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LETTER TO THE GUEST EDITORS

Recommendation for the discrimination of human-related and natural seismicity

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Abstract Various techniques are utilized by the seismological community, extractive industries, energy and geoengineering companies to identify earthquake nucleation processes in close proximity to engineering operation points. These operations may comprise fluid extraction or injections, artificial water reservoir impoundments, open pit and deep mining, deep geothermal power generations or carbon sequestration. In this letter to the editor, we outline several lines of investigation that we suggest to follow to address the discrimination problem between natural seismicity and seismic events induced or triggered by geoengineering activities. These suggestions have been developed by a group of experts during several meetings and workshops, and we feel that their publication as a summary report is helpful for the geoscientific community. Specific investigation procedures and discrimination approaches, on which our recommendations are based, are also published in this Special Issue (SI) of *Journal of Seismology.*

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1 Introduction

A discrimination problem may arise if an earthquake or a sequence of events is felt by the population or instrumentally recorded. It is independent of the size of the earthquake. It also requires that the earthquake occur in a reasonable spatial distance to a rock or soil volume that has been affected by human operations in the present or in the past. The human operations may have stopped long time before the event occurred. Location uncertainties must be considered. The distance under consideration depends on the type of operation and the size of the earthquake. For instance, the stress perturbation beneath the surface loaded over a circle of radius a is still 10% of the magnitude of the "source stress" at a depth of $z \approx 3.7a$ (e.g., Davis and Selvadurai 1996). Considering the fact that source stresses from geoengineering activities may often reach several megapascals, and that Coulomb stress perturbations required to trigger earthquakes may be as small as 0.1 MPa, the reasonable distance of the earthquakes may easily reach three or five times the dimension of the structure (hydrofracture, gas-filled reservoir, cavity) directly affected by the operations.

The induced or triggered events may comprise earthquakes of different type and character, e.g., single or few significant earthquakes (e.g., Ottemöller et al. 2005; Pechmann et al. 2008; Cesca et al. 2011), swarms of weak, shallow earthquakes concentrated in space and time (e.g., Häring et al. 2008; Cuenot et al. 2008), slow slip events (slow earthquakes) with emergent ground motions (e.g., Nachterstädt, 18. July 2009; Korn 2010, personal communication), diffuse pattern of earthquakes occurring over a longer period (e.g., Pandey and Chadha 2003), occurrence of earthquakes over a longer period associated with known fault structures (Dost and Haak 2007), or significant changes in the pattern and behaviour of seismicity (e.g., Richardson and Jordan 2002; Fritschen 2010; Bischoff et al. 2010; Becker et al. 2010).

We not only aim to distinguish human-related and natural earthquakes, but also to discriminate between triggered and induced earthquakes (e.g., Dahm et al. 2010):

- Triggered earthquakes occur on favourable oriented faults in agreement with the existing regional or local background stress field and geological structure. Their magnitude is not controlled by human-induced stress changes, which only cause the event nucleation. However, the human-induced stress changes have the potential to advance failure on an active fault that is prone to natural failure in the future.
- Induced events are entirely controlled by stress changes caused by human operations and would have not occurred without them. Their whole failure process, and not only their nucleation, is driven by the human-induced stress.

The physical reasoning of this definition is to consider the size of the rupture, or magnitude of the event, when discussing a possible human involvement. Additionally, the distinction between triggered and induced event may have economic consequences for the compensation of claims.

2 Investigation procedures

The investigation procedures to be designed in the future are not intended to be a sequential "cookbook" for an investigation of triggered and induced seismicity. Instead, these guidelines are supposed to be a listing and brief discussion of methods and procedures professionals have at their disposal to carry out such an investigation. The methods have to be tested and calibrated on real data. The availability of calibration data is therefore crucial. Furthermore, the guidelines aim to standardize investigations to discriminate natural and triggered/induced seismicity.

Expert knowledge is important to analyse and evaluate a discrimination case. It is important that all experts (e.g., consultants) should perform thorough and unbiased scientific sound evaluations. Appropriate decisions are site- and operation-specific and based on available resources (time, money, existence of historic earthquake catalogs or former studies). The professional investigator has the final responsibility for determining specific procedures and amount of data necessary to complete the investigation in accordance with the current state of knowledge. Modifications of these methods or procedures, reflecting appropriate professional judgement, should be documented and justified. Professional consultants should be expected to provide evidence of training and experience in analysing natural and induced seismicity.

