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Seismic and aseismic motions generated by fluid injections

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HIGHLIGHTS

- Identify the signature of hydromechanical coupling on microseismic activity development.
- Outline the role of aseismic motion generated by deep fluid injection on the development of induced microseismicity.
- Discuss the role of aseismic monitoring for mitigating ground surface disturbances.

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ABSTRACT

Pore pressure increase associated with the injection of fluids in rock masses often generates some microseismicity. But pore pressure variations depend on fluid diffusion, which itself depends on hydromechanical coupling. We identify in the present review paper four different pore pressure levels that control hydromechanical coupling and therefore the development of fluid induced microseismicity. But more importantly, fluid injections have been shown to generate also non seismic motions, i.e. motions that are too slow to be detected by classical monitoring networks. Such aseismic motions have been identified both through direct observations and through their indirect effects. They have been found to affect volumes equivalent to those associated with magnitude 5 earthquakes, when no such large seismic event has been observed. These aseismic slips generate large stress perturbations that have been found in some occasions to develop long after fluid injection has stopped. It is recommended that specific attention be given to these aseismic motions in order to keep nuisances observed on ground surface at acceptable levels.

1. Introduction: from fluid induced seismicity to fluid triggered seismicity

The concept of fluid induced seismicity was formulated by Healy et al.[1] after they observed that the microseismic activity recorded close to the Rocky Mountain Arsenal, near Denver (Colorado), was directly linked to the injection of waste fluids at depth. Nearly simultaneously, Gupta et al.[2] reported that the seismic activity observed in the vicinity of the Koyna Dam, in India, was directly linked to the filling of the dam.

It is now well recognized that an increase in pore pressure at depth may induce some microseismic activity and we concentrate in the present paper on the case of deep fluid injections. Indeed, these provide a unique insight into the various processes involved by a pore pressure increase when the far field stress conditions may be considered as constant over time. For such conditions, the development of induced microseismicity depends only on variations in pore pressure and therefore only on the fluid diffusion process.

We do not address in this paper effects of temperature perturbations nor of fluid–solid chemical interactions and restrain the discussion to the consequences of hydro-mechanical coupling. We show that pore pressure perturbations may induce both, seismic and/or aseismic motions, and this may shed some light on the differences between the concepts of induced seismicity and that of triggered seismicity.

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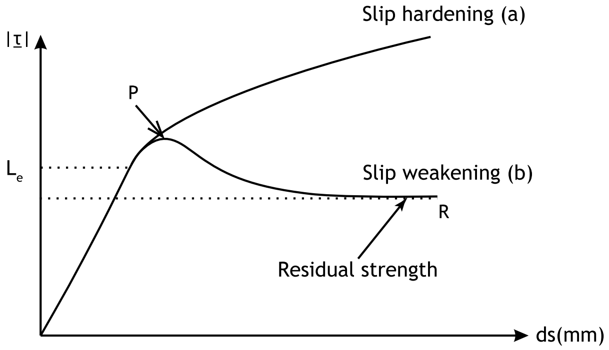

Fig. 1. The concepts of slip hardening (a) and of slip weakening (b). The vertical axis is the magnitude of the shear stress component in the shearing plane whilst the horizontal axis is the amplitude of slip displacement. L_c is the limit of linearity of the shear stress–shear displacement curve. P is peak value of the shear stress magnitude and R its final residual value.

The concept of induced seismicity implies that seismicity stops when the pore pressure returns to a low enough value. It implies both a truly elastic behavior for the geomaterials and a limited extent of the non-elastic disturbances generated by the pore pressure increase. Triggered seismicity refers to situations in which the increase in pore pressure has generated some permanent deformation that may, or may not, lead to ruptures much larger than the domain where pore pressure has been affected. It may be associated with earthquakes the magnitude of which is large enough to create significant perturbations at ground surface.

First we introduce a brief discussion on the mechanical conditions (loading conditions and material properties) that lead to instabilities (dynamic failure processes) at the origin of microseismic activity. Then we identify four different hydro-mechanical coupling phenomena that affect fluid diffusion and discuss the corresponding induced micro-seismic activity. In Section 4, different field examples are briefly summarized for identifying various factors that control the spatial development of fluid induced microseismicity. Finally we discuss consequences for the monitoring of this type of seismicity and propose an injection scheme for mitigating perturbations at ground surface during short term hydraulic stimulations.

2. Seismic versus aseismic slip motions

2.1. The concept of stable and unstable deformation processes

In the mid-seventies, it was recognized that the dynamic characteristics of brittle rock failure observed in the laboratory are entirely dependent on the loading conditions (Wawersik and Fairhurst[3]; Hudson et al.[4]). Instability occurs when the potential energy variation released by failure is larger than the quantity of energy dissipated by the deformation process. The first principle of thermodynamics, which describes the conservation of energy during deformation processes, implies that the excess of potential energy variation is transformed into heat and kinetic energy and it is the kinetic energy that leads to observed dynamic effects. Hence it has been possible, in the laboratory, to control failure by adjusting the loading conditions so as to keep energy dissipated through the deformation process slightly larger than the variation in potential energy stored in the testing system (loading machine + rock sample). By direct application of this principle, Hudson et al.[5] were able to control many failure processes that had been considered previously as being inherently unstable.

As discussed by Scholz,[6] the same principle may be applied to friction (Fig. 1). In particular when the slippage process is slip hardening (increase in friction resistance with slip) slip is stable, whilst if the process is slip weakening (decrease of resistance to slip with slip amplitude) the process may become unstable. This leads for example to the well-known stick–slip phenomenon (Byerlee and Brace[7]), which occurs when the dynamic friction coefficient is lower than the static friction coefficient. Interestingly, the largest the normal stress applied to the slipping surface, the strongest the stick–slip phenomenon.

Since for slip hardening processes slip is always non seismic, an important issue is to determine conditions that may lead to slip hardening processes so as to keep the slip aseismic.

A recent *in situ* experiment, which involved fluid injection in a natural fault at a depth of 280 m (Guglielmi et al.[8]), has shown that for these shallow depth conditions most of the slip was aseismic and that the friction coefficient for the slipping surface increased with velocity from 0.4 to 0.8. It may be speculated that had the injection pressure been dropped whilst slip was still occurring under quasi-static conditions, no dynamic effect would have been observed.

The fact that the friction coefficient varies with the slip velocity has been well documented by laboratory experiments (Dietrich,[9] Johnson[10]) and has led to the proposition of so-called rate and state friction laws (Rice and Gu[11]; Ruina[12]). A commonly used form for such a rate and state friction law is given by Eq. (1) (Scholz, chap. 2[6])

$$\tau = \sigma'_n[\mu_0 + a\ln(v/v_0) + b\ln(\theta/\theta_0)] \tag{1}$$

where τ is the shear stress component in the plane; σ'_n is the effective normal stress supported by the plane; μ, v and θ are respectively the friction coefficient, the slipping velocity and a state variable that describes surface morphological characteristics, whilst the index 0 refers to a specific reference value for these variables. a and b are