GtV
Bundesverband
Geothermie

Induced Seismicity
Position of the German Geothermal Association GtV-BV[1]

1. Background

Experience in recent years has shown that geothermal installations may cause induced seismicity. In no single case were those events hazardous for building construction, traffic, infrastructure or people. However they proved to be the major reason why geothermal energy use lost much of its popular acceptance. As a consequence, the geothermal community has to deal seriously with those problems. Public discussion as well as further research is needed. Protocols have to be developed to control the seismologic consequences of underground installations and the management of geothermal plants. As authorities are aware of those problems, acceptance questions related to seismicity may cause delay or other problems in developing or managing geothermal plants.

In contrast to natural earthquakes, induced seismicity is not unpredictable and can in principle be controlled. After years of research, we now know much more than we did. However, further research is needed.

This paper is addressed to:

- Politicians
- Authorities
- Investors
- Project developers
- Media

It is a position paper of the GtV-Bundesverband Geothermie (German Geothermal Association) and generally reflects the opinion of leading international experts in the field of injection-induced seismicity. The Association was advised by a team of international experts on the formulation.

[1] GtV-Geothermische Vereinigung e.V. is fully responsible for the content of this 'position paper'. The GtV-BV was counselled in this issue by a group of leading international experts. The final paper is not necessarily in agreement with all experts, as experts' opinions diverged on certain points. The expert group consisted of the following members: Baisch (Germany), Baumgärtner (Germany), Bohnhoff (Germany), Bönnemann (Germany), Majer (USA), Wenzel (Germany), Gottlieb (Germany), Heidbach (Germany), Hinzen (Germany), Ritter (Germany), Joswig (Germany), Wassermann (Germany), Young (Canada), Heatherly (Australia), Fritschen (Germany), Jung (Germany), Gritto (USA), Baria (UK), Schulz (Germany), Shapiro (Germany), Rüter (Germany)

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Due to the partially different opinions of the experts, however, the position paper cannot embrace all of the opinions voiced by the experts. Neither is it a scientific publication, so it deliberately does without illustrations, formulae and references.

2. Natural Seismicity

Natural seismicity is part of our natural environment. It is a consequence of continental drift and plate tectonics. However, only the few strong hazardous quakes attract worldwide public attention and these are the reason for a widespread fear. Microseismicity, on the other hand, is an everyday phenomenon but hardly known to the public. About 1000 events with a magnitude between 2 and 3, and about 150 with a magnitude of 3 to 4, are registered daily. The event sources are not equally distributed over the earth but concentrated in tectonically active areas, mostly along plate boundaries.

The prevalence of earthquake activity in a certain area is described as the 'seismicity' of that area. The description is statistical in nature and may include the following elements:

- Local geological and tectonic situation
- Stress field
- Bulletins / catalogues of events from pre-instrumental times
- Bulletins of registered events
- Event localisations
- Statistics, such as Gutenberg-Richter relations
- Focal plane solutions
- Damage reports and macroseismic studies
- Intensity maps

Natural seismicity can be regarded as a natural frame for the induced seismicity. Induced events are by nature generally (statistically) smaller. It has never been reported that an induced event was larger in magnitude than the largest natural events in the area under examination.

For aseismic areas, i.e. areas without natural seismicity, this 'frame' does not exist and thus cannot be used as one of the arguments to estimate the largest possible magnitude of induced events and their likelihood. These areas are nevertheless a priori less at risk.

3. Induced seismicity

Obviously all major activities underground affect the in situ stress field and thus have the potential to generate seismic events. Induced seismicity has been reported from:

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- Water reservoirs
- Mining
- Traffic tunnels
- Excavations
- Oil/gas production
- Underground storage (gas, pressured air)
- Fluid injections
- Mineral water extraction
- Hydraulic fracturing in oil and gas reservoirs

Induced seismicity in the context of geothermal installation has the same origin as with other types of fluid injection. The main mechanism is that the additional fluid pressure reduces the normal pressure and thus the frictional force between the two opposite sides of faults or fractures and may enable sudden movement along those faults.

During operation of geothermal systems, thermo-mechanical effects may become important as well. They may also reduce the frictional forces but most likely only on smaller areas.

Seismicity related to geothermal installations has been reported worldwide. However, nowhere has a hazardous quake (quakes damaging construction, infrastructure and/or harming people) been induced that caused major damage or risk to life. Smaller damages, as in Basel or Landau, have been settled by ex-gratia-payment without closer investigation of their origin, or an amicable claims settlement is pending.

It is essential for public acceptance to know if a larger (natural) event can be triggered either by fluid injection or by a small induced event. We talk about a triggered event if the activated fault plane is much larger and at least partly outside the underground volume influenced by the geothermal installation. For Basel, such triggered events were excluded by the experts. Worldwide, no case of triggering by geothermal projects is known but this does not mean that it is totally impossible.

