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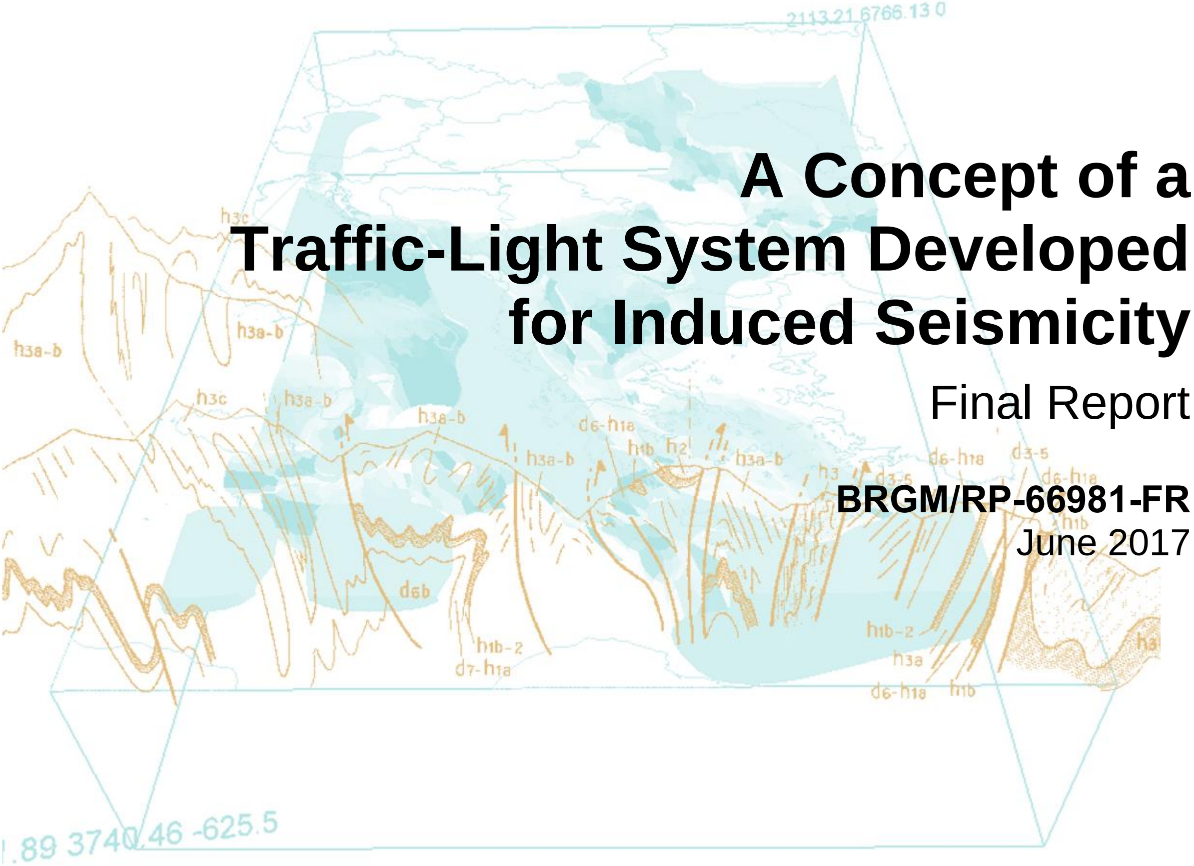

# A Concept of a Traffic-Light System Developed for Induced Seismicity

## Final Report

**BRGM/RP-66981-FR**
June 2017

Geoscience for a sustainable Earth
brgm

# A Concept of a Traffic-Light System Developed for Induced Seismicity

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June 2017

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**H. Aochi (BRGM/DRP), J. Douglas (U. of Strathclyde, UK)**

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| **Checked by:** | **Approved by**: |
| Name: T. Le Guenan | Name: A. Burnol |
| Date: 27/06/2017 | Date: 27/06/2017 |
| Signature: | Signature: |

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# Synopsis

This report of the GEODENERGIES TEMPERER project (http://www.geodenergies.com/) summarizes the concept of a Traffic-Light System (TLS) for induced seismicity for an Enhanced Geothermal System (EGS), in particular, for the purpose of designing the required calibration before any operation. This will be useful for the planned operation of this project at Vendenheim, North of Strasbourg, France.

