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# A simple model for probabilistic seismic hazard analysis of induced seismicity associated with deep geothermal systems

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**Abstract**

In the research project MAGS (Microseismic Activity of Geothermal Systems) a simple model was developed to determine seismic hazard as the annual frequency of the exceedance of ground motion of a certain size. Such estimates of the annual frequency of exceedance of prescriptive limits for the effects of vibrations on buildings and people are needed for the planning and licensing, but likewise for the development and operation of deep geothermal systems.
For the development of the proposed model well established probabilistic seismic hazard analysis methods for the estimation of the hazard for the case of natural seismicity were adapted to the case of induced seismicity. Important differences between induced and natural seismicity had to be considered. These included significantly smaller magnitudes, depths and source to site distances of the seismic events. Hence, different ground motion prediction equations (GMPE) had to be incorporated to account for the seismic amplitude attenuation with distance, as well as for differences in the stationarity of the underlying tectonic and induced processes. Appropriate GMPEs in terms of peak ground velocity (PGV) were tested and selected from the literature. In the paper we present probabilistic seismic hazard analysis (PSHA) results for ground motion which can be linked to engineering regulations (e.g. German DIN 4150). It is thus possible to specify the probability of exceedance of prescriptive standard values and to decide (e.g. by the regulator responsible for commissioning) whether the annual number of exceedances for a site at a given level is acceptable or not. Additionally, hazard curves for induced and natural seismicity are compared to study the different impact at a site. Preliminary results for the circulation period (operation phase of the plant) at a geothermal site in Bavarian Molasse, Germany - for stiff soil, ignoring site effects - indicate higher frequencies of exceedance for induced seismicity than for natural seismicity only for low PGV values.


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*Keywords:* induced seismicity; geothermal system; PSHA method; hazard curve; ground motion prediction equation (GMPE);

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## 1. Introduction

During development and operation of deep geothermal wells, fracture processes can occur at different scale (a typical example is sketched in Fig. 1). Cracks may be generated or expanded which can be detected as microseismic activity using local seismometer networks. The increase of pore pressure on existing fault planes under tectonic stresses may also cause seismic events which can be felt. Similar problems exist in other industrial processes in which the pore pressure is changed, e. g. hydraulic fracturing for shale gas development, production of natural gas and crude oil and injection of liquid waste or liquid CO2.

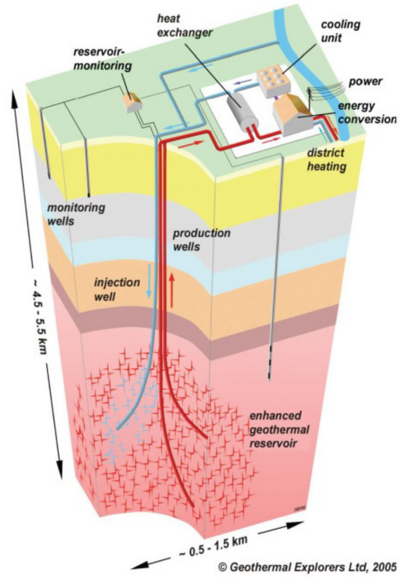


Fig. 1. Artist's sketch of a typical deep geothermal well [1]. Crack processes as sources of induced seismicity are located in a cloudlike body which geometry can be approximated by a cuboid.

In the research project MAGS (Microseismic Activity of Geothermal Systems) funded by the German Federal Ministry of Economic Affairs and Energy (BMWi) a simple model was developed to determine seismic hazard as the probability of the exceedance of ground motion of a certain size. Such estimates of the annual frequency of exceedance of prescriptive limits for the effects of vibrations on buildings and people are needed for the planning and licensing, but likewise for the development and operation of deep geothermal systems. In the paper we present probabilistic seismic hazard analysis (PSHA) results for ground motion which can be linked to engineering regulations (e.g. German DIN 4150, see [2]). It is thus possible to specify the probability of exceedance of prescriptive standard values and to decide (e.g. by the regulator responsible for commissioning) whether the annual number of exceedances for a site at a given level is acceptable or not. Additionally, hazard curves for induced and natural seismicity were compared to study the impact at a site. Preliminary results - for stiff soil, ignoring site effects - indicate higher frequencies of exceedance for induced seismicity than for natural seismicity only for low peak ground velocity (PGV) values.

