Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

A Semi-Analytic Transient Approach to Modelling Plasticity and Stimulation of Geothermal Wells

Aditya SINGH[1], Brecht B.T. WASSING[2], Peter A. FOKKER[1,2]*

* ECN-TNO, Princetonlaan 6, Utrecht, The Netherlands

Peter.Fokker@tno.nl

Keywords: Enhanced geothermal systems, Coupled modeling, Stimulation

ABSTRACT

In the present work, we introduce a coupled hydro-mechanical semi-analytical model for geothermal boreholes. The solution is based on poro-elastoplastic behavior. The material behavior is defined by non-linear elasticity along with a strain-hardening and softening plasticity model. The model uses a time-dependent flow solution in which the permeability in the reservoir can be easily varied, both in space and time. The solution assumes a homogeneous, isotropic rock mass, with horizontal isotropic virgin in-situ stresses and a plane-strain condition. We introduce and validate a modification to the Pijnenburg et al. (2019) plasticity model, using the results of their triaxial tests. This model is then applied to the case of injection and shut-in and fall-off. Injection causes stabilization; shut-in destabilization. Further, we show that in the construction stage, the entire reservoir undergoes some inelastic deformation. This is very different from the results of an elastic-perfectly plastic or elastic-brittle-plastic model.

1. INTRODUCTION

Increasing exploration of geothermal energy has pushed the development of fast tools to improve the operational efficiency of current and future operations. The construction and operation of geothermal boreholes involves coupled chemo-thermo-hydro-mechanical processes. The structural integrity of the boreholes as well as induced seismicity are a few of the major challenges in this area (Békési et al. 2019). The construction and operation of a borehole cause changes in the in-situ stress state, which is the main cause of induced seismicity (Békési et al. 2019, Jaeger et al. 2009). The complexity of the problem also increases due to the large uncertainty in the material property parameters. The large standard deviation in model parameters limits the application of deterministic approaches to the problem. FE (Finite Element) analyses can help in studying the complex problem, but are computationally expensive. They can be efficiently employed in a deterministic approach, but fail to provide the full picture of a geomechanics problem, including confidence ranges of the outcomes: the use of FE analysis in probabilistic approaches is still limited. Analytical and closed-formed solutions are very efficient but they lack complexities which are required to represent the actual engineering problem. Semi-analytical approaches could be a solution to the problem: they are efficient and can be used in assimilation with the incorporation of a fair degree of complexities (Chen and Abousleiman, 2012 and 2017).

In the present work, we employ a coupled hydro-mechanical semi-analytical solution based on poro-elastoplastic behavior, which can handle the time dependent flow and permeability variation in the reservoir. As a plasticity model we use a modified version of the plasticity model proposed by Pijnenburg et al. (2019) for sandstones. The solution assumes that the geomaterial is homogeneous and isotropic, and that the in-situ stress state along the horizontal plane is isotropic. The solution was developed under plane strain conditions.

We first briefly introduce the modified Pijnenburg et al. (2019) plasticity model. It is validated using the triaxial tests results published earlier. Then it is deployed in the semi-analytical solution used by Fokker and Wassing (2019).

2. MODIFIED PIJNENBURG ET AL. (2019) PLASTICITY MODEL

From the set of isotropic compression and triaxial tests Pijnenburg et al. (2019) observed that the Slochteren sandstone shows 30-50% inelastic strain at every stage of compression. They proposed a plasticity model with a yield function similar to the one in the Modified Cam-Clay model (Atkinson, 1993), with the assumption of linear hardening. The yield equation is given as:

$$f(q, p', \sigma^*) = q^2 - m^2 p'(\sigma^* - p') = 0 \quad (1)$$

To fit this plasticity model, the slope m of the critical state line had to be fixed manually (Pijnenburg et al., 2019). The plasticity model used different values of the critical state slope for different values of confinement. To obtain a mathematically consistent model we have considered the slope of the critical state line as a variable, with a functional relationship with the inelastic volumetric strain. This modification helps in the automatic adjustment in the slope of critical state line for different values of confining stress.

A second modification is the introduction of non-linear elasticity in the model. It was observed from the triaxial test results that at lower values of the deviatoric stress the material already shows non-linear elastic behavior. In the modified model the elastic modulus is considered a function of the deviatoric stress and the minor principal stress. The dependence of modulus on minor principal stress is based on the experimental observation of increasing stiffness with increasing confining stress.