The idea of a Traffic-Light System (TLS) is to control the operation (input = injection) with respect to the level of earthquake hazard (frequency and/or magnitude of observed induced seismicity). The application of a TLS is strongly suggested in a recent US protocol. However, the given threshold sometimes had to be scrutinized during the operation or even after the shutdown, when unexpected induced earthquakes of large magnitude occur (e.g. Basel stimulation case in 2006, Blackpool hydraulic fracture case in 2011). BRGM proposed recently to consider the perception of the local population in the TLS through the process of probabilistic seismic risk analysis.

Geothermal heat is a potentially important resource of renewable energy. One of the first cases of the application of a TLS is on the seismicity due to the stimulation of EGS, such as the Soultz-sous-Forêts and Basel sites. Along the Rhine valley, there have been several geothermal projects as heat flow in this region is high enough to be exploited. At the new Vendenheim geothermal operation (www.geoven.fr) that the GEODENERGIES TEMPERER project is focused on, no micro-earthquakes have been reported as stimulation has not started yet (as of the end of May 2017). Nevertheless, a TLS should be prepared, based on the experience of the Basel site. This report focuses on the principle of TLS without discussing the nature of any particular operation and should be therefore useful for other future operations.

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# 1. Introduction

Any subsurface exploitation for energy purposes such as gas extraction/injection or fluid circulation may be accompanied by induced seismicity. Most of these earthquakes correspond to “microseismicity”, which are detected only by high-sensibility sensors; but some of them have a magnitude large enough to be felt by the population or to cause physical damage to infrastructure. It is remarked that some industrial operations were interrupted or halted due to induced earthquakes, even if their magnitudes are moderate (*e.g.* Zang *et al*., 2014; Aochi *et al*., 2016). A common concern within the industry and among the population is optimizing and assuring the performance of the industrial operation as well as assessing and limiting the associated risk.

The idea of a Traffic-Light System (TLS) is to monitor continuously the seismicity and to control it (*i.e.* keep in below a certain level) by adjusting the operation (e.g. slowing down injection/exploitation flux). For example, Häring *et al.* (2008) summarized the 2006 Basel stimulation case. Once an earthquake of local magnitude equal to or larger than 2.0 was detected, some actions were planned. There were four levels prepared from “green” through “yellow” and “orange” to “red” lights (Table 1). As public perception remained qualitative and instrumental observations (*e.g.* peak ground velocity, PGV) was still spatially limited, the most important factor was the local magnitude observed. The criterion for the magnitude was defined after similar experiences such as in Soultz-sous-Forêts, where fluid injections had been successful.

A TLS as described above should remain a basis for any deep geothermal operation. However, the criterion generally used is “passive”, as there is no notion of forecast (Aochi *et al*., 2016). Douglas and Aochi (2014) and Aochi *et al.* (2016) propose estimating earthquake risk through probabilistic seismic hazard analysis (PSHA) based on observed seismicity to assess a criterion based on population perception in terms of seismic intensity. This report summarizes the concept of this TLS.

*Table 1: An example of the Traffic-Light System operated during the 2006 Basel stimulation case according to Häring* et al. *(2008).* $M_L$*: Local magnitude of an earthquake. PGV: Peak ground velocity in the recorded seismograms.*

| | Light | | | |
|---|---|---|---|---|
| | Green | Yellow | Orange | Red |
| Criteria | No public response.<br>Event $M_L < 2.3$<br>PGV > 0.5 mm/s | Few telephone calls.<br>Event $M_L >= 2.3$<br>PGV <= 2.0 mm/s | Many telephone calls.<br>Event $M_L <= 2.9$<br>PGV <= 5.0 mm/s | Generally felt.<br>Event $M_L > 2.9$<br>PGV > 5 mm/s. |
| Actions | Regular operation.<br>Continuing pumping. | Communication to supervisor.<br>Continuing pumping, but do not increase flow rate. | Communication to supervisor.<br>Maintain well head pressure below stimulation pressure (for which the first induced event occurs) | Communication to supervisor.<br>Stop pumping.<br>Bleed off to minimum wellhead pressure. |

# 2. Principle of a Traffic-Light System

## 2.1. GENERAL FRAMEWORK

After the halt of Basel (Switzerland) project in 2006, the impact of induced seismicity has been increasingly studied in the world and, for example, the US applies a protocol for assessing this problem for EGSs (Majer *et al.* 2012). Majer *et al.* (2012) propose the following seven steps are followed:

1) perform a preliminary screening evaluation;
2) implement an outreach and communication program;
3) review and select criteria for ground vibration and noise;
4) establish seismic monitoring;
5) quantify the hazard from natural and induced seismic events;
6) characterize the risk of induced seismic events; and
7) develop risk-based mitigation plan.