## 2. Probabilistic seismic hazard assessment

In this paper, methods for the estimation of seismic hazard for natural seismicity were modified and applied to the case of induced seismicity associated with deep geothermal systems. Fig. 2 illustrates exemplarily the basic steps of probabilistic seismic hazard analysis for the case of natural seismicity for one seismic source region (area or volume source, after [3]). E(z) in Fig. 2 is the expected number of exceedances of ground motion level z, f(m) and f(r) are the probability density functions of magnitudes and source to site distances, respectively. P(Z>z|m,r) is the probability that an earthquake of magnitude m and source to site distance r will exceed ground motion level z. In the case of natural seismicity seismic source regions are determined on the basis of tectonic and geological data and on historical and instrumental seismicity data. In the case of induced seismicity the seismic source region has to be marked by seismic events in a volume surrounding the borehole (see e.g. Fig. 1). Furthermore, also more distant ranges can come into consideration as source regions. Such source regions can be e.g. tectonic faults close to the well which can be activated by drilling and injection.

$$E(z) = \lambda \int_{m_u}^{m_o} \int_{r_{\min}}^{r_{\max}} f(m) \cdot f(r) \cdot P(Z > z \mid m, r) \; dm \; dr$$

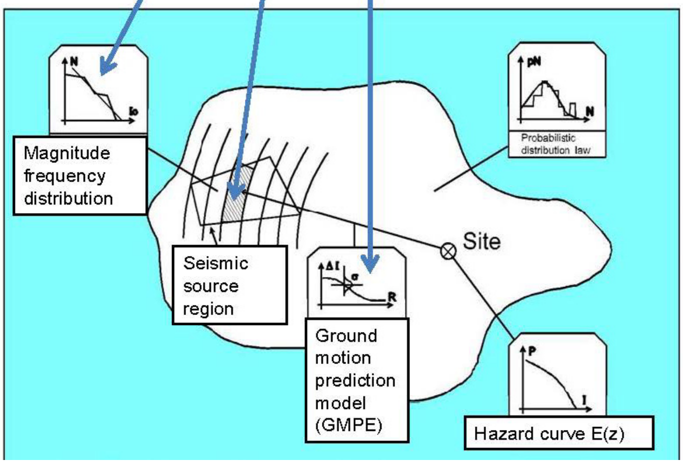


Fig. 2. Illustration of the basic steps of probabilistic seismic hazard analysis for the case of natural seismicity shown exemplarily for one seismic source region, after [3].

## 3. Source model of induced seismicity

Fig. 3 shows our model of PSHA for induced seismicity associated with deep geothermal wells. Seismic activity is dispersed homogeneously in a cuboid volume at the borehole (left in Fig. 3). Several source volumes can be incorporated. The idealization of the source model to be used as input to PSHA software EZ-FRISK [4] is given in the right part of Fig. 3.

## 4. Selection of ground motion prediction models

A ground motion prediction equation (GMPE) is a mathematical expression used to estimate ground motion parameters (commonly spectral acceleration, peak ground acceleration or peak ground velocity). A GMPE is mainly defined by three components: characterization of the source (commonly by magnitude, mechanism and depth), definition of the path (distance) and characterization of the site (commonly by site class or by the averaged shear-wave velocity of the top 30 m of soil (Vs30)).

For the derivation of ground motion prediction equations for the case of induced seismicity significant differences between induced and natural seismicity have to be considered. These include significantly smaller magnitudes, depths and source to site distances of seismic events in question. Due to these differences the application of GMPEs derived for natural earthquakes was not considered because of the large differences for the range of validity of the above mentioned parameters. Therefore the selection of GMPEs appropriate for the case of induced seismicity is a critical part in PSHA. In this paper, seven published GMPEs for small magnitudes were preselected from the literature [see 5, 6, 7, 8, 9, 10 ,11]. A comparison between PGV values obtained from the selected GMPEs and the seismic data recorded at geothermal systems nearby Basel (Fig. 4) and at the Bavarian Molasse (not shown) was performed. For the final selection of the GMPEs, a visual inspection based on the comparison of the residuals was applied. Fig. 4 shows a comparison of observed values of PGV (black dots, after [12]) and calculated values for the preselected GMPEs (colored lines, see legend to the right) for the Basel ML 3.4 earthquake, hypocentral distance in kilometers, see [13]. The median values of PGV estimated with the GMPEs of [6] and, to a lesser degree, of [10] showed good agreement compared to the recorded PGV values (Fig. 4).

