Induced seismicity: Setting the problem in perspective for EGS development

Keith Evans (ETH-Zürich)

Swiss Federal Institute of Technology Zurich
ENGINEERING GEOLOGY

Induced (or triggered) seismicity is nothing new

Induced seismicity is a recognised risk in any Earth-engineering endeavour that changes the stress state or pore pressure of a rock mass

- Reservoir impoundment
- Mining and tunnelling
- Fluid waste disposal through injection
- Oil and gas production
- Quarrying
- Enhanced Geothermal System development

Largest event magnitudes from non-EGS induced seismicity

Magnitudes of the largest earthquakes of each type recognised as most likely to have been induced by man's activities

Reservoir impoundment

Koyna (1982): $M_L = 6.3$
Killari (1993): $M_L = 6.1$
Aswan (1981): $M_L = 5.6$

Long-term fluid injection into:

Basement at 3.7 km at Rocky Mountain Arsenal (Denver): $M_L= 4.0$ (M_L=5.5 1yr after stop)
Fault in limestone at 4.55 km at Paradox Valley Colorado: $M_L = 4.3$ (after 4 yrs inject)
Sandstone above basement at 1.7 km in Ashtabula-NY: $M_L= 3.8$ (M_L=4.2 14 yrs after stop)

Fluid extraction

Lacq gas reservoir, SW France: $M_L = 4.0$
Gas reservoirs in the Netherlands: $M_L = 3.5$

Mining activities

South African gold mines: $M_L = 4.0$
Mines in the Ruhr region, Germany: $M_L = 3.0$

Largest event magnitudes at EGS sites

The largest events tend to occur during stimulation or shortly following stimulation injections when high pore pressures trigger in stress release.

Fenton Hill, **New Mexico** (2.8 km & 4.2 km): $M_m \sim 1.5$
Rosemanowes, Cornwall (2.2 km): $M_L = 1.9$ (Mildly felt)
Hijiori, Japan (1.8 & 2.2 km): $M_L = 2.4$ (Mildly felt)
Soultz, France (3.5 km): $M_L \sim 2.0$
Soultz, France (5 km): $M_L = 2.9$ (Felt)
Basel, Switzerland (5.0 km): $M_L = 3.4$ (Strongly felt - minor damage claimed)
Cooper Basin, Australia (4.1 km): $M_L = 3.7$ (Felt

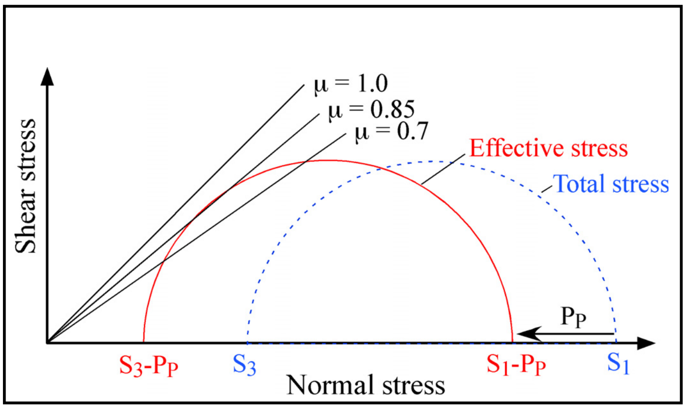
Note:

- The largest events induced by EGS activities to date are comparable to or smaller than the largest events recorded for other types of induced seismicity.
- Not all deep EGS sites produce felt events during large stimulation operations.

Critical stress state of the crust - An explanation of why cases of induced seismicity are common

Over the past 20 years it has become clear that the stress state of Earth's crust is generally characterised by high differential stresses.

Stress measurements conducted in a wide range range of geological situations - particularly at EGS sites - generally indicate that the differential stresses are so high that the rock mass would be verging on failure if its strength were governed by a Coulomb friction criterion with a friction coefficient, μ, in the range 0.7-1.0



Such high differential stress states are called '**critical**' and they are the norm.

All EGS systems developed to date are critically-stressed - ***and a good thing too!*** - because it is the energy released by the high differential stress that drives the shearing and dilation of fractures and hence underpins the stimulation process.

Site dependence of seismic risk

Although relatively high differential stresses may be the norm, there is large ***site-to-site variability*** in the seismic response to stress perturbation - from major damaging earthquakes to innocuous microseismic responses.

