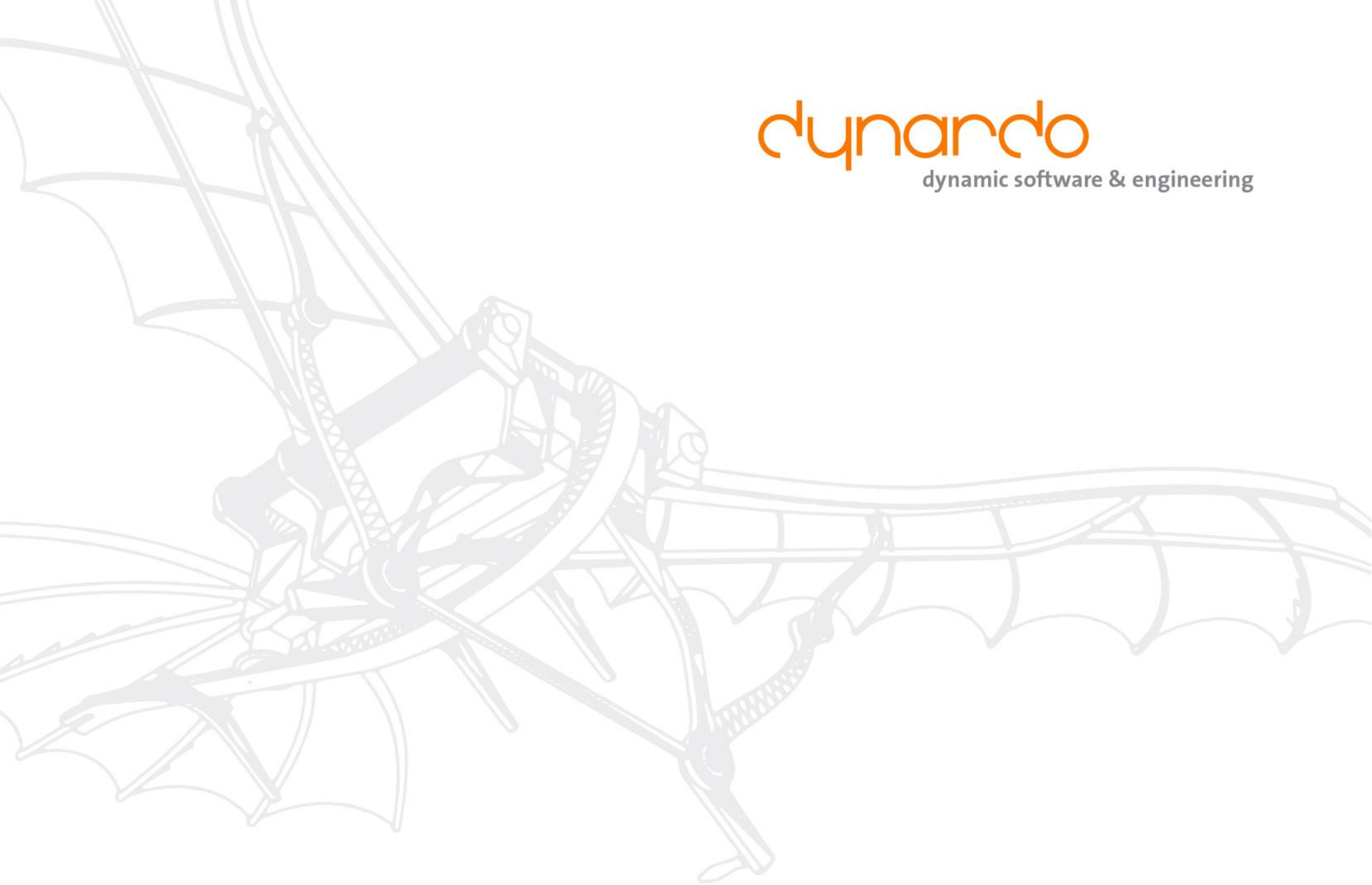

Lectures

optiRiss - Simulation based optimization and risc evaluation of enhanced geothermal systems

