GeoTHERM
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Freitag, 27. Februar 2026, 9.30 Uhr
Ortenauhalle Kongress 1
Tiefe Geothermie

Friday, 26 February 2026, 9.30 am
Ortenauhalle Congress 1
Deep geothermal energy

Probability of triggering significant earthquakes through geoenergy projects

Die Wahrscheinlichkeit, dass Geoenergieprojekte bedeutende Erdbeben auslösen

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Predicting maximum possible earthquakes triggered by massive subsurface interventions is an urgent practical problem. To address this problem, we propose to distinguish between the probability of well-controlled induced seismic events and the probability of triggered tectonic earthquakes with out-of-control ruptures extending well beyond the operating domain. To put this approach into practice, we introduce the concept of the seismotectonic continuum and combine it with the seismogenic index model and the lower-bound statistics of the frequency-magnitude distribution of induced earthquakes. On this basis, we propose to calculate and monitor the worst-case probability of triggering a large-magnitude tectonic earthquake in a continuum. To illustrate our approach, we consider several case studies including the classical case study of the Denver earthquake series of 1962-68, the Groningen gas field and the Pohang geothermal site in South Korea.

The magnitude of large runaway earthquake ruptures is determined by the surrounding tectonic fault networks that constitute the seismotectonic continuum (Shapiro et al., 2021). The frequency-magnitude distribution of earthquakes in the continuum is given by the Gutenberg-Richter (GR) statistic (Gutenberg and Richter, 1954) of the tectonic setting. The seismogenic index is a measure of the potential induced seismicity for a unit measure of a geotechnological impact at a particular location. It is similar to the Gutenberg-Richter a value. The seismogenic index and the Gutenberg-Richter b-value are properties of the seismotectonic continuum.

The probability of an induced earthquake is increased due to underground activity in a limited operational domain. The estimation of the parameters of the seismotectonic continuum, i.e., the b-value and the seismogenic index, requires the use of the seismogenic index formulation. Moreover, it may be necessary to use the lower-bound statistic of the frequency-magnitude distribution of induced earthquakes to take into account the geometric limits of the operational domain. This is the case, for example, in the Groningen gas field (Boitz et al, 2024).

The seismotectonic continuum parameters and the time-dependent volumetric integral of Coulomb Failure Stress changes in the operational domain are then used to compute the worst-case probability of a potentially triggered maximum magnitude earthquake. This probability is an integral measure of the seismogenic impact of subsurface operations. This probability should be monitored in real operational time. It is also an estimate of the probability of such an earthquake after the technological activity. A statistically sound observation of the b-value is challenging during the early stages of operations. A potential alternative is to obtain a realistic estimate of the b-value from (a priori) available regional seismicity data.A real-time monitoring of the seismogenic index is feasible.

We use here the 1962--1968 induced Denver earthquakes (Healy et al., 1968) as an example of the application of the concept of the worst-case probability of earthquake triggering (see Figure 1). Approximately 6.3*105 m3 of wastewater injected down a single 3671-m-deep well that was drilled into the fractured Precambrian crystalline basement below the Rocky Mountain Arsenal. The fluid injection began in March 1962. It was terminated in February 1966 due to the induced seismicity. We estimate the seismogenic index for the Denver site. A sudden increase in the seismogenic index (the yellow curve, SI) to -0.7 can be observed. We compute the probability of a hypothetical Mw5.5 event (red curve, W). Our computations show that the probability of such a large event was already non-vanishing (≈ 5%) before the beginning of the second phase of pressure-driven injections. Significant earthquakes (Mw4.6-4.7) had already begun to occur in early 1965. The largest earthquake (Mw5.3) occurred on 9 August 1967. A worst-case-M max probability monitoring would allow predicting a high probability of such a strong event.

