A Hybrid Empirical Green's Function Technique for Predicting Ground Motion from Induced Seismicity: Application to the Basel Enhanced Geothermal System.

Benjamin Edwards[1*], N Staudenmaier[2], C Cauzzi[2], S Wiemer[2]

[1] School of Environmental Sciences, University of Liverpool, Liverpool, UK; * ben.edwards@liverpool.ac.uk
[2] Swiss Seismological Service, ETH Zurich, Zurich, Switzerland

Abstract

A method is demonstrated for the prediction of site-specific surface ground-motion due to induced earthquakes occurring in predictable and well-defined source zones. The method is based on Empirical Green's Functions (EGFs), determined using micro-earthquakes at sites where seismicity is being induced (e.g., hydraulic fracturing and wastewater injection during shale oil and gas extraction, CO2 sequestration, conventional and enhanced geothermal injection). Using the EGF approach a ground motion field (e.g., an intensity map) can be calculated for a potentially felt induced event originating within the seismic zone. The approach allows site- and path-specific effects to be mapped into the ground motion field, providing a local ground-motion model that accounts for wave-propagation effects without requirement of 3D velocity models or extensive computational resources. As a test case, the ground motion field for the mainshock (M_L = 3.4, **M** = 3.2) resulting from the Basel Enhanced Geothermal System was simulated using only seismicity recorded prior to the event. The performance of the method was significantly better than a previously developed generic ground motion prediction equation (GMPE) for induced earthquakes and showed improved performance through intrinsic inclusion of site-specific effects relative to predictions for a local GMPE. Both median motions, and the site-to-site ground-motion variability was captured, leading to significantly reduced misfit relative to the generic GMPE. It was shown, however, that extrapolation beyond a couple of magnitude units leads to significant uncertainty.

Method

For small earthquakes we can assume a point source, such that the displacement spectrum is given by:

$$\Omega_{mn}(f) = E_m(f)G_{mn}(f) = E_m(f)B_{mn}(R,f)S_{mn}(R)T_n(f) \quad (1)$$

with $E(f)$ the far-field representation of the source displacement, and $G(f)$ the Green's function between source and site. The Green's function is a product of the path [anelastic and geometric attenuation: $B(R,f)$ and $S(R)$] and site effects, $T(f)$. We use the Brune (1970) far-field model (n=2, γ=1) or the modification after Boatwright (1982) (n=2, γ=2):

$$E(f) = \frac{\Omega_0}{\left[1+\left(\frac{f}{f_c}\right)^{n\gamma}\right]^{1/\gamma}} \quad (2)$$

with Ω_0 the far-field signal moment (the low frequency amplitude of the far-field displacement spectrum in Nm) and f_c the source corner frequency.

The approach taken here centres on the fact that given two 'point-source' events in the same location, the Green's function will be the same. Given this fact we can modify the recorded Fourier spectrum of a small earthquake ($\Omega_1(f)$) to account for an increase in event magnitude to the target spectrum ($\Omega_2(f)$):

$$\Omega_2(f) = E_2(f)G(f) = A(f)E_1(f)G(f) = A(f)\Omega_1(f) \quad (3)$$

Given two events (the recorded event (event 1) and the target simulated event (event 2)) the ratio of their spectra is given by:

$$A(f) = \frac{E_2}{E_1}(f) = \frac{\Omega_{0,2}}{\Omega_{0,1}}\frac{1+\left(\frac{f}{f_{c,1}}\right)^2}{1+\left(\frac{f}{f_{c,2}}\right)^2} \quad (4)$$

With: $f_{c,x} = 0.4906\beta\left(\frac{\Delta\sigma_x}{M_{0,x}}\right)^{\frac{1}{3}}$ and $M_{0,x} = 10^{1.5\mathbf{M}+9.05}$

Data

We use a database of events recorded by the Swiss Seismological Service (SED) in Basel, Switzerland during and after the enhanced stimulation of a deep geothermal system that eventually induced a M_L = 3.4 (**M** = 3.2) earthquake on the 8th December 2006.

