A priori detection capability of a microseismic monitoring network

Emmanuel Gaucher and Thomas Kohl[1]

[1] Karlsruhe Institute of Technology (KIT), Institute of Applied Geosciences, Division of Geothermal Research, Adenauerring 20b, Geb. 50.40, 76131 Karlsruhe, Germany

emmanuel.gaucher@kit.edu

Keywords: seismic monitoring, induced seismicity, network sensitivity, magnitude of completeness, geothermal field

ABSTRACT

In Germany and other countries worldwide, the risk of seismicity induced in deep geothermal fields is seriously considered. It becomes current practice to implement local seismic networks to monitor the geothermal operations of enhanced and also hydrothermal systems. Within such context, the quantification of the capability of a network to detect a seismic event of predefined magnitude in the target zone is crucial. Here, we describe a method to estimate the sensitivity of networks deployed in areas where no natural or induced seismicity occurred in the zone of interest yet. The method is based on the calibration, for the existing network, of an amplitude-magnitude-distance relationship using the recorded regional seismicity. Applied to a detection procedure involving the signal amplitude and after extrapolation to short distances, it is possible to quantify the probability of detecting an event local magnitude at a given location. We apply this procedure on the seismic network deployed in Bruchsal (Germany) hydrothermal field. Since monitoring started, mid-2010, no induced seismicity was identified in the area despite the good working order of the system. Hence, the question of the a priori detection capability of the network was raised. According to our approach and the applied detection procedure, there is 95% probability that no seismic event with $M_L \geq 0.7$ was induced below the network footprint, at 2.5 km depth, which corresponds to the geothermal reservoir level.

1. INTRODUCTION

Mid-2010, a permanent seismic network deployed over Bruchsal (Germany) deep geothermal field became operational. This local network is intended to record the seismicity possibly induced by either the production of the geothermal water or its reinjection, at depths between 2 and 2.5 km. After more than 2 years of monitoring, no induced seismicity was detected despite the good working order of the network, and the quantification of the network effective detection capability became crucial. In other words, the question of the smallest earthquake magnitude the seismic network can detect was raised.

Such a characteristic can be modelled during the design phase of the seismic network prior to its deployment. Theoretical approaches are used and link a detection criterion based on the expected ground motion velocity recorded at several geophones with the moment magnitude of the earthquake (e.g. Freudenreich et al. 2012). Unfortunately, several parameters describing the seismic source and the propagation medium which are difficult to estimate a priori must be assumed (e.g. radiation pattern, intrinsic attenuation). Moreover, the effects related to the instrumental response (e.g. coupling) are also neglected. In our case, we decide to apply an observation-based approach which can benefit from the measurements made under real conditions over the last months. Hence, quantification of the effective seismic background noise is available as well as seismograms of local and regional seismicity. Similar approaches have been mainly developed for nuclear test ban surveillance (e.g. Bungum and Husebye 1974; Ringdal and Kværna 1989; Ringdal and Kværna 1992); however, they often provide detection capability for zones outside the network footprint, typically several tens or hundreds of kilometres, and benefit from catalogues of earthquakes recorded in the targeted zones which is not suitable for us. So, we propose a procedure to compute, a priori, the effective detection capability of a seismic network, at a kilometric scale, in target zones within which no seismicity was yet observed.

2. SEISMIC MONITORING IN BRUCHSAL

Bruchsal geothermal field is located in the state of Baden-Württemberg (Germany), in the Upper Rhine Graben, where a high temperature gradient of about 50°C/km is observed. The geothermal pilot project uses a well doublet and a Kalina cycle power plant to deliver 550 kW into the electrical network. The injection and the production wells of the doublet are separated by an offset of about 1.5 km and are drilled to 2 km and 2.5 km depth respectively (Herzberger et al. 2010). Water is produced from the Buntsandstein, Rotliegend and Zechstein sedimentary units overlaying the crystalline basement, at a flow rate of about 25 L/s and at temperature of 120°C.