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Introduction

Enhanced geothermal systems (EGS) generate geothermal electricity without the need for natural convective hydrothermal resources. Until recently, geothermal power systems have exploited mainly resources where naturally occurring heat, water, and rock permeability is sufficiently high to allow energy extraction. However, by far most of geothermal energy within reach of conventional techniques is in more or less dry and very low permeable rock. In such locations EGS technologies enhance geothermal resources through 'hydraulic stimulation'.
EGS systems are currently being developed and tested in France, Australia, Japan, Germany, the U.S. and Switzerland. Some of the projects started as hot dry rock (HDR) project and converted to projects which “just” enhance conductivity of available fracture systems (Sueltz). Therefore we have to expect that target zones are not really dry and even a massive granite formation will be an in situ fractured rock mass. That leads to a real challenge of optimizing the stimulation procedure to the in situ conditions of the target rock reservoir zone.
Within the German joint research project optiRiss, a software environment was developed to generate a parametric reservoir model, calibrate the reservoir model to all available data and investigate potentials for EGS systems to a window of possible operational parameter of drilling and stimulation. In this paper, we will introduce the numerical model for the generation of the heat exchanger using hydraulic stimulation and for the production. Furthermore, we will discuss the parametrization, calibration and optimization of the reservoir model. Finally, the application of the model and the related workflows to a granite reservoir in Thuringia, Germany, is presented.

Numerical reservoir model

In the numerical model, the generation of the heat exchanger is considered as a three-dimensional coupled mechanical-hydraulic problem. A fluid is pumped into the reservoir. Because of the generally low initial rock permeability, the pore-pressure increases (hydraulic part). As a result, the stress field is changed and existing joints are reopened or new cracks are initiated (mechanical part). The development of these fractures increase the reservoir permeability and impacts the pore-pressure distribution. The coupled problem is solved by using three-dimensional finite element models. In order to simulate the complex fracture network in jointed rocks, i.e. the initiation, propagation and coalescence of multiple cracks and existing joint sets, a homogenized continuum approach is applied, cf. Wittke (1984). In this context, the cracks are not modelled in a discrete way, but represented in a homogenized sense by using a multi-surface plasticity model for jointed rock in the mechanical part and Darcy’s law in the hydraulic part. The analysis is performed with the finite element software ANSYS. The standard functionality of ANSYS is enhanced by a specific material model for jointed rock (multiPlas library), a generally anisotropic hydraulic element, coupling routines and a collection of APDL macros controlling the simulation flow.