54 small events (M_L ≤ 2.7, Figure 1) occurring prior to the mainshock and located in the seismic cloud of induced earthquakes were used to provide an estimate of the shaking expected for the **M** = 3.2 event. Moment magnitudes were estimated using the M_L to **M** conversion of Goertz-Allmann et al. (2011).

For $\Delta\sigma_x$ a constant value of 5 MPa was used. This is slightly higher than the measured value for the **M** = 3.2 event, but represents a realistic average value in the case that the value is not known a-priori. Data are all recorded on either Streckeisen STS-2 broadband seismometers or Kinemetrics EpiSensor accelerometers with instrument response deconvolved using station specific poles and zeros.

We focus on the peak ground velocity (PGV), which is useful as it is a measure of ground-motion on which Swiss DIN and SN norms for vibration disturbances are based.

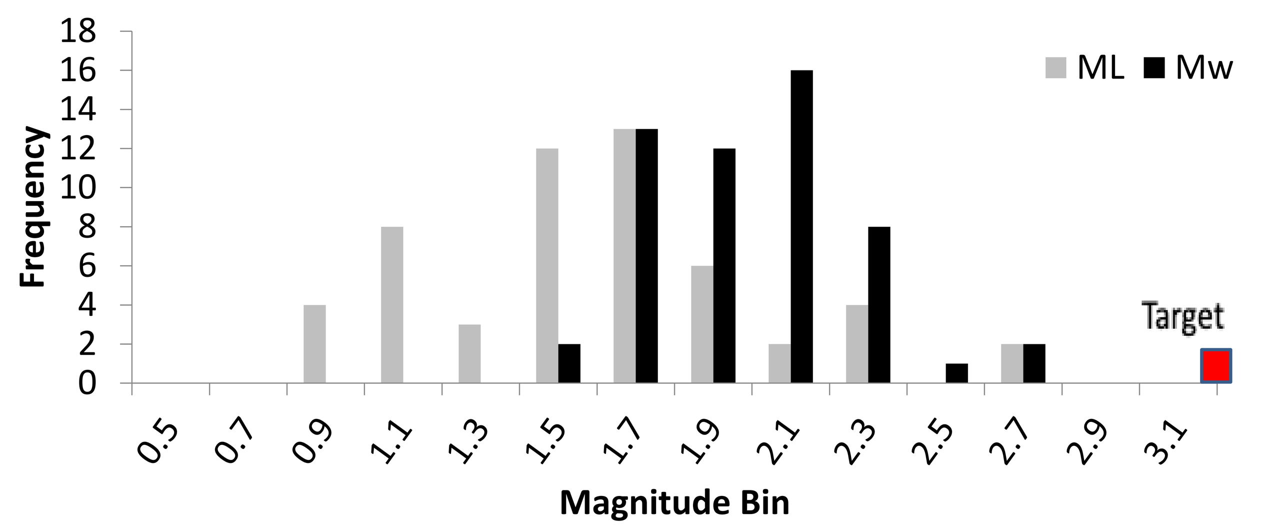


Figure 1. *Histogram of the event magnitudes used to estimate PGV values of the mainshock.*

Existing Approaches

The ground motion prediction equations (GMPE) of Douglas et al. (2013) (developed for induced seismicity) and Cauzzi et al. (2015) (developed for regional tectonic events in Switzerland) are shown in Figure 2 and 3. The performance of the Douglas et al. GMPE good at distances of interest for induced seismicity, (e.g., R < 30 km), with PGV values falling within the model's (large) standard deviation. Beyond 50 km (where the GMPE is not calibrated) it systematically underestimates the observations. The Cauzzi et al. GMPE provides unbiased predictions over a wide range of distances.

