Expected level of seismic activity caused by volumetric changes

Miroslav Hallo,[1] Leo Eisner[2*] and Mohammed Y. Ali[3] review theories and case studies suitable for estimating the maximum seismic event induced by fluid injection or more generally volumetric changes and show that theory proposed for the mining industry is applicable to fluid injection as an upper bound for induced seismicity.

The seismic activity caused by volumetric changes like mining extraction or fluid injection can cause significant social issues (e.g. Basel: Kraft et al., 2009; Blackpool: Eisner et al., 2011; DFW seismicity: Frohlich et al., 2011). Large magnitude seismic events can cause damage to the operation equipment, damage the borehole by the offsets on faults, and damage buildings not to mention adversely affecting public opinion. Unexpected high levels of the seismic activity can even lead to the termination of a project as happened in Basel (Kraft et al., 2009; Deichmann and Giardini, 2009). Therefore, estimation of the possible highest magnitude of the seismic event caused by operations can be very beneficial for the operators and it can minimalize impacts on the project progress.

On the other hand, microseismic events (i.e., events with relatively small magnitudes) can track activated fractures or waterfront during the fluid injection operations (e.g. Cotton Valley: Rutledge et al., 2004; Oman: Sarkar et al., 2008) and help to make safe operations. Such microseismic monitoring can be performed by a downhole array of receivers or by surface monitoring networks (e.g., Maxwell et al., 2010, Duncan and Eisner, 2010). Because of the limited sensitivity of these monitoring systems (e.g., Hallo, 2012), estimating the probability of success of a monitoring project requires knowledge of the probable level of the seismic activity (Oates et al., 2011).

In this study, we have investigated the level of seismic activity caused by volumetric changes, especially by fluid injection into the rock. We are proposing a method for estimating the total seismic moment, level of probable seismicity, and possible magnitude of the strongest event caused by volumetric changes. Such estimation could be useful for monitoring network design, seismic risk management, and also for adjustment boundaries of the 'traffic light' monitoring systems (Majer et al., 2007).

Seismicity and a change in volume

The seismicity that results from ground deformation can be associated with a change in volume (McGarr, 1976; Shapiro et al., 2010). Change in volume refers to removal of a volume of solid rock in mining or injection of fluid volume. Both activities produce shear stresses released by (micro-) earthquakes. Maxwell et al. (2009) proposed that there are numerous other factors influencing the seismic activity during fluid injection, but the stress changes appear to be one the dominant factor. The most objective parameter for measuring the level of seismicity is the total released seismic moment. It can be defined as the scalar sum of seismic moments and it is proportional to the released energy.

Theoretical total seismic moment

In the model proposed by McGarr (1976) the total released seismic moment (Figure 1), results from ground deformation associated with a change in volume ΔV:

$$\sum M_{TOT} = K\mu|\Delta V|, \quad (1)$$

where $\sum M_{TOT}$ is the theoretical total seismic moment, μ is the shear modulus and K is a factor close to 1. Theoretical total seismic moment is the sum of seismic moments considered as scalar measures of seismic deformation in this model. However, the model does not incorporate aseismic deformation within the medium (change in volume is accommodated only by seismic failures), so the total released seismic moment is smaller than the theoretical value calculated by equation (1):

$$\sum M_0 = \sum M_{TOT} - \sum M_A, \quad (2)$$

where $\sum M_0$ is the total released seismic moment and $\sum M_A$ is the aseismic energy. This fact is very often neglected, which can produce errors of several orders of magnitude. The seismic efficiency ratio defined as $\sum(M_0) / \sum(M_{TOT})$ is dependent on rock types and injected or removed material (i.e., rock, water, CO_2).