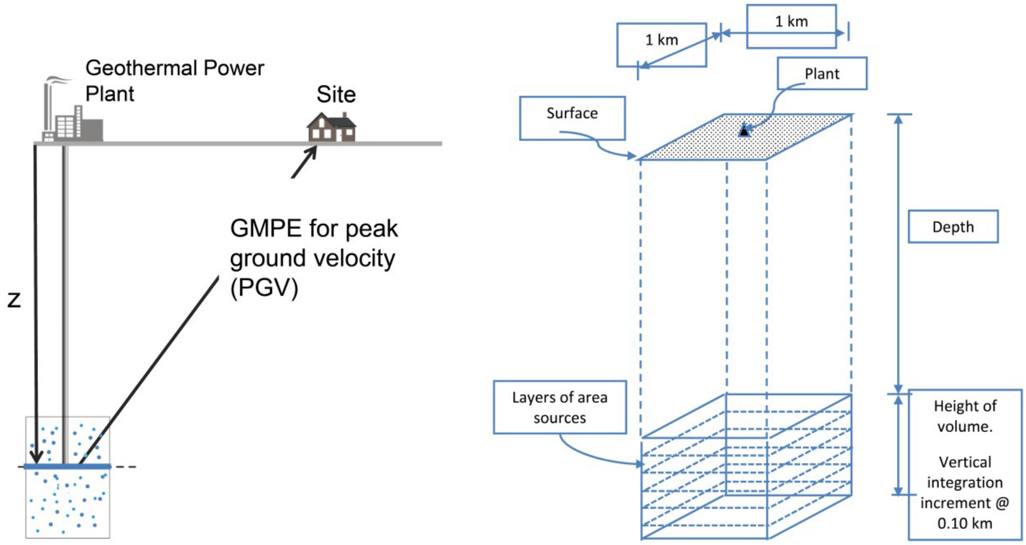


Fig. 3. Model of PSHA for induced seismicity associated with deep geothermal wells. For details see text.

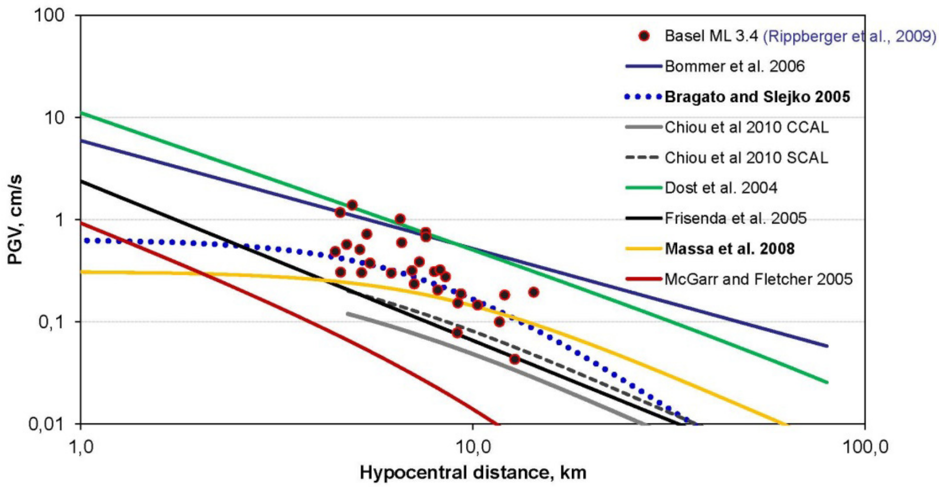


Fig. 4. Comparison of observed values of PGV (black dots, after [12]) and calculated values for the preselected GMPEs (colored lines, see legend to the right) for the Basel ML 3.4 earthquake, hypocentral distance in kilometers (for more details see [13]).

## 5. Seismic parameters of induced seismicity: example from a geothermal site in Bavarian Molasse, Germany

The induced seismic source can be characterized based on physical constraints like the volume of injection. The volume of injection as well as the hypocenter locations provided in catalogs of monitored seismicity in example cases is useful to define the limits of depth and lateral extent of the induced seismic sources. These limits are important for developing the numerical model of the seismic hazard analysis. In our example we use data from a seismic catalogue based on data of a close-in seismic monitoring network in the Bavarian Molasse (from [14]) to infer the necessary input parameters for the PSHA calculations (Figs. 5,6).