Small induced events may be used for characterization of the reservoir and to explore the reservoir surrounding and development. This method is usually called 'Passive Seismics' and is an important and useful method in geothermic reservoir management.

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4. Legal Background

In Germany the use of geothermal energy from deeper holes is regulated by the Mining Act. This stipulates that:

- care must be taken to protect the surface in the interest of personal security and public traffic
- a general destructive impact must not be foreseeable.

Generally this means that smaller damages may be acceptable but have to be compensated. This basic principle of mining law follows from the long-standing necessity to secure resources. Nowadays this also extends to the public interest in using geothermal energy as a renewable energy source.

5. Estimate of maximum magnitude and return period

The estimation of the maximum possible magnitude in a certain area is a major requirement for any seismological expert accompanying a geothermal project. A first estimate is given by the evaluation of the natural seismicity in that area as this gives a frame for possible induced events. As a project progresses, serious estimates become more and more possible. The first drill hole will give insight into the local stress field. Recordings from a seismological net during drilling and stimulation will allow the use of statistical methods.

In general we have different approaches to estimate the maximum possible event and the return periods:

- The deterministic approach
- The probability (statistical) approach
- The empirical approach
- Controlled operational (step by step) approach

The first three of these approaches are described shortly in the annex. In the following the controlled operational (step by step) approach will be presented.

Relationships between injection parameters and seismicity can be evaluated not only by theory in advance but also during operations.

It is obvious that even with a good knowledge of the local and regional tectonic and geological site conditions the other approaches will only allow a rough estimate to be made of the maximum magnitude and the associated seismic risk. To avoid larger events we therefore need another method, which can be called a “controlled operational approach” or “step by step” approach. According to this approach all operations relevant for induced seismicity have to be designed in a way that the risk of inducing seismic events increases only slowly and the events remain (statistically) below the perceptibility level.

All relevant steps, like drilling, stimulation, hydraulic testing and production have to be accompanied by seismic monitoring and control. Continuous evaluation of the statistics and spatial distribution of the recorded events should accompany these measurements; deterministic calculations may also be embedded. This means that the controlled operational approach is finally an intelligent, careful and practical combination of all available approaches. Incoming additional information can be easily included. Part of the controlled (step-by-step) operational approach may be:

- Monitoring and reaction plan
- Monitoring drilling activities
- Monitoring stimulations
- Monitoring production

5.1. Monitoring and reaction plan

Essential to the controlled operational approach is the monitoring of the induced seismicity. This is done by running real time seismic nets. Generally two nets are needed which can be combined technically to a single net with some stations meeting the needs of the seismological net and others those of the emission net.

Essential for a seismological net are a good coverage for locating events and a low trigger threshold to register large numbers of small events. Thus a sufficient data base for statistical evaluations can be provided. Some of the stations may be planted in boreholes. There are no binding regulations here.

Emission nets have to comply with national standards regarding instrumentation, planting and interpretation. In Germany under the DIN regulations it is essential to record peak ground velocities (PGVs).

These nets should preferably be managed by public institutions or private companies contracted by public institutions. This is especially advantageous if nets from neighbouring installations overlap. In addition, it increases public acceptance.

A (published) reaction plan should be laid down that is based on the online PGV recordings and defines different responses depending on the recorded PGVs. This makes sure that statistically the PGV will not exceed a certain value throughout the activities.

The monitoring concept and the reaction plan should be developed in agreement with all parties, including the mining authorities.

5.2. Drilling

Until now no induced seismicity has been observed during drilling activities. It is, however, recommended that the step-by-step approach and monitoring starts before the first drilling starts to get a satisfactory seismological database as early as possible.

5.3. Hydraulic stimulation

Hydraulic stimulation is usually the operation with the highest risk of induced seismicity in the chain of activities during installation and production of a geothermal plant. Stimulations inherently will always be accompanied by seismic events. There must be a plan starting with low pressure, low rates and low volumes of injection fluid and limited injection time or volume and a systematic increase of those parameters until the stimulation result is gained. A detailed and published reaction plan defines all measures to be taken if PGV values exceed predefined values. This gives a high probability that tangible or even damaging events can be avoided.

5.4. Production

After production has reached steady state conditions, extracted and injected fluid volumes are in balance, injection pressure is constant or decreasing and below the critical pressure for the onset of shearing. The danger of further induction of seismic events is much smaller than in the case of injection only without recovery (waste fluids, supercritical CO_2). Monitoring can be done with smaller nets than during stimulation.

Special care has to be taken when production is interrupted or restarted or production parameters are changed. In general, changes may cause increased seismic reactions.

