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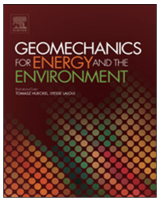

Special Issue on *Injection Induced Seismicity*

Selected papers from the Mini-Symposium on Induced Seismicity of the 2nd International Symposium on Energy Geotechnics, SEG 2018, at Swiss Institute of Technology at Lausanne, EPFL, September 25-28, 2018

One of the most important geophysical observations of the last decades regards a large increase of seismicity due to fluid injections in the crust, even in areas presenting initially low seismic hazard. While human induced seismicity results in general in tiny rupture processes, recent induced earthquakes were stronger than expected, as for example the 2011 Oklahoma earthquake[1].

It is known that many faults throughout the Earth's crust are in a state of critical equilibrium[2]. Anthropogenic fluid injections during hydraulic fracturing reservoir impoundment, the injection of waste water or CO2 storage can induce stress perturbations in the underground and lead to fault reactivation and enhanced seismic activity. Moreover, long-lasting regular natural earthquake sequences (e.g., Umbria-Marche 1997–1998, L'Aquila 2008–2009) are often associated with elevated pore fluid pressures at seismogenic depths (see e.g. Ref. 3). Although, these examples are clear evidence of the effect of pore fluids on fault strength and its seismic behaviour, the mechanics of fluid-Induced earthquakes remains poorly understood. Evaluating the seismic hazard (at a given site) from both natural and human-induced causes remains difficult to assess.

Given the above circumstances, large efforts have been recently made to understand the stability of reservoirs, from the scale of the laboratory to the scale of crustal fault. Experiments have been conducted to study the effect of fluid pressure on the frictional properties of faults (e.g. Refs. 4, 5) and on intact and saw-cut specimens highlighting the influence of pore pressure buildup on the stability of fault at different scales (e.g. Ref. 6), as well as about the influence of faults permeability and fluid viscosity (e.g. Refs. 7, 8), and the stability of faults submitted to fluid pressure oscillations (e.g. Ref. 9). However, at the scale of the crust, field observations highlighted that earthquake nucleation due to hydraulic stimulation is vertically offset from the injection well, and are not consistent with injection depth[10,11]. These observations suggest that nucleation of earthquakes may be due to poroelastic strain transfer and pore pressure-driven aseismic slip, that outgrowths the pore pressure front[12].

This special issue consists of five papers selected from the invited and technical presentations to the Mini-Symposium on Induced Seismicity organized in the framework of the 2nd International Symposium on Energy Geotechnics, SEG 2018, at Swiss Institute of Technology at Lausanne, EPFL, September 25–28, 2018, under the auspices of TC 308 of International Society of Soil Mechanics, Geotechnical Engineering, after a peer-review process. Each paper deals with fluid induced seismicity, observed at different scales, from the scales of microcracks[13,14], to the scale of stimulated reservoirs[15], up to the scale of large crustal faults[16,17].

The paper by Nicolas et al.[13] explores the diffusion of fluid in a highly cracked rock sample at the laboratory scale using in-situ pore pressure measurements. Sample permeability is seen to decrease by two orders of magnitude with increasing confining pressure and deviatoric stress, implying that sample permeability is highly sensitive to stress. The authors also examine the migration of a pore pressure pulse applied on the side of the sample during deformation using fiber optic sensors inserted at different locations. The fibre optic sensors one after the other have shown a sudden pore pressure increase in response to the pulse as a function of their location along the sample. Their measurements have been modelled with a diffusion equation under constant permeability. This study highlights the fact that fiber optic sensors are a powerful tool to measure local pore pressure to help to understand the hydro-mechanical behaviour of low-permeability porous materials, that could open new perspectives in experimental poroelasticity.

The paper by Benson et al.[14] reviews some of the advances in the field of fluid-induced seismicity, with a particular focus on the use and application of new and innovative laboratory methods to better understand the complex, coupled processes in shallow subsurface energy extraction applications. In particular, the authors discuss the relation between acoustic emission, fluid injection rates and mechanical deformation.

The paper by Gischig et al.[15] presents the reasoning for and first results of large scale fluid stimulation experiments in crystalline rock with implications for induced seismicity in deep reservoirs. The authors give an update on the innovative work being done in the Grimsel test site, and in the upcoming Bedretto project (Switzerland). They conclude that stimulation experiments show a large variability within a 10 m scale rock volume and hence the reservoir stimulation needs to be tested at a 100 m scale.

The paper of Michas and Vallianatos[17] analyzes earthquake swarm activity in Northern Greece between 2012 and 2014. They identify two different clustered activities separated by a period of low activity based on relocated earthquake catalogs. Based on

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statistical modeling and observed seismicity migration, they conclude that the earthquakes were likely driven by CO_2 discharge and vertical fluid migration.

The paper by Haddad and Eichhubl[16] analyzes the effects of fluid injection and fluid production locations on fault reactivation potential in a faulted reservoir using a finite difference poroelastic simulation. The km-scale model is composed of tabular lithologies (i.e. sedimentary rocks and crystalline basement) forming two deep reservoirs surrounded by low permeability rocks, which are crossed-cut by a normal fault. Authors show that the ability of a fault to be reactivated is sensitive to the location of fluid injection and production and provide guidance for preventing fault reactivation during injection and production activities. The novelty of this work consists of including a complex geometry with stacked reservoir layers and a fault thickness adopting a fully coupled poroelastic and pore fluid-flow numerical approach associated with a Mohr–Coulomb failure criterion.

In summary, the suite of papers that makes up this themed issue presents a recent research covering a wide range of approach (field studies, laboratory experiments, modelling work) to study induced seismicity in geo-reservoirs and in nature. In our opinion, this wide scope and the relevance of the research presented makes this themed issue a valuable reference resource in the field.

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