Shapiro et al. (2010) proposed a theory where (in the case of hydraulic injection) the number of events (and adequate

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total seismic moment) is proportional to the fluid volume injected together with a parameter (the seismogenic index) that quantifies the seismotectonic state at the injection location. Alternatively, Maxwell et al. (2009) proposed the seismic injection efficiency, which is analogous to the seismic energy ratio determined from equation (2). Both of these theories (Shapiro et al., 2010; Maxwell et al., 2009) are similar to the modified McGarr equation (2). But they introduce significant additional complexity without a better fit to the observed dataset and they involve unknown physical variables in the equations (such as concentration of pre-existing cracks).

Case studies

There are several published case studies of the significant seismicity caused by operations involving volumetric changes. However, these volumetric injections are different. To compare them with theoretical values we assumed linear dependence of total released seismic moment on the injected (removed) volume. These dependences have been extended to span similar injected volume as in Figure 1. According to these measurements of seismicity during hydraulic fracturing in gas reservoirs (Rutledge et al., 2004; Eisner et al., 2011; Maxwell et al., 2009), geothermal reservoirs (Baisch et al., 2009), and saltwater disposal reservoir (Frohlich et al., 2011), the released total seismic moment appears to be similar or smaller than the value predicted from equation (1) (Figure 2 and 3). This is consistent with the proposal that part of the total moment determined from equation (1) is absorbed to incorporate aseismic deformation within the medium as illustrated by equation (2). We also note that the described case studies represent maximum seismic moment released due to injection as some of the cited seismicity (e.g., Frohlich et al., 2011) is only circumstantially related to fluid injection and induced seismicity might be several times smaller.

Figure 2 shows resulting dependences on injected volume from the total seismic moment observed during several enhanced geothermal systems (EGS) and saltwater disposal projects (Baisch et al., 2009; Frohlich et al., 2011). The total released seismic moments and their respective dependences (Figure 2) are very similar to the theoretical total seismic moment determined from equation (1) for reasonable shear modules (Figure 1). Such similarity indicates that a significant part of the injected energy was released seismically. Furthermore the seismic energy ratio determined from equation (2) has values close to 1 to 0.005 in the case of EGS and granitic rock formations.

Figure 3 shows several measurements from hydraulic fracturing of the sedimentary formations (Blackpool, Cotton Valley, and projects proposed by Maxwell et al., 2009). Blackpool (Eisner et al., 2011) could be considered as an extreme case of hydraulic fracturing with abnormally high seismicity, however the total observed moment is still lower than theoretical total seismic moment predicted by equation (1). The hydraulic fracturing projects published by Maxwell et al. (2009) and Rutledge et al. (2004) show significantly lower released seismicity (and total seismic moment) than the McGarr prediction of equation (1). This is probably caused by significant energy loss by aseismic processes. Hence the seismic efficiency determined from equation (2) will be much lower than in the case of EGS. This seismic energy ratio has the values approximately in the range of $2*10^{-5}$ to $6*10^{-9}$ in the case of hydraulic fracturing without significant seismicity (most of the projects). In the case of the hydraulic fracturing with abnormally high seismicity (extreme cases), the seismic