The seismic network which is monitoring the zone since June 2010 is composed of four stations located maximum 4 km away from the production and injection wells. Each station contains a 3C-geophone of 4.5 Hz natural frequency installed at 100 m depth in a dedicated well. The primary target of the monitoring is the volume located between the injection and the production intervals, from ~2.5 km depth up to the surface. As soon as the network was operating, a detection procedure to automatically select seismic event candidates was defined. Then, an operator periodically reviews all candidates to confirm whether they are events induced in the reservoir or not. In the detection procedure, one seismic trace can trigger when the envelope of its amplitude exceeds a predefined fixed threshold which is estimated from the seismic background noise. And, to get a seismic event candidate, several triggers from individual traces within the network must occur over a common period of time.

3. METHOD

To compute the network detection capability four steps are carried out. First, a reference catalogue of the local seismicity issued by an independent network must be available. Second, the amplitudes of the earthquakes identified in the catalogue are measured on the Bruchsal network stations, in accordance with the trace detection processing. Third, a relationship between the earthquake local magnitude provided by the reference catalogue, the associated amplitude and the hypocentral distance is calibrated for each station. These steps constitute the pre-processing phase which is site specific. Finally, from the calibrated relationships, the network detection process can be converted into a probability to detect a given earthquake magnitude anywhere in the underground.

3.1. Data pre-processing

The earthquakes listed in the catalogues provided by the Rheinland-Pfalz seismological center (RLP), the German seismological central observatory, and the European-Mediterranean Seismological Centre were compiled for the Jun. 2010 – Nov. 2012 period. The resulting reference catalogue contains more than 1850 earthquakes with magnitude ranging between -1.5 and 4.8, for distances from the network between 21 and about 600 km (Figure 1).

Following the automatic screening procedure applied on the continuous records, several earthquakes of the catalogue were automatically detected on the Bruchsal network (green circles on Figure 1). Others could only be identified a posteriori by looking at the corresponding seismogram (orange circles); and several earthquakes were not visible at all (red circles). As observed, the obtained magnitude-distance distribution of the detected (and visible) events follows, at first order, a linear relationship between the local magnitude and the hypocentral distance, as would apply in homogeneous propagation medium without signal intrinsic attenuation.

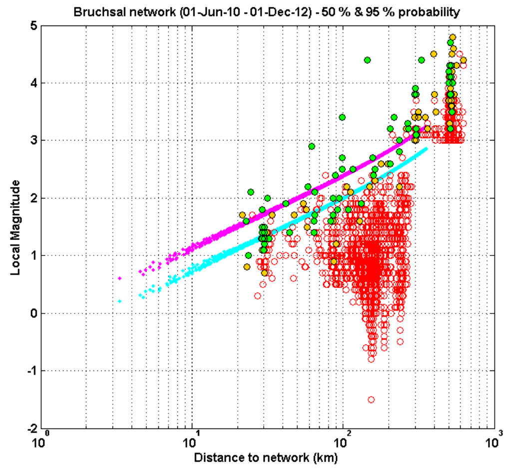

Figure 1: Magnitude-distance distribution of the reference catalogue earthquakes. The green, orange and red circles represent respectively the events automatically detected by the Bruchsal network, not detected but visible, and not visible. The pink and cyan dots show the network detection capability with 95% and 50% probability respectively.

From this analysis, one can fit a relation, for each station, between the signal amplitude measured for the detected and visible earthquakes, and the corresponding local magnitude and hypocentral distances as provided by the reference catalogue. According to Stange (2006), the local magnitude measured at one station located in the state of Baden-Württemberg, like Bruchsal, can be written:

$$M_L = \log A + 1.11 \log r + 0.95\ 10^{-3}\, r + c, \qquad \textbf{[1]}$$

with A the Wood-Anderson amplitude in mm and r the hypocentral distance measured in km. This equation results from the calibration of the standard local magnitude scale as proposed originally by Richter (1935) and revised magnitudes scales as presented by Bormann (2012). The terms sitting at the right of the $\log A$ correspond to the so-called distance correction factor where the $\log r$ term is associated to the geometrical spreading of the seismic waves, the term proportional to r is related to the intrinsic seismic attenuation, and the constant c to regional and station-dependent effects. Stange (2006) found that $c = 0.69$.