There is currently ***no regulatory methodology*** for evaluating ***a-priori*** the seismic hazard associated with risk-engendering activities - the risk is often assessed on a project-by-project basis by consulting companies.

- rarely is a project terminated at the planning stage because of seismic risk. Rather, ***the risk is usually managed*** through monitoring with provision for remedial action.

EGS system development is no different to other activities that pose an induced seismic hazard, except that current experience would suggest the ***seismic risk is lower***.

Nevertheless, the development of EGS systems would be promoted by developing **mitigation strategies**.

Approaches to mitigation

Regulatory authorities would like guidelines on the seismic risk posed by EGS system development to help with the granting of concessions.

Broadly speaking, there are three approaches

- **No a-priori regulation** - the mitigation being exercised through real-time monitoring of seismicity with prescribed threshold reponses (e.g. the Traffic-light system proposed by Bommer) - *This is real-time, reactive risk mitigation and it is the approach most often adopted.*
- **A-priori regulation** through the use of *empirical guidelines* derived from an assessment of case-histories of induced seismicity to elucidate the effect on maximum magnitude of depth, proximity to faults, 'criticality' of stress state (i.e. implied value of μ), level of background seismicity.
- **Forecasts** of the rock mass response to fluid injection using *numerical simulators* conditioned by parameters derived from site investigations.

Deterministic approaches to risk evaluation

Can numerical models conditioned by observables derived from site investigations be used to predict the maximum magnitude likely to result from injection?

There has been substantial progress in the past few years in developing *coupled, multi-physics numerical models* that simulate the stimulation process, including shear failure of discrete fractures.

Currently, these models necessarily simplify such things as fracture constitutive failure laws and typically exclude poroelasticity and seismic radiation. However, it is likely that the realism of these simulators will continue to improve with advances in computing power.

But even if simulators were available today that included *all the relevant physics for simulating the rock mass response to fluid injection*, there is the question of whether they could be parametrised sufficiently well using *observables from site investigations* to make meaningful predictions.

Constraining models with parameters derived from site investigations - simple considerations

Assume: 1) *significant seismic events always occur on faults;*

2) the distribution of faults within the neighbourhood of a prospective site is known from surface mapping and geophysical investigations.

To evaluate the *potential for these structures to host large events* when weakened by a diffusing pore-pressure front, it is essential to specify (amongst other variables including hydraulics parameters!):

- **stress distribution prevailing on the faults**
- **strength distribution of the faults**

It is probably not enough to specify a single stress tensor and single strength parameter for the whole fault.

Dynamic simulations of the fault failure process that including stress transfer and poro-elasticity show that the ***spatial variations*** of these parameters play a major role in determining the size of failure in a single event.

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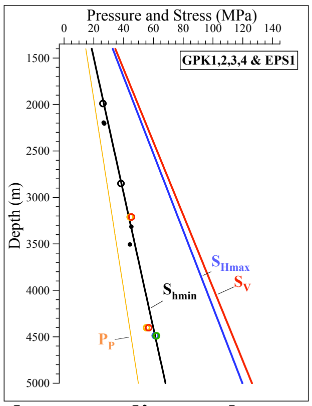
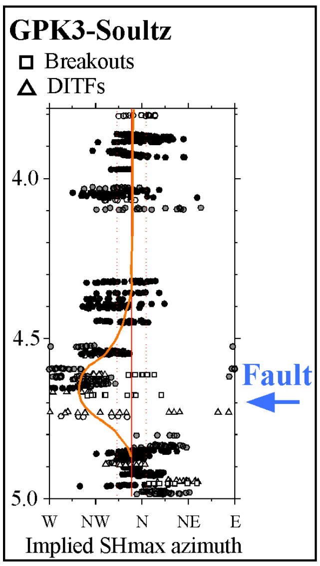
The difficulty of characterising stress on faults

If an exploratory borehole is drilled, then we can, *in principle*, estimate stress along the hole (in practice it is not easy to measure the full stress tensor).

This yields a *reservoir stress characterisation* defined by the depth trends of the stress attributes - *used in modelling*.



Soultz stress linear charact.



However, is commonly observed that *stress is locally perturbed at faults* and fractures - and it is likely that faults will exhibit *strong in-plane variations* in stress due to their complex internal structure and slip distribution.

Thus, although it may be possible to estimate the stress at at the well - it is not possible to determine the variations of stress that occur on the fault plane, even if it cuts the well.

