This document is a translation from German of parts of the recommendation
FKPE Arbeitsgruppe "Induzierte Seismizität"
Milestone "Seismische Überwachung"

Substantial parts of this recommendation were adopted in the guidelines for seismic monitoring by GtV, the German geothermal association (link)

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Milestone "Seismic Monitoring"

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Preamble

The present recommendation describes the metrological requirements for the acquisition of induced seismicity related to geotechnical facilities. In the following, geotechnical facility means a subsurface facility for resource extraction (e.g. deep geothermal energy, hydrocarbons) or disposal (e.g. CO_2-squestration, gas storage, waste disposal). The recommendation is restricted to the minimum metrological requirements for the reliable acquisition of all possibly felt induced earthquakes (with ground velocities larger than 0.3 mm/s) that are related to the geotechnical facility. It should be noted that an understanding of the underlying processes with the measures described is generally not possible due to incomplete acquisition of smaller earthquakes.

The necessary technical effort for monitoring induced seismic events at geotechnical facilities critically depends on the type of geotechnical facility and hence on the requirements on the monitoring by the regulatory authority. If, for example, only a general observation of seismicity is requested, this can be achieved with a 3-component monitoring station complying with the requirements on measurement accuracy and data availability as described below. If a localization of events, an acquisition of the spatio-temporal development of seismicity or discrimination between natural and induced seismicity is requested, a substantial instrumental effort is necessary.

A) Measurement Accuracy
At individual measuring sites a compressional wave with ground velocity amplitude of 6 μm/s at a minimum signal/noise ratio of 3 in the frequency range between 5-40 Hz must be detectable. 3 orthogonal components of the ground velocity have to be measured where the accuracy of the time base has to be in the order of milliseconds.

B) **Operation of a Monitoring Network**
If source parameters are to be determined in addition to general observations, at least 5 observation stations must be continuously operated in the vicinity of a geotechnical facility (within a distance <10 km of the geotechnical facility). The locations should be chosen in such a way that (1) specification (A) is complied with and (2) an accurate determination of hypocenters is achieved within the reservoir and its immediate vicinity (2σ-accuracy horizontally: ±500 m, vertically: ±2000 m).

C) Data Integration

Emission measurements for the determination of source characteristics and immission measurements (DIN 45669) to estimate vibration (DIN 4150) should be consolidated to obtain a comprehensive data basis for seismological analysis. Seismological measurement data of selected stations should be provided to the responsible Seismological Service to perform its duties. Conversely, seismological measurement data provided by the industry, authorities and research institutions should be integrated into the operated monitoring network.

D) Transparency

It is recommended to disclose measurement data in centralized databases to enable transparency, verifiability and application of advanced processing techniques.

Comments and implementation instructions:

<u>Ref A) Measurement Accuracy</u>

- In order to monitor a progression in time towards felt events, already those events should be measured reliably and localized (if applicable) that are below the threshold of perception (0.3 mm/s in rare cases, cf. DIN 4150-2[1]). Moreover, a Gutenberg-Richter relation with a sufficient number of events should possibly be compiled in order to facilitate a forecast of stronger events (approximately 1 magnitude above observed seismicity). With a focal depth around 2-5 km in a sedimentary basin environment this requirement corresponds to measuring an earthquake of local magnitude $M_L \sim 1$. In other environments M_L can adopt different values (depending on focal depth, amplification factors of near surface sediment layers etc.). To detach oneself from local magnitude and its uncertainties (station magnitude, averaging, lack of significance with respect to intensity and impact, respectively), ground velocity is to serve as a point of reference. A value of 6 µm/s should be measured reliably.
- Seismic immissions can be felt starting from ground velocities of 0.3 mm/s in exceptional cases (DIN 4150-2), whereas this usually applies to shear waves. To reliably detect this value and to determine a Gutenberg-Richter statistic for the occurrence of events, in the following a factor of 0.1 is considered (i.e. 0.03 mm/s or 30 µm/s). An empirical factor of 0.2 is estimated to obtain a value for compressional waves (P) from this amplitude value for shear waves (S). Measuring and identifying P- and S-waves is necessary in order to recognize seismic events and localize them when indicated. A signal/noise ratio of at least 3 is required for phase identification and determination of onset times. This lower sensitivity threshold does not pose a problem for conventional seismometers or geophones. 3-component sensors (1 vertical and 2 orthogonal horizontal) have to be employed.
- Starting from a signal/noise ratio (SNR) of around 3, a seismic wave can reliably be identified and its onset time can be determined. This is the decisive criteria for the measurement and hence requires noise amplitudes smaller than 6/3 µm/s or 2 µm/s, respectively. An amplitude interval is to serve as a reference for the computation of the signal/noise ratio in the time domain. This interval comprises 95% of amplitude values (I95) of the time series under investigation (without mean value) containing seismic noise (see figure). I95 should be within the range ±2µm/s. If a SNR>3 cannot be obtained (e.g. due to high background noise), measuring should be carried out inside a wellbore. The reference value I95 (see below) must be maintained during continuous operation (24/7). It is recommended to carry out test measurements to determine the signal/noise ratio at potential monitoring sites before setting up stations. These test measurements are to determine the variation of the average noise amplitudes (I95) and to estimate the occurrence of transient noise signals in the measured frequency domain.

