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The Implementation of Time Dependency into PSHA Associated with Induced Seismicity

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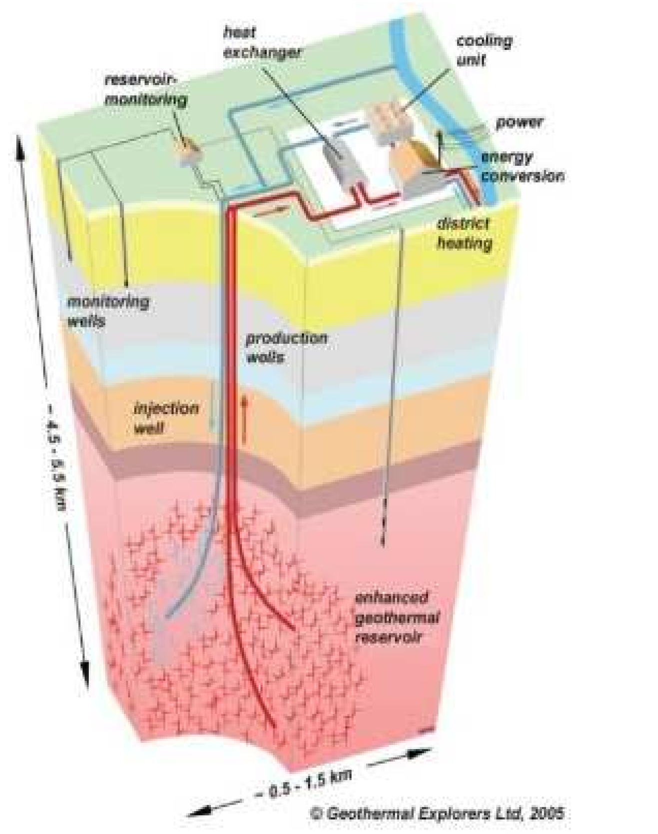

Fig. 1: Schematic representation of a typical deep geothermal well. Induced seismic activities are located in a cloudlike body whose geometry can be approximated by a cuboid.

1 Introduction

In this study, seismic hazard of induced seismicity in geothermal areas of Upper Rhine Graben (Insheim and Landau) and Bavarian Molasse (Unterhaching) is investigated using probabilistic seismic hazard analysis (PSHA). This study was conducted in the framework of research project "Microseismic Activity in Geothermal Systems" (MAGS) funded by the Federal Ministry for Economic Affairs and Energy of Germany (BMWi). The extended methodology established for natural seismicity included the development of seismic sources (Figure 2), the magnitude recurrence models (Figure 3 and 4) and ground motion prediction equations (GMPEs) (Table 3) in the case of induced seismicity. The issue of non-stationary (time-dependent) seismic activity due to time-varying geothermal operations is addressed as well. In these analyses, catalogs of microseismic activity observed by local networks at the geothermal plants were used. In order to detect time-dependency in seismic activity and to consider it in PSHA, the catalog was divided into time spans and magnitude recurrence parameters were calculated for each time span during production phases. Significant differences in seismic activity of the time spans were not found at Insheim (Table 1) but were found at Unterhaching (Table 2). As a consequence, the seismic hazard levels determined by stationary and non-stationary seismic hazard assessment differ negligibly at the Upper Rhine Graben site (Figure 5) and considerably at the Bavarian site (Figure 6). It is significant to take time-dependency into account in PSHA in the case of induced seismicity due to time-varying geothermal operations.