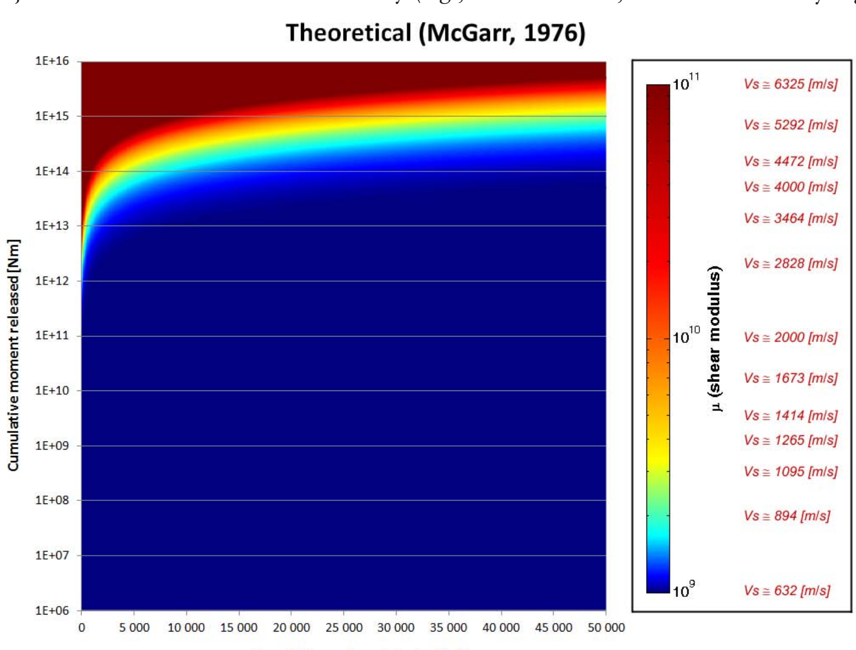

Figure 1 *Theoretical total seismic moment without aseismic deformations as a function of the injected volume (in the model proposed by McGarr, 1976). Different values of the shear modulus μ from equation (1) are presented by colour map. The shear modulus is approximately proportional to the shear wave velocities for assumed density of 2500 kg/m³. Factor K is set to 1 in this graph.*

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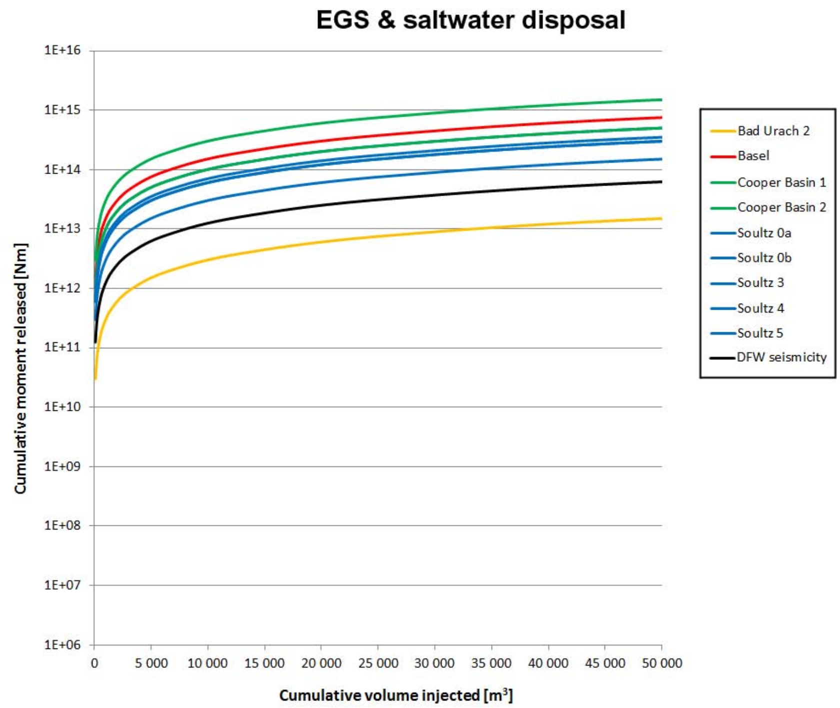

Figure 2 *Total released seismic moment observed during several enhanced geothermal systems (EGS) and saltwater disposal projects shown as a function of the injected volume. All curves show a linear dependence on the volume injected and they have been extended to span similar values of injected volume as in Figure 1.*

energy ratio can be in the same range as in the case of EGS and hence the McGarr theory represents the upper bound on the total seismic moment.