In our approach, we replace the original Wood-Anderson amplitude by the amplitude of the detection trace. So, for the earthquakes detected and visible on the Bruchsal stations, the maximum amplitudes on the detection traces were measured as well as the preceding background noise. This was carried out on the S-wave arrivals which are by far the strongest arrivals within the seismograms, and thus better represent the triggering of a seismic event candidate. About 80 seismograms were processed in total. The optimization of equation [1] consisted in finding the c constant suitable to the Bruchsal stations and the modified amplitude. The linear fit was performed between the local magnitudes of the catalogue and the distance correction factor using a couple of minimization criteria: least-square and least-absolute. Also, uncertainty analysis was performed by randomly perturbing the input amplitudes by the corresponding preceding noise prior to fitting.

For 3 among 4 stations, the *c* values are similar within the 95% confidence level, whatever the minimization criteria. Only 1 station exhibited larger discrepancies of *c* values due to the relatively high background noise level and to fewer available measurements. So, the solutions of the random least-absolute criterion were kept. To terminate the calibration of the local magnitude relation, the magnitude residuals at each station were computed. This shows that the expected local magnitude is not perfectly recovered but follows a Gaussian distribution. This feature will be used to introduce probabilities in the quantification of the detection capability.

3.2. Detection capability

Once the magnitude-amplitude relationship is calibrated, few steps remain to compute the network detection capability. First, the underground is regularly meshed and the distance from every node to every station is computed. Then, for all channels belonging to one station, the corresponding detection threshold is taken as the amplitude value in equation [1] and the equivalent threshold magnitude is calculated for each node. In practice, this threshold magnitude follows the cumulative Gaussian distribution fitting the computed residuals and becomes equivalent to the probability to detect an event as a function of its magnitude. Finally, for a given probability level and assuming that N_{Cha} channels must simultaneously trigger to get a seismic event candidate, the magnitude detection capability, at each node, corresponds to the N_{Cha}est smallest magnitude. Because we calibrated the amplitude-magnitude relationship for each station and not for each channel, the magnitude probabilities for triggering channels which belong to the same station are not independent. So, instead of multiplying the probabilities of each of the best N_{Cha} triggering channels for a given magnitude to get the final probability, only the smallest probability among the best channels within each station are multiplied. This criterion is less penalizing than treating all channels as independent. Also, not taking into account the uncertainty in the magnitude determination would lead to too optimistic detection capabilities.

4. RESULTS AND DISCUSSION

Figure 1 compares the real capabilities of the network detection with those predicted with 50% and 95% probabilities. As observed, with 95% probability, only two non-detected earthquakes remain above the estimated detection capability; up to 200 km. So, our approach looks consistent with the observations and the effective network sensitivity.

Figure 2 shows a horizontal section of the detection capability around the seismic network, with 95% probability. The depth of interest, 2.4 km, corresponds to the depth of the geothermal water production. As observed, close to the network and below it, the effect of the discrepancies between the channel detection thresholds is clear since the iso-detection contours are not radial, especially compared to the larger offsets. There is 95% probability that a micro-earthquake of M_L=0.7 located just below the network, at 2.4 km depth, will be detected. It means in our case that no earthquake with $M_L \geq 0.7$ occurred in the vicinity of the Bruchsal geothermal reservoir since monitoring started.

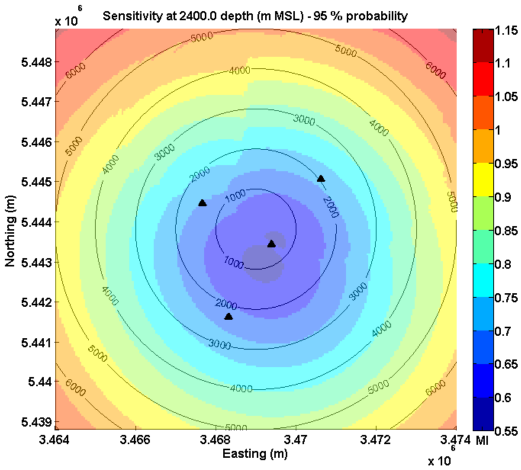

Figure 2: Bruchsal network detection capability. Horizontal section centered on the production well at 2.4 km depth. The color code represents the minimum detectable local magnitude.