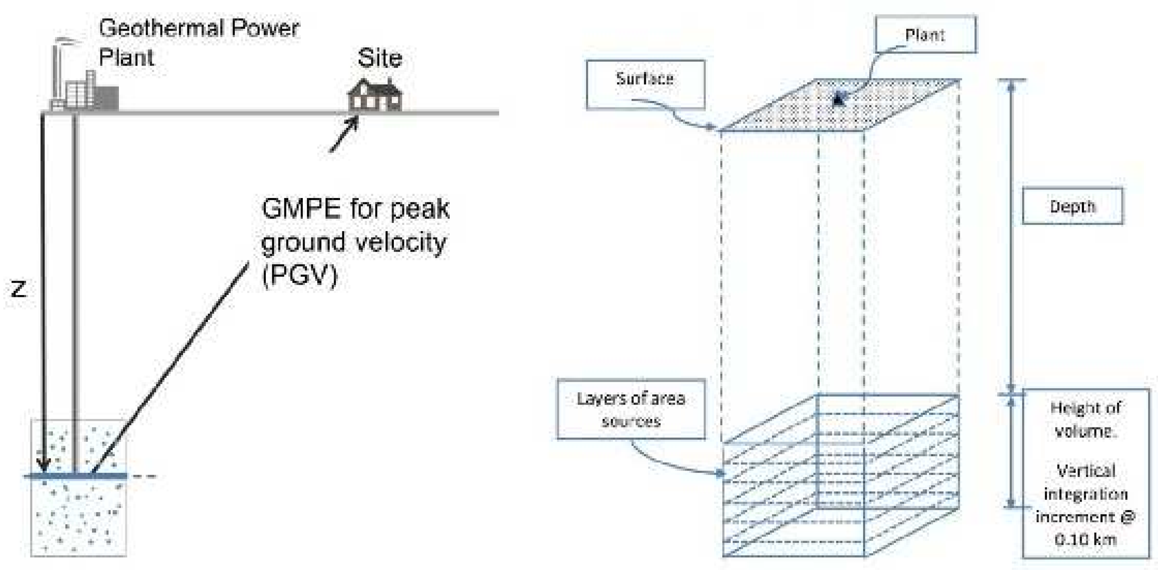

Fig.2: Model of PSHA for induced seismicity associated with deep geothermal wells. Seismic activity is dispersed homogeneously in a cuboid volume at the borehole. The idealization of the source model to be used as input to PSHA software EZ-FRISK (RISK ENGINEERING, INC., 2011) is given in the right part of the figure (Schlittenhardt et al., 2014).

2 Magnitude recurrence model (the whole catalog)

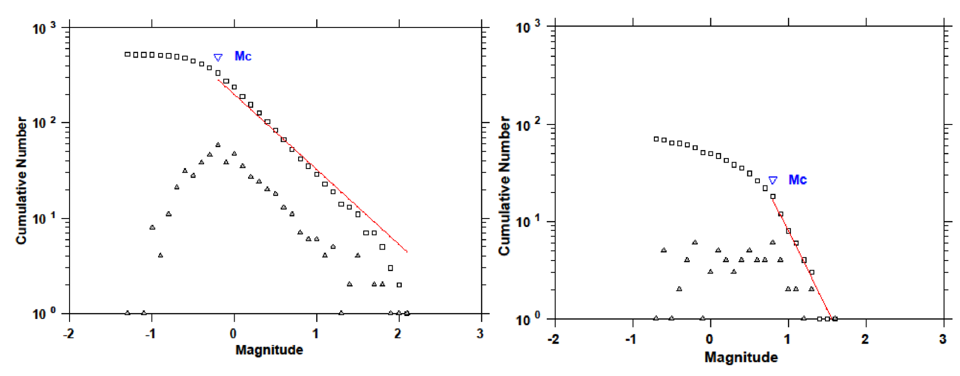

Fig.3: Magnitude recurrence models of induced seismicity at geothermal fields of Insheim (left) and Landau (right) in Upper Rhine Graben. Gutenberg-Richter recurrence parameters are derived using maximum curvature method and ZMAP software (Wiemer, 2001). The magnitude recurrence parameters are a=1.85, b=0.8 and M_c=-0.2 for Insheim and a=1.92, b=1.61 and M_c=0.79 for Landau.

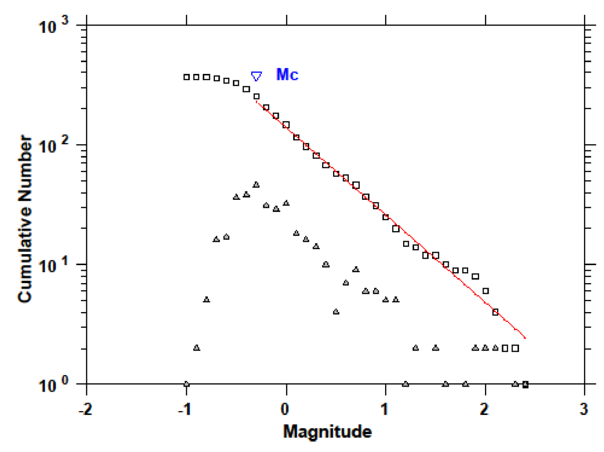

Fig.4: Magnitude recurrence model of induced seismicity at geothermal field of Unterhaching. Gutenberg-Richter recurrence parameters are derived using maximum curvature method and ZMAP software (Wiemer, 2001). The magnitude recurrence parameters are a=1.52, b=0.73 and M_c=-0.32.