Expected level of the seismic activity

The values of the total released seismic moment provide information on the total seismic activity caused by a volumetric change. The distribution of total seismic moment released among events can be estimated from combining the Gutenberg-Richter (Gutenberg and Richter, 1954) and moment magnitude formulae (Kanamori, 1977). And the number of events having magnitude greater than a given value is determined by *a* and *b* values in the Gutenberg-Richter law. Hallo et al. (2013) presented a method determining the corresponding magnitude of the largest seismic event. It can be shown that the ratio between moment of the largest event M_0 and total released seismic moment is dependent only on the constant *b* (*b*-value). For a *b*-value of 1.5 (corresponding to a local magnitude), this ratio is 0.5 and it leads to a conclusion that 50% of the total seismic moment can be released in the strongest seismic event. For a *b*-value of 1.0 (corresponding to a local magnitude) nearly 100% of the total seismic moment occurs in the single seismic event. Hence the magnitude of the strongest seismic event could be determined from the relevant *b*-value by formula for the moment magnitude (Kanamori 1977):

$$M_w = \frac{2}{3}(\log_{10}(M_0) - 9.1), \quad (3)$$

where M_0 is the moment tensor in Newton-meters.

Conclusions

The proposed method of estimation of the largest possible maximum magnitude is supported by a number of case studies of the seismicity caused by volumetric injections. The model proposed by McGarr (1976) is sufficient for all types of volumetric injections as an upper bound of total seismic moment. This moment can only be reduced because of the aseismic deformation within the medium. In this model the total seismic moment is linearly dependent on the amount of injected (removed) material and energy loss is governed by the seismic efficiency. The seismic efficiency is defined as ratio between the total released seismic moment and the theoretical total seismic moment without aseismic deformations. Several case studies rescaled to the same volumes show that this efficiency is different for different rocks, different injected fluids, and different type of stimulation (e.g., hydraulic fracturing or long term water injection). From the previous case studies this ratio was estimated to be in the range of 1 to 0.005 in the case of EGS, and in the range of $2*10^{-5}$ to $6*10^{-9}$ in the case of hydraulic fracturing.

The possible magnitude of the strongest event caused by volumetric changes is dependent on relative moment released in large and small seismic events (b-value). The release of nearly all moment in a single event happened for b-values around 1 and smaller.

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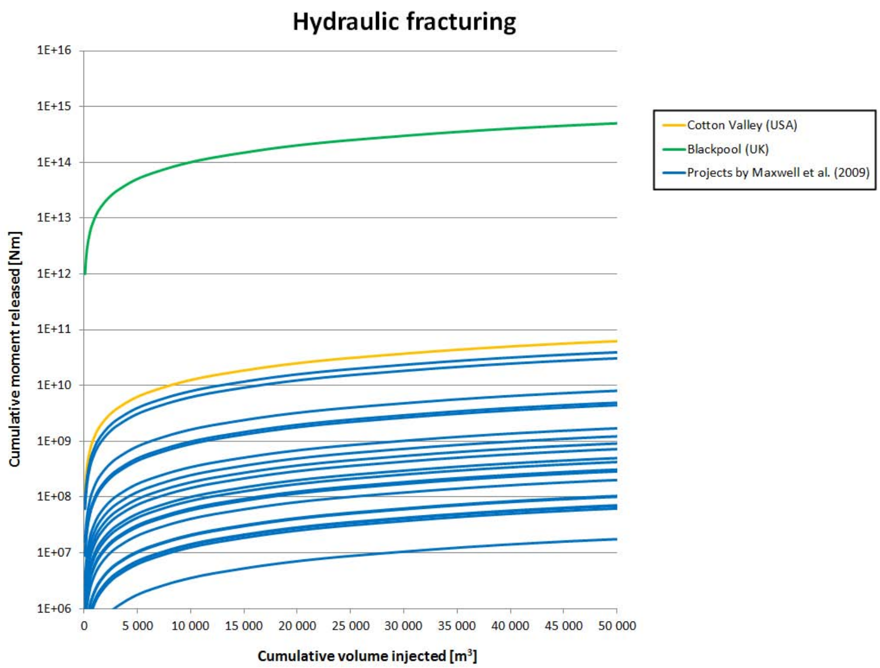

Figure 3 *Total released seismic moment observed during several hydraulic fracturing projects in oil and gas reservoirs shown as a function of the injected volume. All curves show a linear dependence on the volume injected and they have been extended to span similar values of injected volume as in Figure 1 and 2.*

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