[1] This value is valid for measurements in the foundation of constructions. DIN 4150-2 designates a perception threshold of KB_{Fmax}-values between 0.1 and 0.2. The KB_{Fmax}-value (maximum weighted vibration severity) represents the maximum of the running effective value of a frequency-weighted vibration signal, the determination of which is defined in DIN 4150-2. A value of v_{max}=0.3 mm/s is obtained considering the amplification of vibration towards upper floors and the fact that the KB_{Fmax}-value of single events of short duration is approximately 1/3 of v_{max}.

For the analysis of site noise see also: Groos J. & Ritter, J., 2010. Seismic noise: A challenge and opportunity for seismological monitoring in densely populated areas. In Ritter, J. and Oth, A. (eds.), *Proceedings of the workshop Induced Seismicity*, Cahiers du Centre Européen de Géodynamique et de Séismologie, Vol. 30, 157 pp., ISBN N° 978-2-91989-709-4).

- The frequencies to be measured on the ground surface cover a range between 5 Hz (S-waves) up to 40 Hz (P-waves) for earthquakes with local magnitudes $M_L<\sim3$. Stronger events can excite lower frequencies. Therefore, at least 4.5 Hz geophones have to be employed while the measurement of lower frequencies is optional. The sampling rate must be at least 100 Hz. In wellbores efforts should be made to measure signals with a frequency content up to at least 80 Hz (sampling rate of 200 Hz) given that higher frequencies can be observed here.

- The accuracy of the time base of the measured seismic data must be in the order of milliseconds. Synchronization in the milliseconds range or below can easily be realized assuming a standard synchronization of the clock of the acquisition system with an external time signal. It is recommended to utilize GPS for time synchronization (this is essential, e.g., for the computation of accurate relative localization of seismic events, see below).