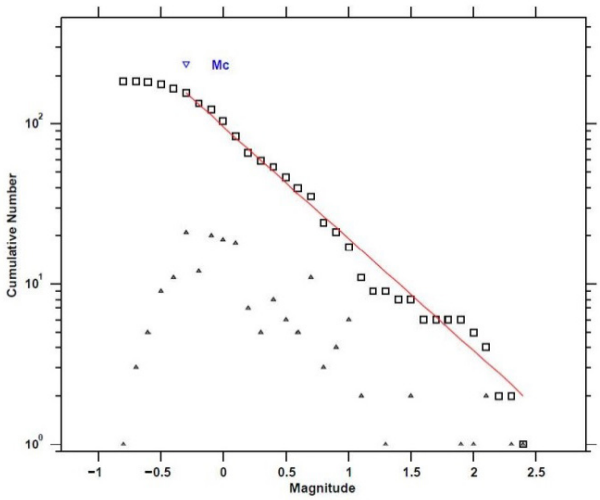


Fig.5. Magnitude-frequency relation (local magnitude) for a geothermal site in Germany (Bavarian Molasse) in cumulative and non-cumulative representation (squares and triangles, respectively). Gutenberg-Richter parameters a = 95.5 and b = 0.7 (cumulative number of earthquakes for magnitude m=0 and slope of regression line, respectively) as well as magnitude of completeness Mc were derived using the program Zmap [15]. Time period covered is 4.25 years.

| Activity at $m_{min}$ [1/a] (local magnitude) | b-value | Minimal magnitude | Maximum magnitude | Depth range [km] | Ground motion prediciton models (GMPE) | Soil class |
|---|---|---|---|---|---|---|
| $\lambda_{GB}$ = 22.4 | b=0,7 | $m_{min}$ = 0 | $m_{max}$ = 5 | 4,9 – 5,2 | • Massa et al. (2008), w=0,5<br>• Frisenda et al. (2005), w=0,5 | Stiff sediments |

Fig. 6. PSHA input parameters for analysis of induced seismicity at a geothermal site in Germany (Bavarian Molasse).

## 6. Results of probabilistic analysis for induced seismicity and comparison with natural seismicity

In the previous sections the main ingredients for PSHA – source model of induced seismicity, appropriate ground motion prediction equations, seismicity parameters (Gutenberg-Richter b-value and activity rate, etc.) – were provided as a basis for the calculation of the probability of exceedance of ground motion at a given site. Peak ground velocity (PGV) can be regarded as a particularly suitable ground motion parameter because it is linked to engineering regulations (DIN 4150, [2]) that describe the effects of vibrations in buildings on persons and on structures. Thus, the number of exceedances of assigned threshold values per year (PGV threshold for annoying effects on persons or threshold for potentially damaging effects) can be determined. On this basis the established principles stipulated in engineering regulations for the impact of vibrations can be transferred to the handling of induced seismicity. Fig. 6 shows the input parameters for the PSHA calculations for a geothermal site at the Bavarian Molasse. The depth range was adjusted according to communication with the operators of the monitoring network [16]. The calculated annual number of exceedance for this site is shown in Fig. 7 as a function of PGV. The figure shows the mean hazard curve for the two ground motion prediction equations given in Fig. 6 (in this case and for other cases studied logic tree analysis was used to take into account the uncertainty of insufficiently known input parameters). Threshold values - limiting value of perception (0.05 cm/s) and limiting value of damage to residential buildings (0.5 cm/s) - are marked by vertical lines. The resulting number of exceedances per year for the two limiting values (0.35 1/a and 0.04 1/a) are also given in Fig. 7. With the methodology presented here, a tool for the calculation of the annual number of exceedances of given threshold values for PGV is available.

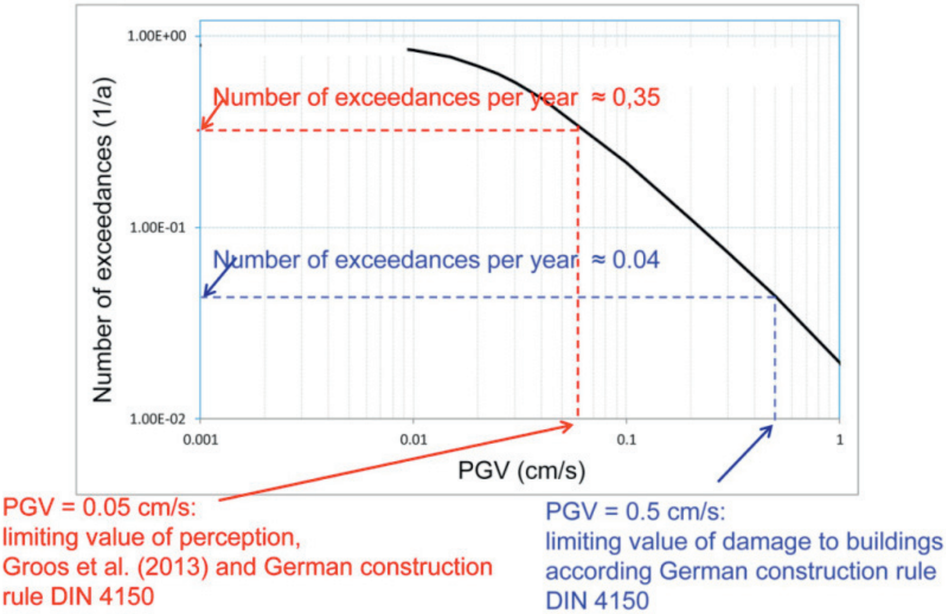


Fig. 7. Hazard curve for induced seismicity (mean annual rate of exceedance of peak ground velocity, PGV) for a geothermal site in Germany (Bavarian Molasse). Limiting values of perception and of damage to buildings according to German regulation DIN 4150 [2] are indicated by dotted vertical red and blue lines, respectively [17, 18].