The modified plasticity model has been matched to the triaxial stress-strain response. The results of the comparison are shown in the Fig. 1: the model very closely predicts the behavior of the high porosity sandstone and also at lower deviatoric stress the model

[1] University of Utrecht, Geosciences, Earth sciences
[2] ECN-TNO, Applied Geociences

predicts the non-linearity of the stress-strain behavior. A detailed discussion of the model will be the part of a full length publication that is currently in preparation (Singh and Fokker, 2019).

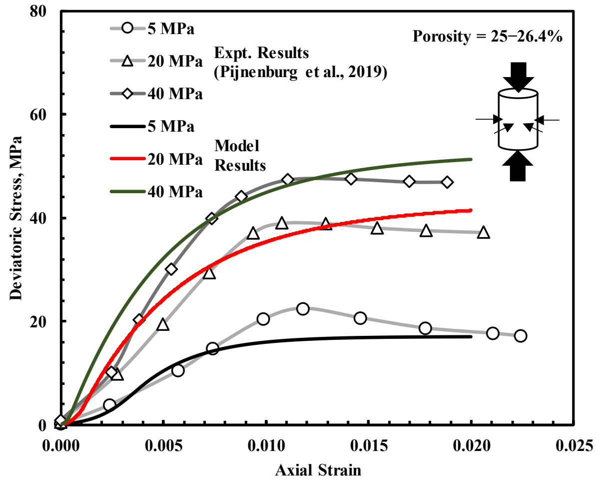

Figure 1: Comparison of triaxial experimental response of Slochteren sandstone with modified Pijnenburg et al. (2019) plasticity model

3. MODELLING APPROACH

The construction of a borehole causes the in-situ stress distribution around it to change, and this change is calculated with the approach given by Chen and Abousleiman (2012; 2017), under the assumption that the over-consolidation ratio is very close to 1. The latter assumption reflects the behavior observed by Pijnenburg et al. (2019), that the material shows inelastic compression during all stages of compression. As a consequence, the region near the borehole experiences both elastic and inelastic deformation and there are no distinct elastic or plastic regions.

After the adapted stresses in the ground due to the construction of borehole have been calculated, the second step is to calculate the changes in the stresses due to the operations – fluid injection or production. Operational processes such as injection causes the formation of two type of regions. These regions are poro-elastic region and poro-elastoplastic region.We follow a semi-analytic timestepping approach that was introduced elsewhere (Fokker and Wassing, 2019; Fokker, Singh and Wassing, 2019).

Stress perturbations are first assumed to be elastic. The responses and their magnitude are thus calculated using linear poroelasticity and stress equilibrium:

$$\Delta\sigma_{ij}' = 2G\left[\Delta\varepsilon_{ij} + \frac{\nu}{1-2\nu}\Delta\varepsilon_{kk}\delta_{ij}\right] \quad (2a)$$

$$\frac{\partial\sigma_r'}{\partial r} + \frac{\sigma_r'-\sigma_t'}{r} + \alpha\frac{\partial\Delta P_o}{\partial r} = 0 \quad (2b)$$

Equation (2a) defines the poro-elastic relation between the stress and strain and Eq. (2b) is the equilibrium equation for axisymmetric conditions in the polar co-ordinate system. σ' represents effective stresses, ε is strain, ν is Poisson's ratio and G is the shear modulus. The subscript letter r and t represent stresses in radial and tangential directions. ΔP_o is the pore-fluid pressure increase.

The distribution of the increase in pore pressure near the borehole region is calculated based on a semi-steady-state solution. The pressure distribution near the borehole is calculated from Darcy's law:

$$\frac{\partial\Delta P_o}{\partial r} = \frac{Q_{inj}}{2\lambda r\pi h} \quad (3)$$

Q_{inj} is the injection rate, r the radial distance, h the reservoir height and λ the ratio of permeability to viscosity.

The new stress state calculated from the Eq. (2) and (3) is now checked for the yield condition (Eq. 1). If it is below the yield surface then the state calculated is considered the stress state at next time step; otherwise the stress state is calculated using the adopted approach given by Chen and Abousleiman (2012; 2017) considering the solution to Eq.(3) in it.

4. RESULTS AND DISCUSSION

For the present paper we have considered two cases. The first one is an injection case, the second one is injection and pressure fall-off after shut-in. The simulated injection time is 26 × 10^5 sec. The injection rate is assumed to be 0.1 m^3/ s in a 100 m thick reservoir. The mechanical properties are adopted from the case of the Slochteren sandstone with a porosity of 25-26.4 %.