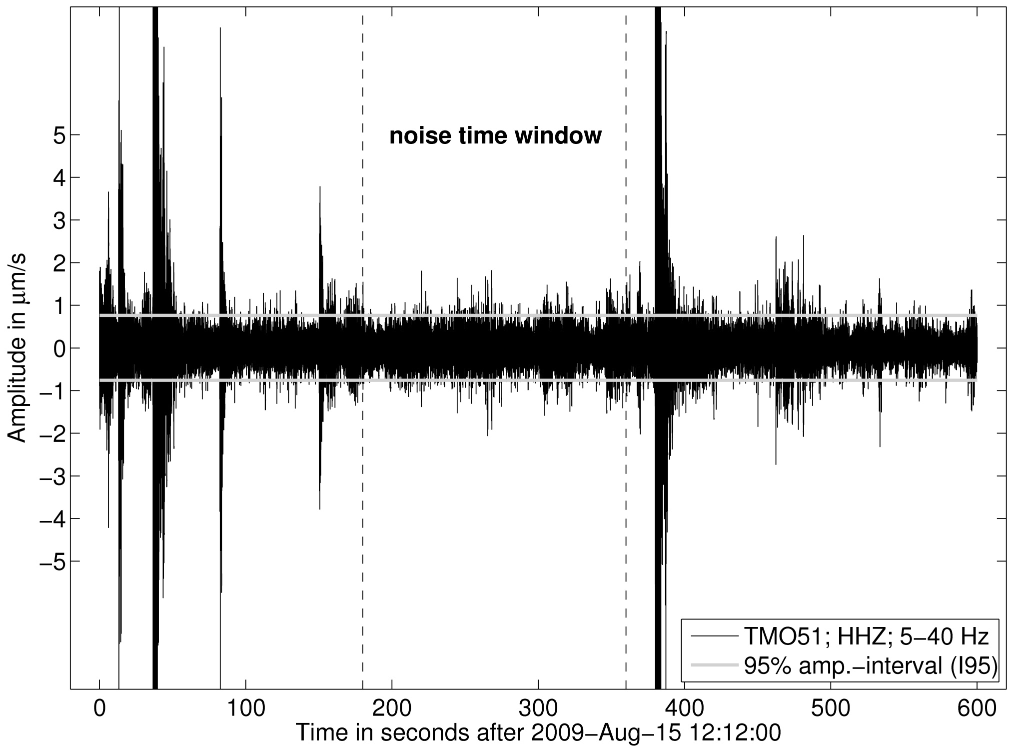

Figure: Diagram of the amplitude interval I95 (in between the grey lines) for the evaluation of the noise level. 95% of the measured amplitude values are inside I95. Transient noise signals can briefly exceed this amplitude. The larger, partially saturated events in the diagram are induced earthquakes. The location of TMO51 is in the Upper Rhein Graben (surface station at the periphery of a community), I95 in this case is below the required value of ±2 µm/s.

Ref B) Operation of a Monitoring Network

- The configuration of a monitoring network is based on the results to be obtained by the supervision: Detection of single events, accuracy of the hypocentral parameter determination (latitude, longitude, depth and origin time) as well as local conditions (signal/noise ratio, location permit, infrastructure etc.).
- If only the reliable detection of single, felt events is required within the framework of a general monitoring, one station that complies with the requirements mentioned above is sufficient if additionally a data availability of 98.5% can be guarantied.
- If, furthermore, a localization of seismic events is intended, accuracy for the determination of the epicentre coordinates of ±500 m should be obtained (uncertainty of 2σ). In addition to reasonably well determined P- and S-wave onset times (compressional and shear waves), a suitable velocity model is required.
- The determination of hypocentral depth strongly depends on the quality of the velocity model, especially for shear waves. It is recommended to calibrate the velocity model and/or travel times. This can, for example, be achieved by calibration shots in wellbores, initial stimulation events, sonic-log / full-wave-sonic-log measurements or VPS (vertical seismic profiling). Uncertainties of ±2000 m (2σ) in hypocentral depth should not be exceeded.
- Various measurement configurations are possible to achieve the localization objectives mentioned above. According to experience at least 5 monitoring stations are required. It has to be considered that, due to station failures for technical reasons, insufficient monitoring possibilities (station located on nodal plane, unusual noise events etc.), under certain circumstances additional redundancy is required. To obtain a good depth localization, not all stations should be placed too far away from the potential source. The azimuth between stations should be as small as possible to obtain a good horizontal resolution for the localization. There should be no gap in azimuth coverage with respect to the source larger than 90°.
- In addition to absolute localization described above, attention is drawn to the relative localization technique. Correspondingly determined hypocenters are determined very accurately relative to each other which assist, for instance, in characterizing the development of seismicity in the reservoir.
- The confirmation of resolution ability of the monitoring network should be provided by numerical modelling before starting the surveillance.
- Continuous real-time data transfer (time delay of a few seconds) to a data centre (e.g. at the operator and/or a public data portal), automatic quality control of recordings and automatic detection as well as notification (e.g. of the operator) represents the state of the art. In the case technical problems occur during data transmission, measuring should be switched to hybrid mode (e.g. only 'state-of-health' and triggered waveforms are transmitted) when indicated. Measuring can, to some extent, be carried out even with no real-time data transmission. Technical progress in mobile communications technology (e.g. LTE-standard) will solve still remaining problems within a short period of time.