The proposed approach has several limitations and relies on the extrapolation at short distances of an amplitude-magnitude relationship calibrated for distance larger than 20 km. So, we assume that the geometrical and intrinsic attenuations of the seismic waves will behave similarly below the network and for few-kilometer ray-paths. Yet, the geological structure of Bruchsal is complex (e.g. Meixner et al. 2013) and the hypothesis of an equivalent or homogeneous propagation model between the reservoir and the network is strong.

The fixed amplitude threshold at the base of the detection procedure is in reality combined with a standard STA/LTA detection procedure. However, the detection capability computation as proposed here cannot be applied on such ratio that does not correspond to a linear transformation of the original recorded signal. Consequently, the effective capability of the network may be better than modeled, especially during quite periods.

To obtain the network capability in terms of location, it would be necessary to link location criteria with seismogram amplitude criteria. This may be done for example by requiring several body-wave phases (instead of using only the S-wave arrivals as presented) and setting stronger criteria associated to the fixed amplitude threshold for each phase. So, the combination of the location channels would change although the principle would remain similar, and still several configurations may be tested.

5. CONCLUSION

The observation-based method we presented quantifies the detection capability of an existing local seismic network. To be applied, the network should be running for a period of time long enough to record several local and regional earthquakes but not necessarily located in the target zone. These earthquakes are used to calibrate an amplitude-magnitude relationship at each network station, knowing that the amplitudes are at the basis of the detection of seismic event candidates. The extrapolation at short distances of these relationships and their combination according to the network detection procedure provides the final detection capability probability of the network in the target zone.

This approach offers an alternative to a fully theoretical detection capability modeling and likely better handle real field conditions such as seismic wave attenuation, site effects, instrumental effective responses that are intrinsically taken into account during the calibration. It is particularly suitable for so-called learning period of monitoring, which follows the network implementation and precedes specific operation surveillance. But, the technique is not restricted to any specific application and can be applied to existing local seismic networks monitoring mining, underground storages, and other geothermal fields. Once the calibration phase has been performed, it enables to simulate several detection scenarios and, for example, the effect of losing one station during monitoring can be modeled to assess the robustness of the network design.

In Bruchsal geothermal field, no seismicity closer than 20 km was recorded by the existing network during the first 2 years of monitoring. According to our analysis and the detection procedure applied on this network, it means that there is 95% probability that no seismic event with $M_L \geq 0.7$ occurred below the seismic network down to the reservoir depth at 2.4 km.

REFERENCES

Bormann, P.: Ds3.1: Magnitude Calibration Formulas and Tables, Comments on Their Use and Complementary Data, *New Manual of Seismological Observatory Practice (Nmsop-2), Iaspei*. Ed. Bormann, Peter, *GFZ German Research Centre for Geosciences*, Potsdam, (2012), 19.

Bungum, H., and Husebye, E. S.: Analysis of the Operational Capabilities for Detection and Location of Seismic Events at Norsar, *Bulletin of the Seismological Society of America,* **64**, (1974), 637-656.

Freudenreich, Y., Oates, S. J., and Berlang, W.: Microseismic Feasibility Studies – Assessing the Probability of Success of Monitoring Projects, *Geophysical Prospecting,* **60**, (2012), 1043-1053.

Herzberger, P., et al.: The Geothermal Power Plant Bruchsal, *World Geothermal Congress*, (2010).

Meixner, J., et al.: Significance of Transfer Faults in Graben Systems for the Geothermal Utilization, (2013), Submitted.

Richter, C. F.: An Instrumental Earthquake Magnitude Scale, *Bulletin of the Seismological Society of America,* **25**, (1935), 1-32.

Ringdal, F., and Kværna, T.: Continuous Seismic Threshold Monitoring, *Geophysical Journal International,* **111**, (1992), 505-514.

Ringdal, F., and Kværna, T.: A Multi-Channel Processing Approach to Real Time Network Detection, Phase Association, and Threshold Monitoring, *Bulletin of the Seismological Society of America,* **79**, (1989), 1927-1940.

Stange, S.: Ml Determination for Local and Regional Events Using a Sparse Network in Southwestern Germany, *Journal of Seismology,* **10**, (2006), 247-257.

Acknowledgements

This work was carried out in the frame of the LOGRO research project which was funded by the EnBW Energy Baden-Württemberg AG and the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).