3 Data gathering

The following data are of relevance to design and execute a discrimination study:

(1) Background data

- Instrumental and historical (regional) background seismicity including its statistical properties before, during, and after the engineering activities (maximum magnitude, magnitude of completeness, *b* value, etc.); see recommendations of the FKPE monitoring group (http://www.gpi.kit.edu/downloads/fkpe_ueberw_ind_seis.pdf) for an adequate monitoring programme
- Regional stress field and tectonic-induced stress model
- Characterisation of pre-existing crustal faults
- Depth of basement (e.g., Klose and Seeber 2007) and sediment-related stress-rate model

(2) Site inspection, specific site geology and tectonics

- Characterisation of local geology and layering, including strong rigidity contrasts and decoupling layers (e.g., salt)
- Description of local material inhomogeneities
- Poroelastic parameters

(3) Seismological source parameters of the specific event(s) under study

- Epicentre and depth location including uncertainties
- Source mechanism (focal solution, moment tensor)
- Source time duration, source radius (size of rupture) and derived parameters (e.g., Kwiatek et al. 2011)
- Spatial–temporal pattern of seismicity (if appropriate)

(4) Compilation of engineering parameters of the human-related actions, e.g.:

- Location, start, and duration of operations (including blasts and explosions)
- Induced pore pressure and stress changes
- Volume and rate of injected or withdrawn fluids/excavated rock volume
- Water level and mass of water pounded in a lake
- Engineering structures as support pillars, tunnels, etc.
- Mining operation pattern as, e.g., long-wall mining, grid mining

4 Discrimination approach

Three different discrimination models are suggested. All three models are trying to define the probability that an event is human-made or natural. Combining the results of the different models, e.g., by using a Bayesian Logic Tree, is not discussed. Further models may be added in the future, e.g., for other case studies and after calibration on real data.

4.1 Physics-based probabilistic model

This model, although often difficult to apply because it requires a detailed knowledge of geometry and rock parameters of the area, has the advantage of investigating the physical causes (i.e., stress changes) that led to the triggered or induced events. The approach is based on a Coulomb failure criterion, a rate-and-state seismicity model (e.g., Dieterich 1994), and a comparison with the natural background seismicity or background tectonic stress rate. The model is suited to test both the occurrence of a single event (e.g., Passarelli et al. 2012) as well as an observed event rate change. In the case of a single event, its hypocenter is tested for the classification of a triggered event, while a spatially integrated distribution is used to test the induced case. In case a change in the activity rate is observed, this change can be compared with model predicted rate changes due to static stress changes as well as changes in the stressing rate. This can be used to quantify the probability of an event rate change caused by the induced stress changes. The method has several assumptions and steps and a detailed description can be found in literature (e.g., Passarelli et al. 2012). The general idea of the probabilistic approach is simple. The constant tectonic loading of the study area causes a background seismicity rate. This natural seismicity rate may either be estimated from earthquake catalogs or derived from assumptions on the tectonic loading (Dieterich 1994; Klose 2011; Passarelli et al. 2012). The time- and space-dependent Coulomb stress perturbation induced by the human operation has to be estimated (see, e.g., code Aster, http://www.code-aster.org). With help of the seismicity model (e.g., Dieterich

1994), the human-related seismicity can be simulated. The Bayesian discriminator then simply tests whether the probability of the occurrence of an event at the location and time observed is higher for the natural (tectonic) or for the human-related case (e.g., Passarelli et al. 2012). Then, a probability of being "triggered" by the human operation can be given. If the induced case shall be tested, the probability density function (pdf) has to be integrated over the complete area of the rupture plane.

4.2 Statistics-based seismicity model

In contrast to the physics-based model, the statistical model is based on empirical relations of natural seismicity. It requires an ensemble of earthquakes to detect changes in the statistical parameters of the seismicity (e.g., Hainzl and Ogata 2005), which may be correlated with human operations subsequently. By neglecting physical constraints, this statistical approach requires less input data and uses only earthquake catalogs. However, it does not provide information on the cause of the observed parameter changes. It is based on two well-known properties of natural seismicity, namely a constant background activity rate and the behaviour of aftershock sequences according to the Omori–Utsu law (Utsu et al. 1995). Their combination leads to the epidemic-type aftershock sequences (ETAS) model (Ogata 1988, 1998), which has become the standard model for describing short and intermediate time seismicity patterns (Zhuang et al. 2011). The application of this model consists of two steps. First, the model parameters are estimated with their uncertainties based on maximum likelihood estimates to precursory seismicity in the region under consideration. If the catalog is too sparse, generic parameters can be employed. In the second step, the probability is calculated that the observed number of events in the specific space-time window under consideration can be explained by the ETAS-type natural activity. This is given by the exceedance probability of a Poisson distribution with the mean value given by the expectation of the ETAS model. The final conclusion should be drawn under appropriate consideration of the uncertainties of the ETAS parameter estimations. Software for ETAS parameter estimation and forward simulations is available, e.g., at http://bemlar.ism.ac.jp/www2/SASeisUpCollection/SASeis2006/.