In the last step (number 7), it is proposed to apply a TLS, which provides a clear set of procedures to be followed in the event that certain seismicity thresholds are reached. It is worth noting that it is expected that the TLS always shows a green light if everything goes as planned. In this section, we consider the calibration of the TLS by considering the population perception. Figure 1 schematically shows the probabilistic seismic hazard analysis applied to on-going induced seismicity (Douglas and Aochi, 2014; Aochi *et al*., 2016). Four steps should be considered:

(1) the seismicity is characterized not only by its maximum magnitude but also by a magnitude-frequency relation;

(2) for each earthquake, the ground motion level is estimated through relations called ground motion prediction equations (GMPEs);

(3) for any given ground motion level (here PGV is chosen), the probability of exceedance is computed;

(4) the ground motion level can be translated into terms related to the perception of the population, *e.g.* the probability of being “felt”.

In the following sections, we describe each module in detail and our choice of model and parameters.

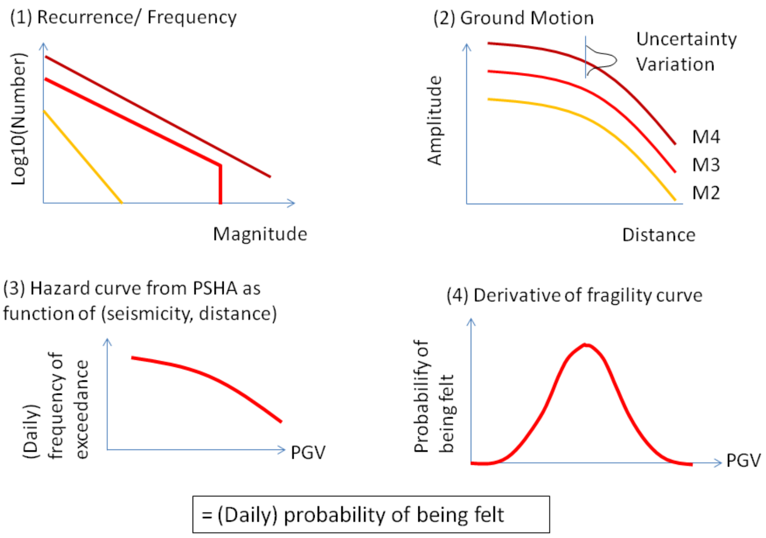

*Illustration 1: Schematic illustration of Probabilistic Seismic Risk Analysis applied to on-going induced seismicity, after Aochi et al.(2016).*

## 2.2. INPUT SEISMICITY DATA

The most important input is the seismicity data. The protocol by Majer *et al.* (2012) mentions the importance of monitoring the change of the seismicity rate before and during the project, and the discrimination of induced events from natural ones. Here, we do not consider any particular site. Let us assume that the seismicity catalogue is obtained according to any operation over a short time (up to 1 week). TLS can be coupled with this catalogue. It is also possible to use any catalogue simulated statistically (Mena et al., 2013) or mechanically (Douglas & Aochi, 2014; Aochi *et al*., 2016). For the purpose of probabilistic seismic hazard analysis, one needs to characterize the seismicity. Any seismicity – fracture phenomena in nature – is fractal, and generally follows a power-law, often called the Gutenberg-Richter law:

$$\log_{10} N(M) = a - bM$$

where: $N(M)$ is the number of events having a magnitude equal to or larger than *M* and *a* and *b* are constants to be determined from the catalogue. We remark two difficulties in applying this model to induced seismicity.

Firstly, the seismicity is not stationary during the operation and certainly evolves with time according to the natural situation as well as human control. PSHA for natural seismicity is generally calculated by assuming that the seismicity during the past decades is stationary and so will be in the next decades or centuries. However, the requirement for induced seismicity is for hour or week scales. The simplest assumption one can do is that the seismicity is stationary in the limited time period of interest, say the last few hours. Also mechanical insights may help in predicting the seismicity. The number of earthquakes may be proportional to the injected fluid volume, for example.