6. Experts' statements and experts' guidance

Experts' statements are possible in every phase of a geothermal project. The content and value of those statements will depend strongly on the available database. Statements can be updated when the database grows. This means that an expert has to accompany or guide the project continuously. This is part of the controlled operational (step-by-step) approach

7. Research

Further research is needed and highly recommended. In particular, knowledge of the relationship between operational parameters and seismicity has to be expanded. Methods of modelling the complex underground situation including fluid-rock interaction are extremely important. Modelling the static (structural) situation and dynamic fluid flow has to be completed by finding codes to simulate the kinematics of internal rock-volume-movement and related inertia forces.

8. Conclusions

Geothermal installations have until now never caused hazardous earthquakes causing structural damage or putting human life at risk. Particularly in Germany, only minor damages have been reported and have until now not even been proven in court.

Geothermal projects are performed under the Mining Act. This states that care must be taken that no personal harm occurs and that traffic or general infrastructure is not damaged and no damage to public goods is done. Smaller damages on buildings have to be compensated if they occur.

Nevertheless induced seismicity that has been experienced in a few isolated cases is a serious acceptance problem. The natural fear of ‘earthquakes’ is deeply rooted; they are regarded as (and are) unpredictable and not manageable.

In contrast, geothermal installations can be produced and run in a way that makes even small noticeable seismic events unlikely. The entire process (installation and production) can be controlled. The controlled operational approach (step-by-step) is recommended, including seismological monitoring.

Experts may find that at some locations the seismic risk is unacceptable because of very special geological conditions. No geothermal project should be established in those (rare) areas. Those special areas could be areas of superficial and uncompacted alluvial deposits or areas with an extensive natural historical seismicity with catastrophic results

9. Recommendations and measures

Based on the preceding explanation the GtV-BV deems the following points as necessary:

To avoid larger seismic events, the "controlled operational method" or "step by step" approach should be adopted in geothermal projects. According to this approach all operations relevant for induced seismicity have to be designed in a way that the risk of inducing seismic events increases only slowly and the events remain (statistically) below the perceptibility level.

Essential for that is a continuous monitoring using seismic real time nets. Both a seismological net with a low trigger threshold and an emission net are needed. It is essential to record peak ground velocities (PGVs)[2]. These nets should be managed by public institutions or private companies contracted by public institutions; the results have to be accessible to the public.

Based on the measured data a reaction plan must be drawn up, that should also be made public.

The monitoring concept and the reaction plan should be developed in agreement with all parties, including the mining authorities.

Monitoring must cover all phases:

- Drilling (even though no induced events have yet been recorded during geothermal deep drilling operations)
- Hydraulic stimulation: the operation with the highest risk. There must be a plan, stipulating that pressure, rates and volumes of injection fluid and injection time or volume are increased systematically until the stimulation result is gained.
- Production: the risk is extremely small during this phase, therefore the monitoring nets can be reduced. Special care, however, has to be taken when production is interrupted or production parameters are changed.

Every project should be monitored continuously by a seismological expert.

Further research is necessary, in particular to expand our knowledge on the relationship between operational parameters and seismicity. The current scientific level of risk evaluation and risk containment has to be presented as the basis for further research.

[2] In Germany the peak ground velocity (PGV) is the criterion as stated in DIN 4150. Generally speaking PGV values below 5 mm/s may not cause any damage. Severe damage on buildings can be expected above 70 mm/s. Higher frequency events are less damaging.

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The project owners are requested to prove a comprehensive and convincing insurance coverage. Any worries concerning inadequate payments in the case of damage have to be met with high insurance sums (e.g. € 50m) and precautions against the cancellation of premiums. Especially for smaller damages that cannot be ruled out (e.g. cracked plaster) a non-bureaucratic claims settlement must be ensured (e.g. by appointing an ombudsman or ex-gratia payments).

The monitoring concept and the insurance coverage have to be coordinated to guarantee both preparatory conservation of evidence and adequate alleviation of evidence in the case of damages to the citizens living in the area possibly affected by a geothermal project.

It has to be considered how the citizens' rights to participate in the administrative process of approval for a project can be extended. The existing prescriptions in the German Mining Law are sufficient for that. The recently demanded introduction of a planning approval for geothermal projects is excessive.

Communication on induced seismicity between all involved parties, in particular the citizens, project owners, scientists and the authorities, has to be improved. On the basis of the current scientific findings it has to be made clear that earthquake does not equal earthquake. Microseismic events, like the ones occurring about 50 times per month in the context of the research project in Soultz-sous-Forêts (France), cannot be equated with damaging earthquakes harming people's health or substantially affecting their property.

GtV-BV will further develop its active public relations work, in particular with a new online platform (www.geothermie-dialog.de) and by organising events on location. Information must be given, appropriately based on a broad range of knowledge and opinions, so that it cannot be accused of simply glossing things over.

All concerned parties and individuals are invited to discuss with the GtV-BV the preceding recommendations and the positions on the issue of induced seismicity that have been put forward in this paper.