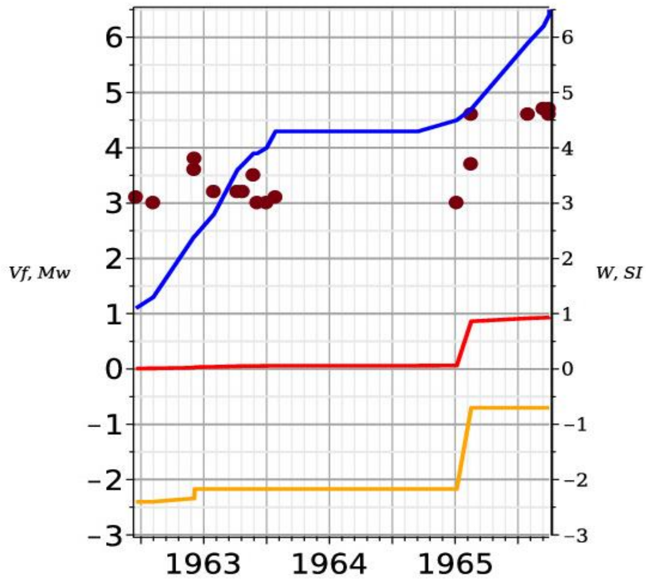

Figure 1: Mw ≥ 3 earthquakes (red dots are earthquakes magnitudes) at the Denver Rocky Mountain Arsenal wastewater injection site. The earthquakes and injected volumes are after Healy et al., 1968). The injected fluid volume (Vf) over time is given by the blue line in 105m3. Exceedance probability of Mw > 5.5 events at the Denver Rocky Mountain Arsenal wastewater injection site (W) is given by the red line as a function of time. The seismogenic index (SI) is given by the yellow line.

This approach to the seismicity in the Groningen gas field has shown the following (Boitz, 2024). Due to a long production history, the theoretical worst-case probability of triggering an Mw 5.5 earthquake in a seismotectonic continuum is significantly higher in Groningen than in Pohang (South Korea), where a Mw 5.5 earthquake was actually triggered. However, due to the fact that the Groningen seismogenic domain is geologically restricted to sedimentary layers, the Groningen gas field is inherently stable and triggering of large tectonic earthquakes is probably very unlikely there. For example, due to the long production history, earthquakes with Mw ≥ 4 must have occurred there several times. However, such earthquakes have never been observed in the Groningen gas field. Our approach therefore indicates that the physical conditions for triggering large tectonic earthquakes on faults that extend into the basement do not exist. Seismicity in Groningen can be characterized as exclusively induced. This is also evident from the frequency-magnitude distribution of Groningen seismicity, which follows the lower-bound statistic (Fig. 2).

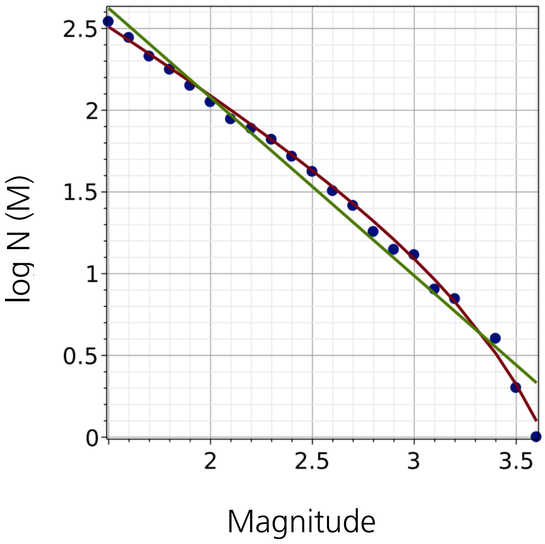

Figure 2: Frequency-magnitude distribution of seismicity in the Groningen gas field. The observations are represented by blue dots. An approximation by the GR statistic is made by the green straight line. The red line corresponds to the lower-bound statistic (Boitz, et al., 2024) with the Gutenberg-Richter parameters a =3.7, b =0.76 and the maximum induced magnitude equal to Mw4.0.

Conclusions: The Seismogenic Index (SI) was originally introduced to characterize the intensity of fluid-induced seismicity. This quantity can be used to predict the induced seismic hazard of planned underground fluid operations. Recently, the SI model has been generalized to include arbitrary physical processes affecting the Failure Coulomb Stress. In combination with the concept of the worst-case probability of a critically-large triggered earthquake, real-time monitoring of the SI provides an effective control tool for forecasting the induced seismic hazard.

References

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