3 Magnitude recurrence model (time spans)

Tab.1: Time-dependent Gutenberg-Richter recurrence parameters of Insheim (Upper Rhine Graben)

No	T	T+ΔT	ΔT (Months)	M_c	b	a (annual)
1	10.2013	09.2014	11	-0.11	0.87	1.85
2	10.2014	09.2015	11	-0.23	0.78	1.93
3	10.2015	08.2016	10	-0.2	0.86	1.80

Tab.2: Time-dependent Gutenberg-Richter recurrence parameters of Unterhaching (Bavarian Molasse)

No	T	T+ΔT	ΔT (Months)	M_c	b	a (annual)
1	06.2010	10.2011	16	0.12	0.643	1.60
2	11.2011	04.2013	17	-0.36	0.91	1.60
3	05.2013	08.2014	15	-0.32	0.82	1.56

4 Selecting and ranking the GMPEs

- Residual analysis (Residual=log(observed)-log(estimated))
- Euclidean distance-based ranking (EDR) method (Kale and Akkar, 2013)
- Magnitude, distance, site class and component considerations
- Log-likelihood weighting method (Scherbaum et al., 2009)

Site	GMPE
Insheim	Massa et al. (2008) (0.40) Atkinson (2015) (0.38) Frisenda et al. (2005) (0.22)
Landau	Frisenda et al. (2005) (0.39) Atkinson (2015) (0.31) Massa et al. (2008) (0.30)
Untehaching	Chiou et al. (2010) (0.55) Massa et al. (2008) (0.24) Atkinson (2015) (0.21)

Tab.3: The selected GMPEs with their weights at different geothermal sites

5 Time-dependent PSHA Results

$$E_i(PGV > PGV_0) = \int_T \int_M \int_R \int_\varepsilon \lambda_i(t) I(PGV > PGV_0 | m, r, \varepsilon) \times f(m, b_i(t)) f(r) f(\varepsilon) dt\, dm\, dr\, d\varepsilon$$

(Convertito et al., 2012; Mignan et al., 2015)