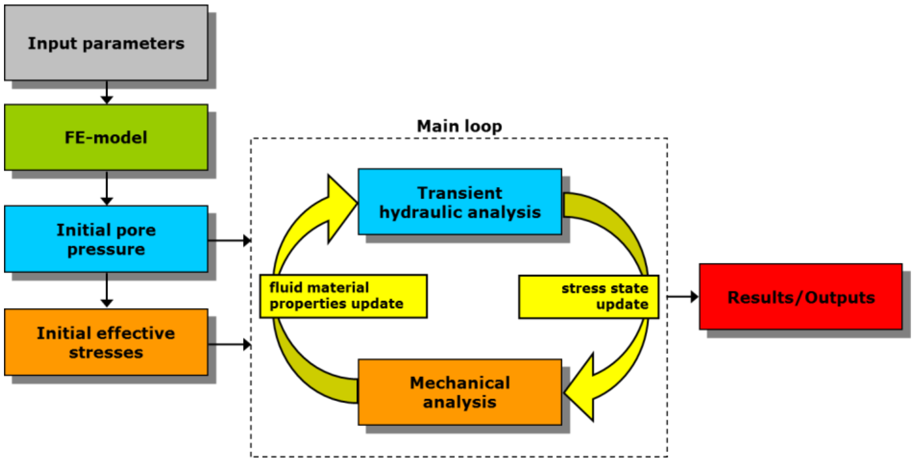


Figure 1*: flow chart of the coupled hydraulic-mechanical analysis.*

Figure 1 illustrates the general flow of the coupled hydraulic-mechanical analysis. Based on a set of input parameters, the finite element models for the mechanical and hydraulic part are generated and corresponding initial conditions are applied. It is to be noted, that most of the model parameters, including the material properties, the reservoir geometry, well/stage design and initial conditions are parameterized by using the ANSYS APDL language. In the main loop the coupled analysis is performed using an explicit approach. Consequently, the two sub-models are independently solved and successively updated after every time-step. In a first step, a transient analysis is performed on the hydraulic model. Based on the pore-pressure distribution, flow forces are calculated and applied in the mechanical sub-model. In the second step, a non-linear static analysis is performed on the mechanical model. The nonlinear behavior of jointed rock is described within the framework of multi-surface plasticity, Simo (1998). The material model combines isotropic yield surfaces for tensile (Rankine criterion) and shear (Mohr-Coulomb criterion) failure of intact rock and anisotropic yield surfaces for tensile (tension cut-off) and shear (Mohr-Coulomb criterion) failure of up to 4 joint sets (strength anisotropies, planes of weakness). Since the propagation of fractures result in an increase of rock permeability, the plastic strains are related to the homogenized hydraulic Darcy conductivity by the cubic law, Wittke (1984). Furthermore, the effect of stresses on the hydraulic joint conductivity is taken into account, using a relationship developed by Gangi (1978). It is to be noted that due to the anisotropic failure modes, a generally anisotropic conductivity tensor is obtained. Finally, the conductivity in the hydraulic sub-model is updated and the next time-step is performed.

Calibration, optimization and risk evaluation

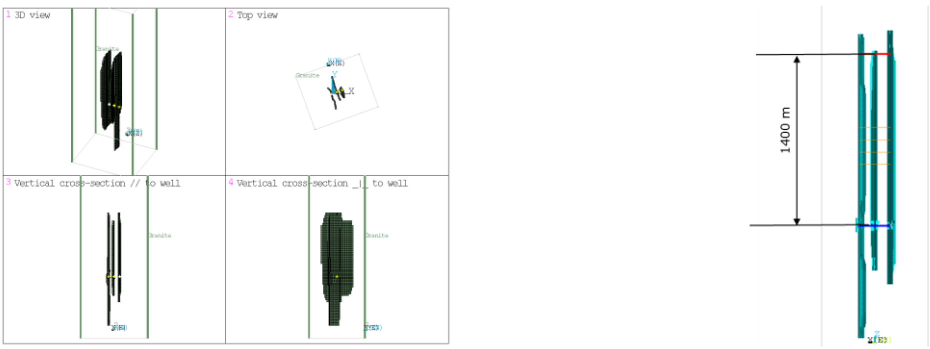
In the context of enhanced geothermal systems, the workflow outlined in the previous section is applied in the simulation of the hydraulic stimulation (generation of the heat exchanger) as well as the production. The reservoir model is generally described by a large amount of parameters. Although most of the parameters have a clear physical meaning, the direct measurement of the reservoir parameters is difficult or impossible. Therefore, a calibration of the model with respect to the best available measurements is necessary. In this context, measurements from diagnostic fracture injection tests (DFIT), the pressure history during hydraulic stimulation and micro-seismic events, representing the fracture extension, are taken into account.