A similar approach for a statistics based model is suited for borehole fluid injections: the time-dependent *a* value of the Gutenberg–Richter relation is divided into a constant background activity and a time-dependent component associated with engineering parameters as the injected flow rate or mass rate (Shapiro et al. 2010). If the assumed relations are calibrated for a specific site and if the time-dependent *a* value (seismogenic index) and the constant *b* value can be estimated from the observed seismicity, the occurrence probability of future induced events can be calculated. The method implicitly utilizes the fact that human activities induce rates of stress change, which exceed the natural stress changes. Seismicity induced by human activity thus tends to correlate well with changes in the geoengineering parameters like rate of volume extraction in a mine or well head pressure applied in a fracturing experiment.

4.3 Source parameter approach for collapse-type events

Induced seismicity may, in certain cases, show specific rupture processes, which are not observed for the case of natural seismicity. In particular, collapses, pillar bursts and blasts following mining or other anthropogenic operations can be modelled by means of isotropic and non double couple (non-DC) source models. On the contrary, the isotropic term is negligible for the case of natural (tectonic) "shear-crack" events, as well as for induced or triggered events occurring as shear crack along preferential surfaces or pre-existing faults. The assessment of non-DC and isotropic components may be used to assess the induced origin of an earthquake (e.g., Ford et al. 2008; Cesca et al. 2012).

The following recommendations are provided:

(1) Whereas a high isotropic and non-DC component may indicate the induced origin (collapse, pillar burst, explosion), a low percentage should never be used to discriminate human-related or natural tectonic shear-cracks.

(2) The interpretation of the full moment tensor for moderate magnitudes and local distances is difficult, if spurious source components arise as consequence of poor data quality, wave propagation mismodelling (e.g., caused by the use of a simplified velocity model) or specific network configuration. An extensive testing of the inversion approach with known and/or synthetic datasets should therefore be performed to evaluate the robustness of the inversion and discrimination approach.

(3) Given the limitations discussed in (2), a probabilistic approach should be followed. In case of candidate earthquakes to be identified as induced events, the probability can be based on the uncertainties of the source parameters (isotropic and non-DC source terms). Uncertainties can be estimated, for example, by perturbing the dataset (e.g., station configurations) or the adopted velocity model (e.g., Heimann 2011). Source parameter uncertainties are needed to derive a pdf to be used within a Bayesian approach to infer the likelihood of a given scenario (e.g., Cesca et al. 2012).

(4) Additional source parameters can be used to support discrimination findings. For example, shallow hypocenters, slow rupture and lack or reduced number of aftershocks may support the discrimination of induced events.

5 Final report and data retention

The final report should include all of the documentation described above, plus:

- A simple explanation of the consultant's professional opinion as to the cause of the events
- If no cause can be identified, the investigator should recommend additional testing, probing and/or monitoring to determining the cause
- A probability of the event to be triggered or to be induced with a clear reference to the model and data used on which the probability estimate is based, considering all knowledge on human operations and background seismicity at the local site
- Uncertainties of the input parameter to the model, including epicentre, depth locations, strength of the earthquake (moment), rupture type and, if possible, the source and rupture mechanism of the event

We further recommend that the final report and all raw and un-interpreted data should be passed to and retained by a national facility for induced and triggered seismicity. A public database should be maintained and made available to all interested parties or be available by the public.

6 Conclusion

All three lines of investigations suggested here (a, physics-based; b, statistical; c, source mechanisms) require availability of data and parameters (specified in Section 4). Although the probabilistic methods are not standard and there is relatively little experience applying them yet, we believe that they are in principle viable and should be further explored and applied, and that their formulation should be kept in mind when designing a monitoring network or collection of geological/geophysical data. The methods also contribute to distinguish human-triggered and human-induced events, although at different levels. While method (a) directly applies different fault sizes when integrating pdf, methods (b) and (c) investigate whether the rupture and event statistics deviate from the tectonic situation, which is only expected for human-induced events. We recommend a wider application of probabilistic methods in general to discriminate human-related from natural seismicity and to combine the different results in terms of Bayesian methods, such that more case studies will become available.

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