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Magnitude scaling of induced earthquakes

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ABSTRACT

Presented are the results of an earthquake magnitude homogenisation exercise for several datasets of induced earthquakes. The result of this exercise is to show that homogeneous computation of earthquake moment- and local-magnitude is useful in hazard assessment of Enhanced Geothermal Systems (EGSs). Data include records from EGSs in Basel (Switzerland), Soultz (France) and Cooper Basin (Australia); natural geothermal fields in Geysers (California) and Hengill (Iceland), and a gas field in Roswinkel (Netherlands). Published catalogue magnitudes are shown to differ widely with respect to M_w, with up to a unit of magnitude difference. We explore the scaling between maximum-amplitude and moment-related scales. We find that given a common magnitude definition for the respective types, the scaling between moment- and local-magnitude of small earthquakes follows a second-order polynomial, consistent with previous studies of natural seismicity. Using both the Southern-California M_L scale and a PGV-magnitude scale (M_{equiv}) determined in this study, we find that the datasets fall into two subsets with well-defined relation to M_w: Basel, Geysers and Hengill in one and Soultz and Roswinkel in another (Cooper Basin data were not considered for this part of the analysis because of the limited bandwidth of the instruments). M_{equiv} is shown to correlate 1:1 with M_L, albeit with region-specific offsets, while the distinct subsets in the M_{equiv} to M_W scaling leads us to conclude that source and/or attenuation properties between the respective regions are different.

1. Introduction

Enhanced Geothermal Systems (EGSs) aim to provide sustainable, cost-effective and environmentally-friendly energy. They build upon the concepts of classic geothermal energy production, but facilitate the production in case of insufficient fluid conductivity. An EGS project aims to increase reservoir permeability through the use of micro-seismicity, with high-pressure fluids forced into the system creating new, or opening pre-existing fractures in the rock. Such methods provide the potential for initiating geothermal systems in any region with a sufficient temperature-gradient; however, the substantial cost of such projects means that both water-heating and electricity production are required to make them economically viable. The water-heating requirement implies that EGS projects are often set up in populated regions, since the transport of heated water requires costly insulation and transit pipelines. One such EGS project was the Deep Heat Mining Project in the city of Basel, Switzerland. The project aimed to provide up to 3 MW of electricity, in addition to 20 MW thermal energy, through a 200 °C reservoir at 5 km depth. Fluid injection was abruptly halted on the 8th December, 2006, after increasing seismicity culminated in a M_L 2.6 event. A few hours later a M_L 3.4 earthquake caused widespread light damage resulting in insurance claims of over $9 M (Giardini, 2009).

A thorough risk assessment of an EGS project is clearly required in order to assess and mitigate potential losses and appease the local population. Given the induced seismicity related to an EGS, a key component of such a risk study is a seismic hazard assessment. Such hazard studies are typically carried out for sensitive facilities such as nuclear power stations. In these cases, events with magnitudes between M_w 5.5 and 7.5 are typically the most important since they have the most impact on long return-period hazard (Bazzurro and Cornell, 1999). However, in the case of an EGS, magnitudes of interest start at around M_w 2 due to the proximity to populated areas and the goal of avoiding nuisance to the population. In order to provide the frequencies of exceeding given ground-motion (intensity) measures within particular intervals, probabilistic seismic hazard analysis (PSHA) integrates ground-motion estimates over the magnitude-occurrence probability distribution. This is facilitated through statistical analysis of earthquake magnitude catalogues, where the a- and b-values of the Gutenberg and Richter (1944) relation are defined for a given source area. Consistent earthquake magnitude is, therefore, a critical component of PSHA.

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Seismic monitoring of an EGS typically involves several medium- or short-period velocimeters (sensors that measure ground velocity) around the reservoir. This facilitates hypocentre localisation, depending on the methods employed, to within several hundred to tens of metres. Magnitudes are typically provided based on peak-amplitude measures, with correction for the source-station distance. The most common scale is the local- or Richter-magnitude, M_L (Richter, 1935):

$$M_L = \log_{10} A + f(R), \tag{1}$$

with A the peak-amplitude (in mm) on a Wood-Anderson torsion seismometer and $f(R)$ a correction factor for attenuation over distance R. The main problem with such scales is that the agency-dependent application of the attenuation correction often results in significantly different magnitudes being assigned for the same size earthquake occurring in different regions (Fäh et al., 2011). In PSHA, the moment magnitude is usually used, since: it does not saturate at large magnitudes (although this is obviously not an issue for small EGS shocks); it is mostly agency-independent due to the analysis of very-low frequency (hence weakly-attenuated or -amplified) signals and; leads to simple, and therefore robust, recurrence statistics (e.g., a- and b-values). Furthermore, the M_w scale is the only one that can be directly estimated from fault parameters (length, width and offset), typically used to assess the occurrence rate of large (infrequent) earthquakes. Nevertheless, in the case of induced seismicity, it still has to be shown that the M_w scale is appropriate for PSHA, since it is based on fault area and slip, and therefore correlated to low-frequency ground motions. In this study we construct a homogenised earthquake catalogue including moment, local and PGV-equivalent magnitudes for a range of induced events. For convenience we refer to the magnitudes calculated in this work as reference values, since we can assure a common procedure and scale. However, magnitudes are, to an extent, an arbitrary measure. The catalogue magnitudes may include processing for which we cannot account, such as expert judgement. And indeed, the use of regional specific attenuation corrections may be necessary due to differences in the propagation media. This should nevertheless become apparent upon comparison of the different magnitudes.