After model calibration, a sensitivity study is performed with optiSLang. Both reservoir uncertainties and possible variation windows of operational conditions of drilling and stimulation, e.g. pumping rate, pumping volume and drilling direction are taken into account. Because of the parameterized model setup in the presented reservoir simulator, the calibrated model can be directly utilized in the sensitivity module of optiSLang. As a result of the sensitivity study, important parameters are identified for given response values. Furthermore, meta-models of optimal prognosis (MOP) describing the relationship between the important input parameters and the corresponding response values are developed and the forecast quality of the MOP, the so-called coefficient of prognosis (COP), is calculated. If the COP is sufficiently high, that is the generated meta-model has a good

forecast quality, the time-consuming finite element simulations can be replaced by fast evaluations of the MOP. As a result, the optimization of such a complex model becomes possible in acceptable time.
In this paper several response values are defined for the characterization of the EGS. The result of the fracture simulation (hydraulic stimulation) is the fracture network, which can be described in a simplified way by geometrical parameters such as fracture height, fracture length and fracture opening. Furthermore, the surface area of the generated heat exchanger and the pressure levels during hydraulic stimulation are considered as response values. Based on the fracture network the fluid flow during production is simulated and the necessary pressure to produce the fluid as well as the fluid losses is predicted. Additionally, a thermal analysis, taking into account the fracture network and the fluid velocities in the fracture during production, is performed. The heat flow model predicts the fluid temperature at the outlet (production well) and the cooling of the rock.
By combining the fracture simulation with the production simulation the geothermal electricity potentials can be estimated. Furthermore, by introducing cost functions the financial risks of EGS systems can be investigated and quantified. Finally, an optimization procedure is developed based on the sensitivity study. The objective is to optimize the economics of an EGS project by maximizing energy extraction and minimizing related costs and risks.

Example

The entire workflow presented above is applied to a German granite HDR reservoir in Thuringia. In a first step a multi-fracture system is generated using hydraulic stimulation. In order to reduce the simulation time only a representative part of the horizontal well is modeled. In the reference model, three perforations are placed at 4500 m depth within a homogeneous granite layer. The distance between the perforations is 100 m. The perforations are stimulated one after another. Each perforation is pumped with a constant rate of 5 m³ per minute for 1000 minutes.



generated fracture network

placement of the second well

***Figure 2**: Simulation of German granite HDR reservoir in Thuringia.*

Figure 2 shows the generated fracture network. Due to the so-called stress shadowing effect each fracture has a different extension and shape. In a second step the production is simulated. In this context, a second well, the injection well, is introduced in the model. The distance between the production (stimulation) well and the injection well is chosen such that a large heat exchanger surface area is obtained. In the reference model, the injection well connects all three fractures. As a result a maximum distance of 1400 m is possible. In order to guarantee a high joint conductivity between the wells, the distance is further reduced to 1200 m in the production stimulation. An injection rate of 100 litres per second is assumed for the entire system. Assuming that in total 15 fractures can be generated in the reference configuration, a rate of 20 litres per second is applied in the reduced model. This results in an average pressure increase of 5 MPa during production.
In a third step, a sensitivity study is performed for the combined stimulation and production simulation. The study considers uncertainties in the initial conditions (initial pore-pressure gradient, anisotropy of the initial stress field) and in the material parameters of granite (Young’s modulus and strength parameters) as well as operational conditions of stimulation (pumping rate, fluid volume, perforation distance, well orientation and inclination) and of production (total production rate and horizontal well length). Altogether 100 Designs are generated and evaluated using optiSLang.