It is interesting to compare the hazard curve for induced seismicity for a site with a plant in operation (Fig. 7) to the hazard curve for natural earthquakes determined for the same site. For the calculation of natural seismic hazard at the site a seismicity model of [19] was modified. The necessary seismicity data were taken from the catalogue of earthquakes in central, northern, and northwestern Europe (CENEC catalogue) [20]. For the calculations the same program [4] as for the induced seismicity was used; the ground motion prediction equation used is from [21]. The comparison of seismic hazard of natural and induced seismicity in Fig. 8 shows that the contribution of natural seismicity is prevailing and that the contribution of induced seismicity is only relevant for low PGV values; particularly at the limiting value of 0.5 cm/s hazard is dominated by natural seismicity. However it should be noted that these results are only shown to illustrate the development and present the method rather than to introduce a cogent site-specific hazard analysis.

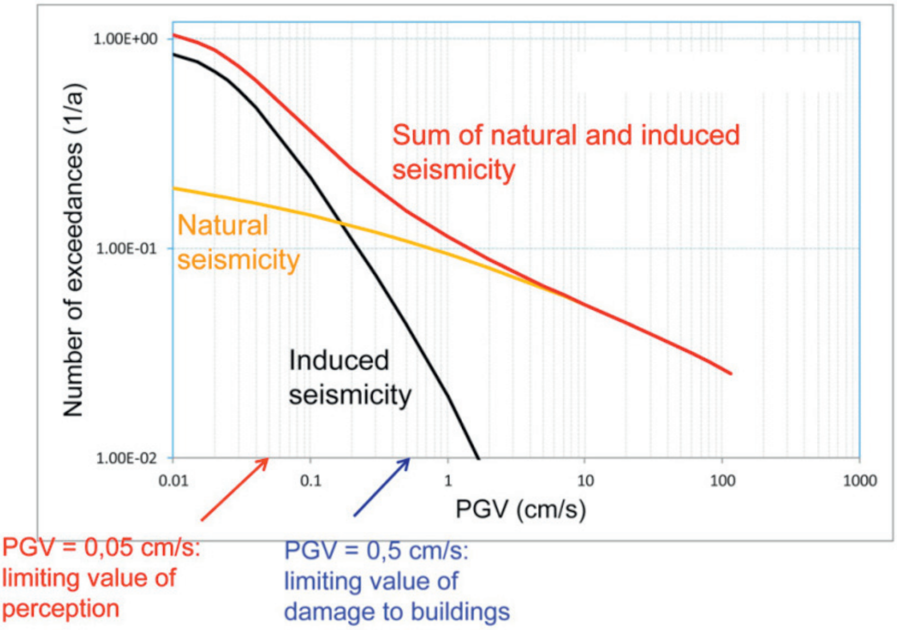


Fig. 8. Comparison of hazard curves of induced (black, from Fig. 7) and of natural seismicity (yellow) at a geothermal site in Germany (Bavarian Molasse) as well as their sum (red curve). Limiting values of perception and of damage to buildings according to German regulation DIN 4150 [2] are indicated by red and blue arrows, respectively.

## Summary and conclusion

PSHA procedures for natural seismicity were adopted to estimate seismic hazard of induced seismicity due to operation of deep geothermal wells. In the developed model seismic source volumes can be placed at the borehole (to consider micro seismicity due to crack processes) but also at greater distance to consider triggering of seismicity in tectonically loaded fault zones, if present. Limiting values of perception of seismic motion and of damage to buildings can be taken from engineering regulations [2] and their frequency of exceedance (hazard) can be calculated by PSHA. The use of such methods in the process of licensing and in public discussion is very valuable. However it should be noted that the results shown her are only preliminary for several reasons. They approximate stiff soil conditions; existing deviating conditions and site effects are currently ignored but will be taken into account using micro tremor and geotechnical measurements in a continuation of the MAGS project. The results are shown to illustrate the development and present the method rather than to introduce a cogent site-specific hazard analysis.

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