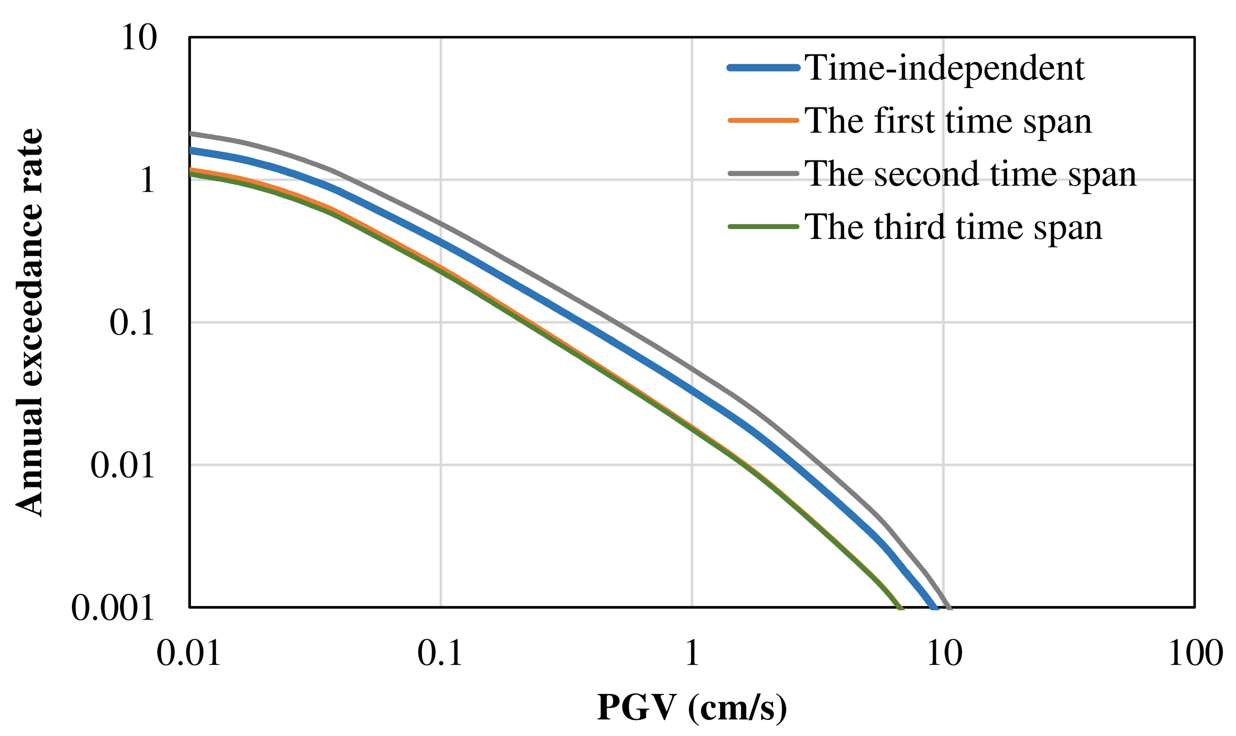

Fig.5: The comparisons of time-independent induced PSHA (the whole catalog) at Upper Rhine Graben site with time dependent PSHA results at different time spans. The difference between time-dependent and time-independent seismic hazard curves is not considerable in this geothermal area.

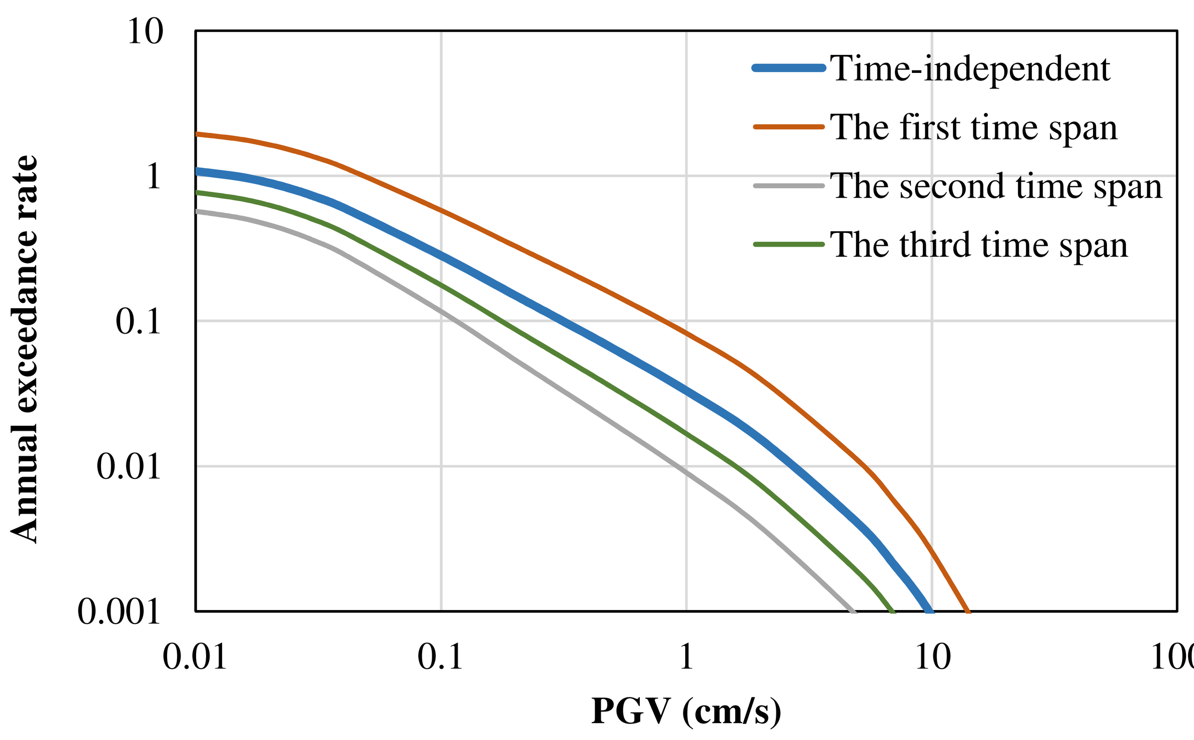

Fig.6: The comparisons of time-independent induced PSHA (the whole catalog) at Unterhaching site with time dependent PSHA results at different time spans The difference between time-dependent and time-independent seismic hazard curves is considerable in this geothermal area.

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