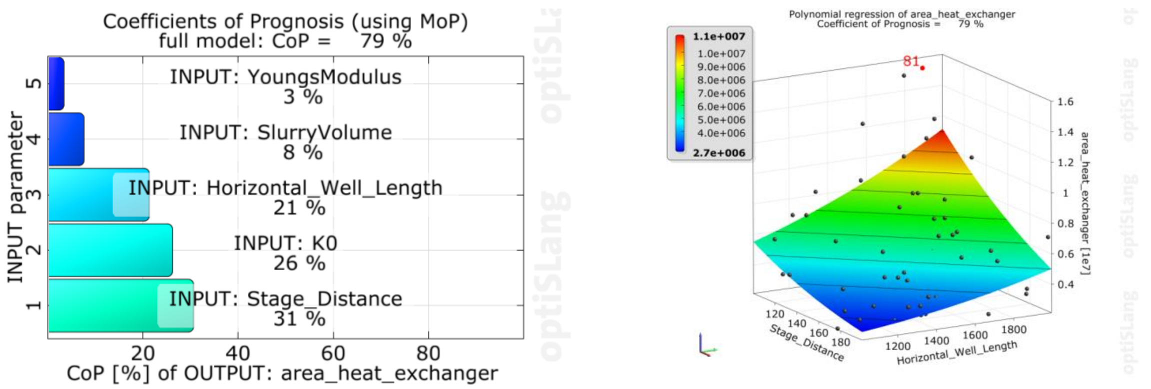


***Figure 3**: Sensitivity analysis - surface area of the heat exchanger.*

Figure 3 visualizes the evaluation of the heat exchanger surface area. Using the meta-model of optimal prognosis, 79% of the variation in this response value can be explained by variation of the input parameters. The heat exchanger area is influenced by the well design parameters, well length and perforation (stage) distance, as well as the anisotropy in the initial stress field (k0). Consequently, the prediction of the heat exchanger area can be improved by reducing the uncertainty in the initial stress field, e.g. more precise measurements. Furthermore, the heat exchanger area can be directly controlled by the well design.

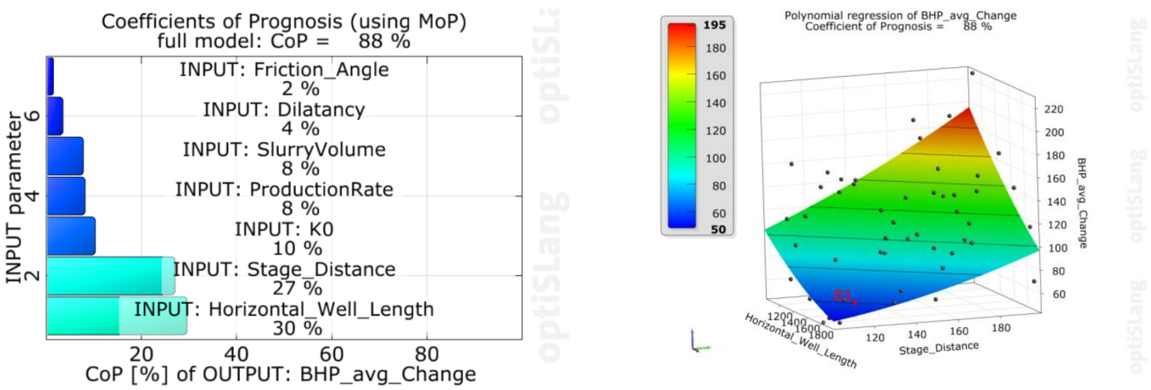


***Figure 4**: Sensitivity analysis – increase of pressure during production.*

Figure 4 illustrates the MOP for the pressure increase during production. Using MOP, 88% of the variation is explained by the input parameters. The pressure increase is mainly influenced by well design parameters.

Conclusion

The presented Dynardo framework for enhanced geothermal systems provides a numerical simulation toolkit for the generation of the heat exchanger using hydraulic stimulation as well as for the heat production. By considering reservoir uncertainties as well as operational parameters in a sensitivity study, the influence of the individual parameters is identified. As a result, the uncertainty of important reservoir uncertainties can be reduced with data acquisition in order to get a better prediction quality. Furthermore, the production can be directly improved by modifying identified important operational parameter. Based on the sensitivity study, meta-models are generated and the prognosis quality of these models is evaluated. The meta-models can be used to replace the time-consuming finite element simulations in the optimization process. By introducing cost-functions the economics of an EGS project can be optimized by maximizing energy extraction and minimizing related costs and risks.

Acknowledgement

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