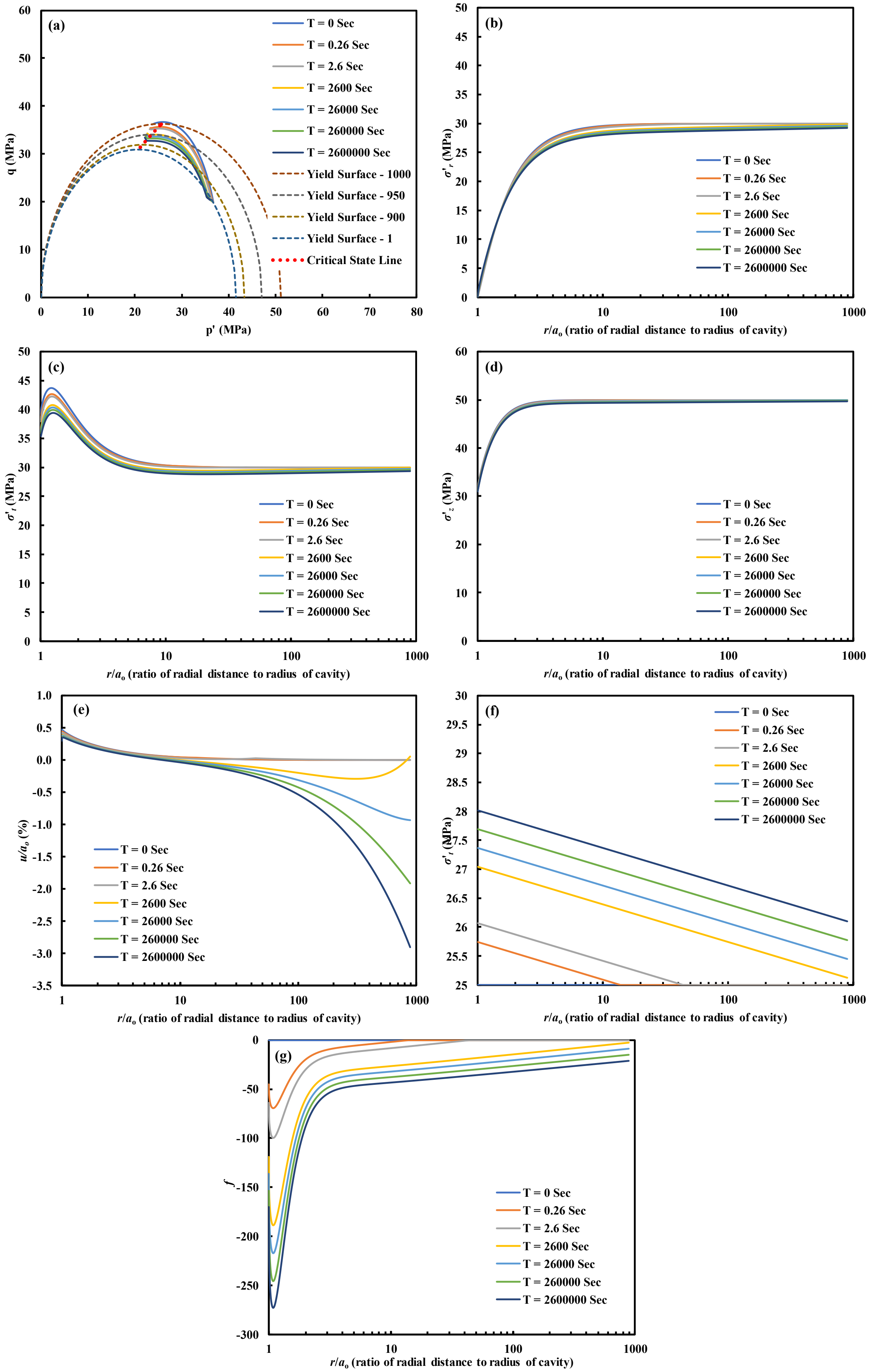

Figure 2: Results for the injection case.