Berlin, 7 July 2010

Annex

1. Definitions

1.1 Magnitudes

Magnitudes describe the strength or energy of an earthquake or a smaller seismic event based on measured ground motion amplitudes. It is a logarithmic scale and thus a seismic event with magnitude 4 releases about 30 times more energy then an event with magnitude 3. Local events are described by the local magnitude ML introduced by Richter. Recently this is more and more replaced by the Moment magnitude MW which is a more physical measure to describe the earthquake source. Moment magnitudes differ slightly from local magnitudes and are usually up to 0.5 higher, depending on the local geology.

1.2 Intensity

Intensities are a scale to describe the human perception and damage caused by an earthquake. Observation and description of the damages to buildings (and landscape) define the intensity value. Intensities are important for quakes from pre-instrumental time, when magnitudes are not available. There is no simple relation between intensities and magnitudes; however relations may be evaluated for certain areas and groups (clusters) of events. There are better correlations between peak ground velocities (PGV) which are measures of the ground motion.

1.3 Damage criteria

Damage criteria are a topic for national legislation and standardisation. In Germany the peak ground velocity (PGV) is the criterion as stated in DIN 4150[3].Generally speaking PGV values below 5 mm/s may not cause any damage. Severe damage to buildings can be expected above 70 mm/s. The DIN 4150 additionally takes into account that higher frequency events are less damaging. The dominant frequencies of fluid-injection-generated large induced events are around 50- 90 Hz, which makes it virtually impossible to cause structural damage.

Sometimes induced seismic events are accompanied by a thunderlike sound. This is due to the high frequencies of the ground motion, and indicates that this event is less dangerous for constructions than a silent event of the same magnitude.

Using empirical relationships, PGV maps can be constructed for an assumed earthquake at a certain location. A precondition is a good mechanical model of the underground especially of the uppermost layers and their attenuation or amplification of seismic waves. These calculations

[3] DIN 4150, Februar 1999. Erschütterungen im Bauwesen - Teil 3: Einwirkungen auf bauliche Anlage

can only give a first impression of the expected impact of an earthquake and need to be validated or calibrated by PGV measurements. Direct measurement of PGV values overcomes also problems reported with the calculation of local magnitudes for events smaller than 4 and which are also present if magnitudes are replaced by seismic moments. Direct measurements of the PGV values are in any case the better choice as damage criterion.

For the international community it would be advantageous to have international standards for damage criteria or at least some harmonisation.

Peak ground acceleration (PGA), as used in seismology for large events, is not adequate for high frequency small induced events and not in agreement with German standards.

2. Description of approaches

2.1 The deterministic approach

The deterministic approach tries to model or simulate possible seismic events in a computer. As with all simulations a suitable model of the relevant parameters (geometry, petrophysics and stress) of the underground and an adequate code (software) to generate fractures in this model are needed. For any given location it will be difficult to establish a suitable static (structural) model of the underground. Even the result of the 3D-seismic exploration, which is necessary in any case, may not give enough detail. Generally, petrophysical parameters and information about the stress field are also hard to get. Key information is the size and orientation of fractures related to the components of the stress field.

The available code for simulation of quakes is also limited. All calculations need validation and calibration by measurements and can not be used in cases where those measurement do not (yet) exist. If the influence of the measured event on calibration and validation of the results is dominant, the method may lose its deterministic character.

In our opinion the deterministic approach is not yet suitable to predict maximum magnitude or return rates but is very helpful for sensitivity analysis and to find out which parameters influence magnitudes and rates. Further research is needed.

For larger events, especially to answer the question of whether triggered events are possible in a given area, the deterministic approach is the only possibility. Also here further research is necessary.

2.2 The probabilistic (statistical) approach

The probabilistic approach is based on a statistical evaluation of registered events without looking at the geological situation and without using any physics or rock mechanics. Central is usually the Gutenberg-Richter relation showing the occurrence frequency of events as a function of their magnitudes, but other statistical methods have recently become available. The probabilistic approach needs a sufficient data base and thus a longer monitoring time with a low enough threshold to record large numbers of small magnitude events. It is necessary to ensure that the data base contains only events from the same cluster as those expected from future induced events.

2.3 The empirical approach

Some researches try to show a relationship between certain reservoir parameters and the maximum magnitude. The parameter used mainly is the size of the reservoir. Some authors use a linear dimension i.e. the diameter of the reservoir, others an area or the reservoir volume. In any case a (linear) relationship is stated based on a sparse data base.

A physical background to those relations is not evaluated. Only a general statement can be made that a big earthquake needs 'room' to develop a sufficient fracture area with an adequate seismic moment.

The definition of the reservoir size may be difficult. In HDR projects it may be defined by the seismic event locations. In 'open' hydrothermal reservoirs it may be defined by the volume of fluid flow or by the volume of additional pressure. These may only be estimated roughly.

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