Secondly, the statistical parameter *b* indicating a decade slope with magnitude requires a large number of earthquakes to be reliably determined. The value of *b* is generally between 0.5 and 2, and close to 1 in many cases. In order to obtain a slope *b*, the catalogue should be sufficiently complete at least over a two-unit magnitude range, requiring many tens or hundreds of earthquakes. If we have only ten earthquakes, the estimation of *b* may not be reliable. This requirement is contradictory to the first one. A short time span of the seismicity catalogue may be stationary, but include fewer earthquakes for determining its statistical features. In such a case, one has to assume the value of *b,* rather than estimate it from the available catalogue.

In practice, ways of calculating statistics on seismicity have been proposed by many researchers. Here we adopt Weichert (1980), in which the relation is expressed as:

$$N = N_0 \exp(-\beta M)$$

where $\beta = b\ln(10)$.

## 2.3. CHOICE OF GROUND MOTION PREDICTION EQUATION

The choice of the GMPE influences the estimation of earthquake ground motion as each GMPE predicts different shaking for the same independent variables. GMPEs provide a relation predicting ground-motion parameters characterizing the earthquake shaking for a given magnitude, distance, and site condition (and possibly other variables). The parameters estimated by these equations include peak ground acceleration, PGV, peak ground displacement, response spectral acceleration and duration for varying uses in earthquake engineering. Here we choose PGV, which was used in previous TLSs and can be related to the perception by the local population.

Douglas *et al.* (2013) studied six cases of induced seismicity of small and moderate magnitudes ($1 \leq M_W \leq 5$) around the world, including Basel and Soultz. The best-fitting coefficients for their empirical GMPEs were obtained for the following equation (Model 1; see Table 2 from Douglas *et al.*, 2013):

$$\ln Y = a + bM_W + c\ln\sqrt{{r_{hyp}}^2 + h^2} + d \cdot r_{hyp} \quad (2)$$

where *Y* is either the median PGV or Pseudo-Spectral Acceleration and a, b, c, d and h are regression coefficients. For our applications, we evaluate the ground motions for a location just above the site (i.e. epicentral distance is zero). The hypocentral distance $r_{hyp}$ is then equal to the depth of events, which can be fixed to the operation well-head depth. The moment magnitude $M_w$ is used within this equation. It should be noted that this equation (and all GMPEs) are associated with a standard deviation that allows the probability of any level of shaking to be assessed (rather than simply the median level).

## 2.4. HAZARD CURVE

The hazard curve, expressing the probability of exceeding a given ground-motion level, x, is calculated using the GMPE and the Gutenberg-Richter relation:

$$\lambda(PGV > x) = \sum_j P(PGV > x \mid m_j) P(M = m_j)$$

The latter is interpreted as the probability of different magnitudes in a limited time span, so that a probability in the coming hours is obtained under the assumption that the same seismicity rate is maintained. As explained in the introduction, the standard TLS is based on an observed magnitude. On the other hand, here the hazard is estimated from all the potential earthquakes at a given point.

## 2.5. PERCEPTION

The perception by the population of the ground motions can be defined as either “felt” or “not felt”. All seismic intensity scales measure the degree of population perception (e.g. felt or not felt) and the level of structural damage caused. Table 2 summarises the European Macroseismic Scale (EMS) and the Modified Mercalli Intensity scale (MMI), both of which are commonly used. Ground shaking due to induced seismicity generally remains relatively weak and rarely causes major physical damages to structures. The main problem of induced seismicity is the minor shaking frequently felt by the habitants, which is related to its social-economic acceptance.

Douglas and Aochi (2014) simply used the relationship between MMI observation and PGV proposed by Worden et al. (2012):

$$
\begin{aligned}
MMI &= c_1 + c_2 \log_{10}(Y) \quad \text{for } \log(Y) \le t_1 \\
MMI &= c_3 + c_4 \log_{10}(Y) \quad \text{for } \log(Y) > t_1
\end{aligned}
$$

where *Y* is the PGV from our analysis. The coefficients $c_1$, $c_2$, $c_3$ and $c_4$ are given in Table 1 of Worden *et al.* (2012). The coefficients are derived from Californian data but should be generally applicable in European contexts. This equation provides the fragility curve of the perception of the inhabitants above the site of interest. The PGVs given by this curve for 10, 75 and 95% probability of being felt roughly correspond to the thresholds of “just perceptible” (0.1 cm/s), “clearly perceptive” (0.65 cm/s) and “disturbing” (1.3 cm/s) of Bommer *et al.* (2006).