2. Determination of moment magnitude

We follow the method of Edwards et al. (2010) for the computation of moment magnitudes for small earthquakes. The method is based on the far-field spectral model of Brune (1970, 1971) and was shown to provide magnitudes consistent within ±0.1 units of moment tensor (MT) solutions of $M > 3$ events in Switzerland. MT solutions require waveform matching of long-period arrivals, which may not be possible for small events due to noise or band-limited instrumentation. In contrast, spectral matching to obtain moments only requires fitting of the flat portion of displacement spectra, which can be done at fairly high frequencies above the background noise for small events. Therefore, such methods are the only suitable approach to determine M_w for such earthquakes.

2.1. Data and processing

Data were available from a range of instrument types depending on location. More information can be found in Douglas et al. (2013). All data were first corrected for the full instrument response to provide traces with units of ground velocity. Analysis windows were chosen based on a 5–95% square velocity integral around the peak velocity. The multi-taper Fast Fourier Transform (mtFFT) with 5–3π prolate tapers was used to convert these into Fourier velocity spectra, and a 1 Hz log-average smoothing filter was applied. Noise windows were taken from the first 5 s of the traces, and processed in the same way. To ensure we did not underestimate the noise, the resulting noise estimates were conservatively raised to ensure that they matched the analysis window amplitudes at the lowest and highest frequencies of the spectrum. Following this, the valid frequency limits ($f_{\min}$ and $f_{\max}$) of the analysis spectra at three times the noise level were determined. To retain a spectrum, we required that this bandwidth ($f_{\max}/f_{\min}$) exceeded 10.

2.2. Model setup

As in Edwards et al. (2010) we assumed a simple $1/R$ geometrical decay, while the anelastic attenuation (t^*) is determined on a path-specific basis during the inversion, along with the spectral plateau (Ω_0) and the source corner-frequency (f_c). In the case of induced events recorded at short distances the attenuation terms should not be critical but the aim here is for consistency rather than precision. For instance, in the case of an increase in the decay exponent of 10% (e.g., $1/R^{1.1}$), the determined M_w would be 0.05 too low at 5 km, or 0.07 too low at 10 km when assuming $1/R$ decay. Site amplification, which is known to strongly vary from site-to-site, is difficult to quantify due to the lack of a reference. The inversion procedure detailed in Edwards et al. (2010) can account for site-specific amplification provided that either the average amplification across the network is known or at least one M_w value is independently available. When most stations are on hard rock, the average amplification can be set to unity, meaning that the resultant site-specific amplification is relative to the network average shear-wave velocity (V_s) profile (e.g., Poggi et al., 2011). However, if strong site amplification exists the assumption of no average network amplification would cause M_w to be overestimated (as site amplification is mistakenly attributed to the source). We, therefore, adopted an approach to estimate the average network amplification through correlation of site effects. The κ_0 parameter (Anderson and Hough, 1984) characterises the high-frequency attenuation that is generally attributed to the upper layers of rock and soil beneath a site, and can be simply measured from the high-frequency decay of the Fourier acceleration spectra. Since it depends on properties of the site, κ_0 has been shown to correlate with the upper 30 m time-travel average V_s (V_{s30}; e.g., Edwards et al., 2011), which is itself known to correlate with site amplification (e.g., Borcherdt, 1994). Edwards et al. (2011) showed that, in Switzerland, the κ_0 could be used to approximate average amplification at a given site, A_j. However, such correlations are known to be associated with high uncertainty. In order to reduce this uncertainty, and increase the degree of freedom of the inversion for M_w, whilst still constraining the trade-off between amplification and magnitude, we therefore fix the average amplification over the network (as opposed to individual station values). When lacking other information, we, can estimate this average network amplification, υ, using:

$$\log(\upsilon) = \frac{1}{N}\sum_{j=1}^{N}\left[1.31\,\log\left(\kappa_{0,j}\right)\right] + 2.32 \tag{2}$$

with $\kappa_{0,j}$ equal to κ_0 at site j. The inversion for M_w was then constrained such that site-specific amplifications had to satisfy the average amplification, υ.

3. Comparison of catalogue and moment magnitudes

In this section we compare the moment magnitudes estimated using the approach detailed above and the magnitudes listed in available catalogues for the six considered sites.

3.1. Basel, Switzerland

The Basel EGS project began fluid injection on 2nd December, 2006 and continued until the 8th when injection was halted due