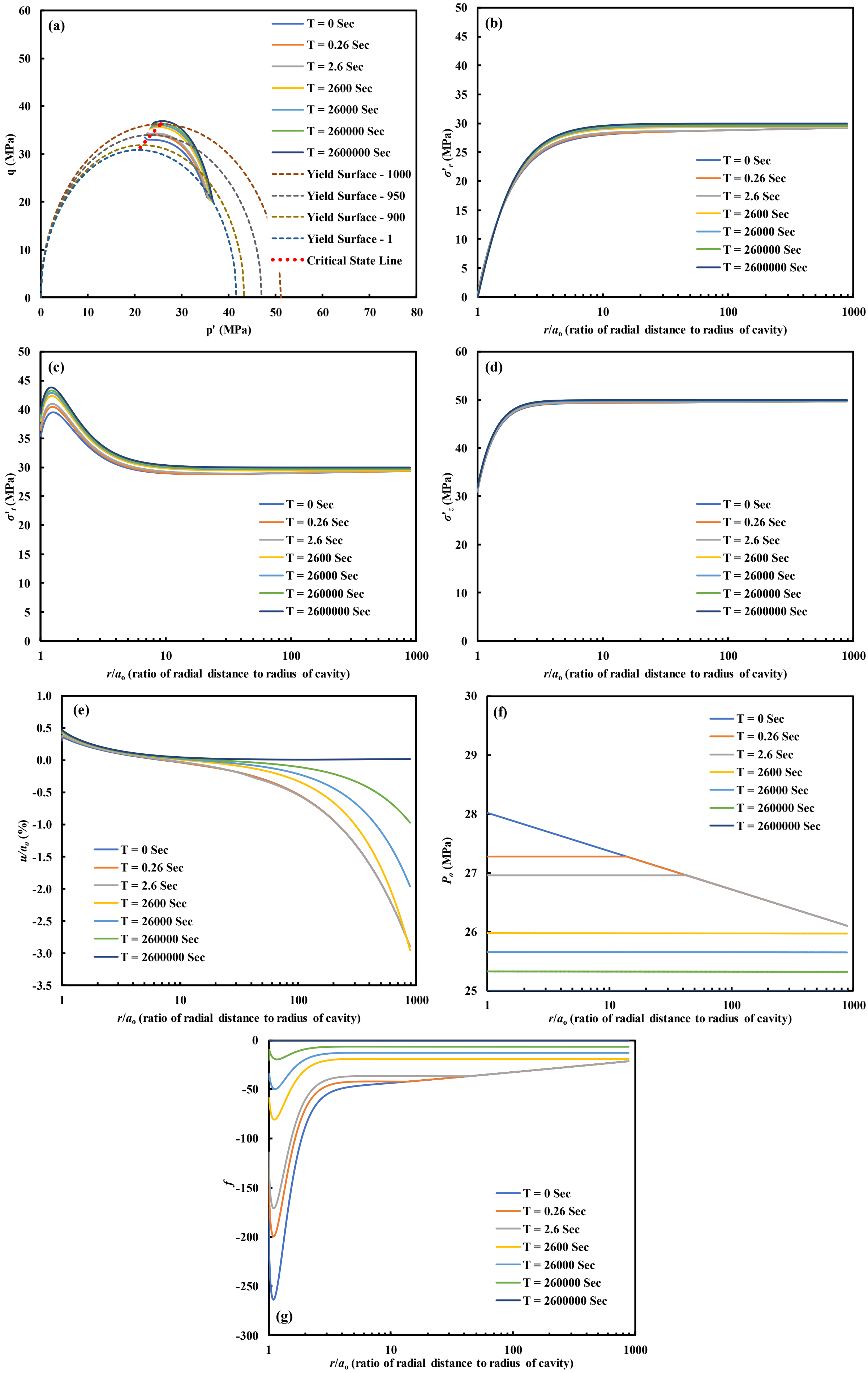

Figure 3: Results for the fall-off condition in shut-in case.