*Table 2 : Brief summary of the European Macroseismic Scale (EMS) and Modified Mercalli Intensity scale (MMI). Both scales have 12 levels, but they are not always identical.*
*The full descriptions provide more details but this table shows only a summary.*

| | EMS | | MMI | |
|---|---|---|---|---|
| Intensity | Class | Observation | Class | Observation |
| I | Not felt | Not felt by anyone. | Not felt | Not felt except by very few under especially favourable conditions. |
| II | Scarcely felt | Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings. | Weak | Felt only by a few people at most. |
| III | Weak | The vibration is weak and is felt indoors by a few people. | Weak | Felt indoors by many, outdoors by few during the day. |
| IV | Largely observed | The earthquake is felt indoors by many people, outdoors by few. | Light | Felt indoors by many, outdoors by few during the day. |
| V | Strong | The earthquake is felt indoors by most, outdoors by many. | Moderate | Felt by nearly everyone, many awakened. |
| VI | Slightly damaging | Felt by everyone indoors and by many to most outdoors. | Strong | Felt by all, many frightened. Damage slight. |
| VII | Damaging | Most people are frightened and run outdoors. Many buildings suffer slight to moderate damage. | Very strong | Damage negligible in buildings of good design and construction. Damage great in poorly built structures. |
| VIII | Heavily damaging | Furniture may be overturned. Many to most buildings suffer damage. | Severe | Damage slight in specially designed structures. Damage great in poorly built structures. Liquefaction. |
| IX | Destructive | Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapse completely. | Violent | Damage considerable in specially designed structures. Damage great in substantial buildings with partial collapse. |
| X | Very destructive | Many buildings collapse. | Extreme | Some well-build wooden structure destroyed. |
| XI | Devastating | Most buildings collapse. | Extreme | Few structures remain standing. Bridges destroyed. |
| XII | Completely devastating | All structures are destroyed. The ground changes. | Extreme | Damage total. |

# 3. Example application

This chapter demonstrates an example of a TLS using the available data of an EGS site. Douglas and Aochi (2014) already applied it on the synthetic seismicity catalogue generated for the 2006 Basel case for the purpose of calibrating the mechanical parameters so as to be consistent with the observed seismicity. For their analyses the observed seismicity catalogue was only partially available: comprising about 70 earthquakes in the magnitude range 1.4 to 3.15 for the period of the first week. Unfortunately this catalogue is not complete for smaller events.

Here we use one of the synthetic catalogues of the seismicity simulated by Douglas and Aochi (2014). Illustration 2(a) shows the temporal variation of the seismicity (Magnitude versus Time: M-T). Illustration 2(b) summarizes the cumulative number of the earthquakes with time. There are about 160 events of magnitudes between 1.1 and 4.0 during less than one week. We update the probabilistic seismic risk analysis every hour using the previous six hours of data.