At left can be seen a 500 m scale perturbation in S_{Hmax}-orientation defined by breakouts (squares) and DITFs(triangles) associated with a fault at 4.7 km depth in well GPK3 at the Soultz EGS site. The sub-horizontal streaks are perturbations associated with fractures.

Stochastic rather than deterministic representations of stress/strength variation

So it is not possible to ***deterministically*** specify the variation in stress on faults.

Similar difficulties apply to the estimation of the ***strength distribution***.

A possible solution is to move to a ***stochastic representation*** of the stress/strength distributions on faults.

Such a representation could perhaps be constrained to some degree by fitting the ***b-value of seismicity*** located near the faults in question.

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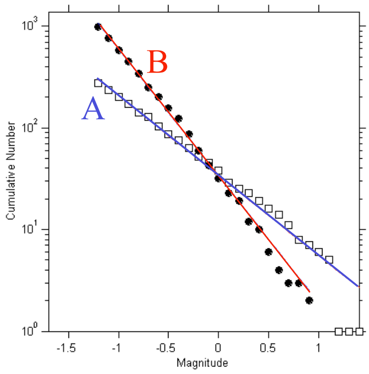
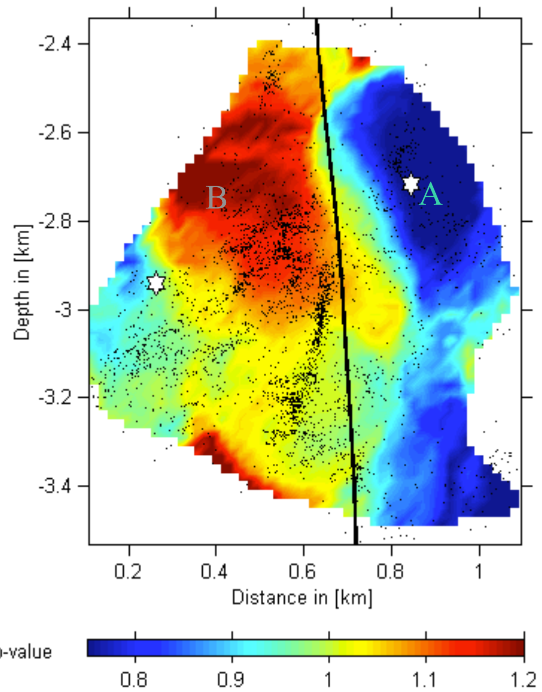
b-value distribution in the Soultz 3 km reservoir

Log(no. of events with mag>M_L) = a - bM_L



Sampling section width = 100 m
Sampling radius = 200m
Sampling Mw cut-off = -1.2



b-value is the slope of the magnitude-frequency relation (Gutenberg-Richter).

Low b-values indicate proportionally more large earthquakes occur than for high b-vals.

b-values thus contain information about the scaling of failure (i.e. patch size).

Seismological constraints on numerical models

b-values introduce ***scaling information*** into the problem, and might conceivably be applied as a constraint to numerical models in real time during injection to help ***forecast*** the likelihood of producing an event that exceeds some prescribed threshold.

The real-time estimation of ***b-value alone***, without applying numerical codes, can be used to say something about the likelihood of generating large events - although since b-values *can vary within a reservoir*, real-time *b-value mapping* should really be used, requiring real-time event location as well as magnitude estimation.

Obviously, b-values can only be estimated *once we probe the rock mass and its faults by injecting fluids* and generating seismicity.

Returning to approaches to problem mitigation

Our ability to estimate seismic risk ***before*** *a well has been drilled and a test injection conducted (i.e. 'a-priori') is much poorer than* ***after***.

Before drilling and injection, we must evaluate the hazard ***a-priori*** based upon on information such as:

- proximity to known faults, active or otherwise.
- proximity to major population centres.
- depth of target reservoir.
- natural seismicity at the locality (possibly including b-value).
- type of stress regime (normal, strike-slip, thrust) and possibly 'criticality'.
- experience gained from similar operations in the locality or region

This would require that ***guidelines be established*** for weighting the impact of such things as fault proximity or depth, - perhaps by examining case-histories, particularly examples related to fluid injection.

Concluding remarks

- Current experience suggests that the seismic hazard posed by EGS system development is somewhat less than the risk posed by other types of activities that can induce seismicity.

- Nevertheless, there is a risk that must be managed, and it is incumbent upon us to devise ways of mitigating the hazard.

- Future EGS projects should take public relations extremely seriously, and engage professional assistance. It is essential to have the support of the local population.