The results of the injection case are shown in Fig. 2. Figure 2a shows the stresses in $p' - q$ space at different time steps. From left to right, the points on the curve are associated with positions ranging from the wellbore to infinity. It is observed that the stress curve at time t = 0 envelopes all the other curves. This is indicative of unloading as the mean effective stress is reducing with time. The dashed lines indicate the yield envelopes for a range of mean effective stresses, to demonstrate how the stress curves relate to them. Figure 2b show the radial effective stress evolution with time. At the wellbore opening the value of radial effective stress is zero, which is required in order to satisfy the inner boundary condition. Figures 2c and 2d represent the tangential and the out-of-plane stresses with time. A comparison with the results of Fokker and Wassing (2019) shows that for the current model the stress distributions are smooth, in contrast to the discontinuity in derivative of the tangential stress that was observed in their elastic-perfectly plastic model. This is related to the strain hardening and softening behavior of the model, which assumes that the over-consolidation ratio is equal to 1 and hence the reservoir will experience both elastic and plastic strain at all points. This means that in the current solution during the construction stage of the borehole, there is formation of a plastic zone. Figure 2e shows the radial deformation. Injection of fluid significantly affects the interior zone. Figure 2f shows the distribution of the pore-fluid with the time using Eq. (3). This distribution was validated by Fokker and Wassing (2019) using the 3D FLAC-Tough2 code: the simplification with the semi-steady-state solution to Darcy's equation predicts the behavior with the reasonable accuracy. Figure 2g shows the value of the yield function. At zero time, the complete domain is yielding due to the construction of the borehole. For later times, however, the yield function decreases, indicating that the stress moves away from the yield envelope and the domain reacts elastically. This behavior starts at the wellbore. Further away, the reservoir continues to react plastically for some time. This behavior was also observed for the elastic-perfectly plastic model presented earlier (Fokker and Wassing, 2019), but there the yielding region was confined to a small volume around the wellbore.

For the fall-off case, the results are shown in Fig. 3. Times indicated in the figure are with respect to the moment of shutin. The sequence of figures is the same as in Fig. (2). It can be observed from the Fig. (3a) that the stress curve of the successive time stepping is moving up and towards the right, which indicates that the material is being loaded under this operation condition. This is related to the equilibration of pressure represented in Fig. 3f. Figures 3b to c show the evolution of the radial, tangential and out-of-plane stress respectively with time. Figure 3 shows that with time the stresses in the reservoir are moving towards the drained state of stress.

5. CONCLUSIONS

We have proposed a coupled hydro-mechanical semi-analytical solution based on poro-elastoplastic behavior. It handles the time-dependent transient flow and can easily incorporate permeability variations in the reservoir. The model is based on a modified version of the plasticity model proposed by Pijnenburg et al. (2019) for sandstones. This version was validated by comparing to experimental triaxial test results and matching the model parameters.

Our solutions are based on the assumption that the geomaterial is homogeneous and isotropic, and that the initial in-situ stress in the horizontal plane is isotropic. Further, the solution assumes plane strain conditions. The application of the developed method is demonstrated using the two cases, for injection and fall-off conditions. Our analysis for a typical injection and pressure falloff scenario demonstrates that injection results in an unloading process near the borehole and consequently stabilization, whereas during shut-in the system is reloaded. The unexpected outcome of the analysis is that the complete domain reacts plastically during well construction.

ACKNOWLEDGEMENTS

The project leading to the results in this article received funding from the European Union's Horizon 2020 research and innovation programmes under grant agreement No 691728 (DESTRESS) and under grant agreement No. 727550 (GEMex).

REFERENCES

Atkinson, J.: An introduction to the mechanics of soils and foundations: through critical state soil mechanics. McGraw-Hill Book Company (UK) Ltd, (1993).

Békési, E., Fokker, P.A., Martins, J.E., Limberger, J., Bonté, D. and van Wees, J.D.: Production-Induced Subsidence at the Los Humeros Geothermal Field Inferred from PS-InSAR. *Geofluids* (2019), Volume 2019, Article ID 2306092.

Chen, S. L., Abousleiman, Y. N.: Exact undrained elasto-plastic solution for cylindrical cavity expansion in modified Cam Clay soil. *Géotechnique* (2012), 62(5), 447.

Chen, S. L., Abousleiman, Y. N.: Wellbore stability analysis using strain hardening and/or softening plasticity models. *International Journal of Rock Mechanics and Mining Sciences* (2017),93, 260-268.

Fokker, P.A., Wassing, B.B.T.: A fast model for THM process in geothermal applications. *European Geothermal Congress*, Den Haag, the Netherlands (2019).

Fokker, P.A., Singh, A., Wassing, B.B.T.: A semi-analytic time-resolved poro-elasto-plastic model for geothermal engineering. Submitted (2019)

Jaeger, J. C., Cook, N. G., & Zimmerman, R.: Fundamentals of rock mechanics. John Wiley & Sons (2009).

Pijnenburg, R. P. J., Verberne, B. A., Hangx, S. J. T., Spiers, C. J.: Inelastic deformation of the Slochteren sandstone: Stress-strain relations and implications for induced seismicity in the Groningen gas field. *Journal of Geophysical Research: Solid Earth* (2019).

Singh, A., Fokker, P.A.: An elasto-plastic model for Slochteren sandstone. In preparation (2019).