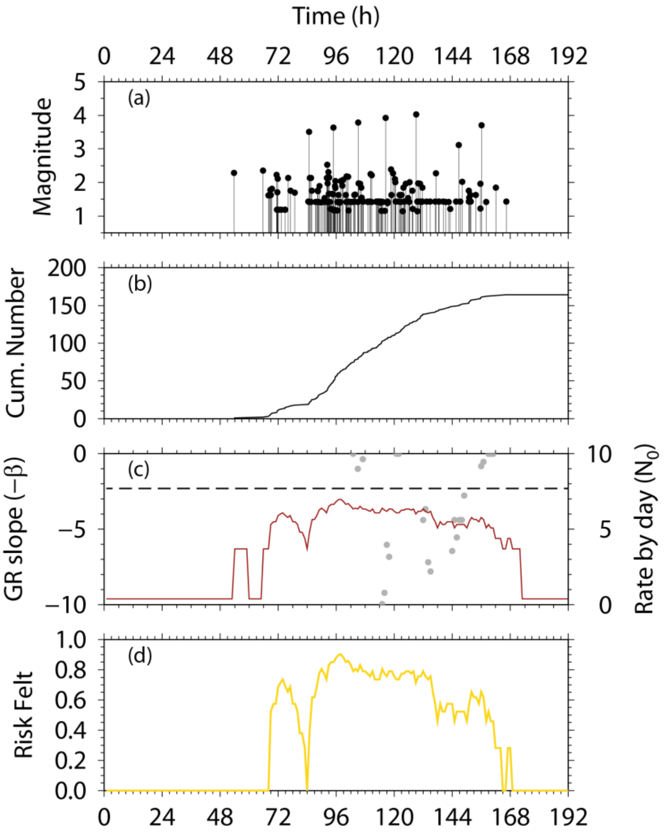

*Illustration 2: Application of a TLS on simulated seismicity. (a) An example of input seismicity catalogue (Time – Magnitude). (b) Cummulative number of earthquakes. (c) Estimation of the parameters characterizing magnitude-frequency relation. The calculation is done every hour using the catalogue for the previous six hours. Parameter $\beta$ can be estimated (grey dots), but it is very unstable due to a lack of data. Fixing $\beta = -\ln(10)$ , i.e. $b = 1$ (broken line), we calculate seismicity daily rate $N_0$ (red line). (d) Corresponding felt risk.*

First, we need to characterize the seismicity. The purpose is to estimate the probability of “felt risk” in the next 24 hours. As pointed out previously, small number of earthquakes (about 10-20 earthquakes at maximum in a window of six hours) does not always provide a stable estimate of the slope of Gutenberg-Richter relation, $\beta$ or *b.* Grey dots in Figure 2(c) show a direct estimation of $\beta$, which varies. We then fix $\beta = -\ln(10)$, i.e. $b = 1$ (solid line) so as to estimate the daily seismicity rate $N_0$, shown by the red line in Figure 2(c). Both estimated parameters are used in the probabilistic seismic hazard assessment.

At every moment of estimation, the probability of daily exceedance as a function of PGV is calculated. The risk is calculated by convolving the hazard curve and the fragility curve for felt motions. The criteria of a TLS should be calibrated using known examples and adjusted for a given situation. For example, here we wanted to avoid moderate earthquakes of magnitude larger than 3, starting from 80 hours. In this case, the estimated risk (more than 0.6) is elevated first at around 72 hours. At this time, we should take some action, namely the first criterion (amber light) would be for felt risk>0.6. A summary learned from this example is listed in Table 3.

*Table 3 : TLS based on « felt risk » in the coming 24 hours. The criterion and the corresponding actions should be adjusted according to the situation.*

| Felt Risk | Traffic Light | Proper Action |
|---|---|---|
| $0.8 \le P$ | Red | Injection immediately stopped. |
| $0.6 \le P < 0.8$ | Amber | Injection rate decreased. |
| $0.4 \le P < 0.6$ | Yellow | Injection rate slowed. |
| $P < 0.4$ | Green | Injection continues as planned. |

# 4. Summary and Perspective

In this report, we have summarized the principles of the Traffic-Light System that has been initially developed by Douglas and Aochi (2014). We have underlinedsome major points for further applications. Comparing to the Traffic-Light Systems based only on observed earthquake magnitude, our system has an advantage in providing an estimate of the increase in “felt risk” based on the observed seismicity before the largest event.

Coupling such a Traffic-Light System with Probabilistic Seismic Hazard Analysis is a current Research and Development topic (*e.g*. Aochi *et al*., 2016; Grigoli *et al*., 2017). The characterization of the seismicity catalogue is the most important ingredient in the estimation of the risk. We had to fix a parameter (called $\beta$ in the Weichert law). However, the risk estimation is significantly influenced by the value of this parameter, as demonstrated in Douglas and Aochi (2014). An open question is how this parameter is related to the geological conditions. On the other hand, efforts are carried out such that any seismicity forecast model is coupled in this system beyond the known seismicity catalogue from the past. The ground-motion estimation and the perception (macroseismic intensity in this report) for small and moderate earthquakes at short distances should be more quantitatively studied by analysing the existing (but not yet studied) data and by installing sensors to collect new data. The perception criterion should be carefully assessed using previous experiences and adjusted according to the acceptability of the operation at the territorial scale.

For the project GEODENERGIES TEMPERER, it will be always necessary to apply the conventional TLS (Table 1). Applying the new TLS (Table 3) still requires research and development for validation. However, the latter has several advantages:

- assess the impact from the whole seismicity (not only from the largest event);
- quantify the perception (integration of fragility curve with hazard curve);
- follow the temporal evolution; and
- provide the probability in a time span of interest.

The criteria deduced from the Basel case (Table 3) appears applicable for similar projects along the upper Rhine. The same method may be applied for other sites according to their geoscientific and socio-economic conditions at the territorial scale.

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**Scientific and Technical Centre**
**Risks and Prevention Division**
3, avenue Claude-Guillemin - BP 36009
45060 Orléans Cedex 2 – France – Tel.: +33 (0)2 38 64 34 34