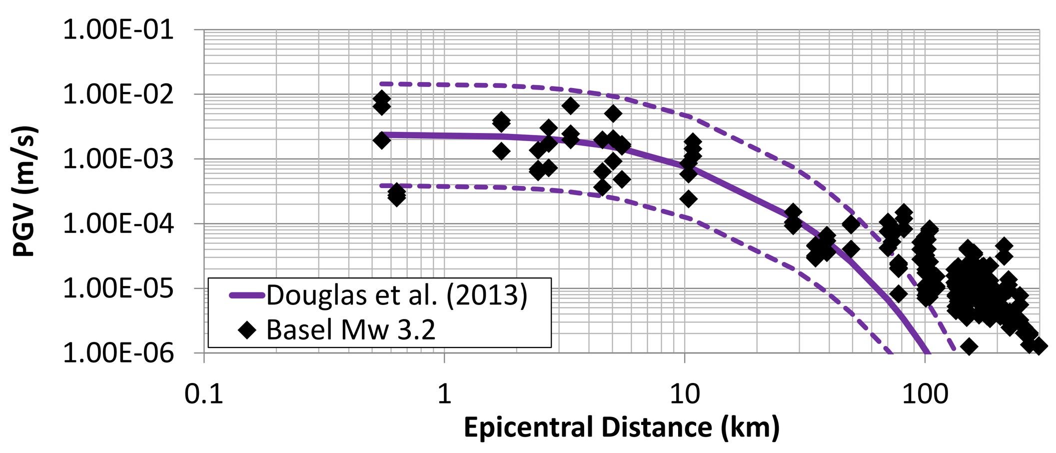


Figure 2. *PGV (3-component) from the Basel **M** = 3.2 event along with the prediction (and plus/minus one within-event standard deviation) from the GMPE of Douglas et al. (2013).*

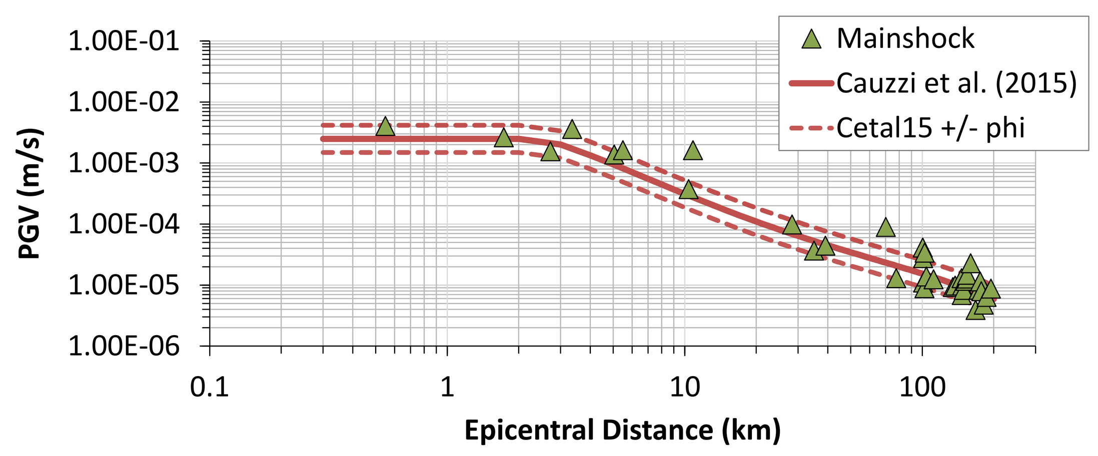


Figure 2. *Comparison of the geometrical mean horizontal PGV (for data points where EGF pairs exist) and the GMPE of Cauzzi et al. (2015).*

Hybrid EGF Approach

54 small events (Figure 1, 427 records at 49 stations) were used to predict PGV for the mainshock (Figure 4). Contoured PGV maps were generated using (i) GMPEs and the (ii) EGF predicted PGV (Figure 5).

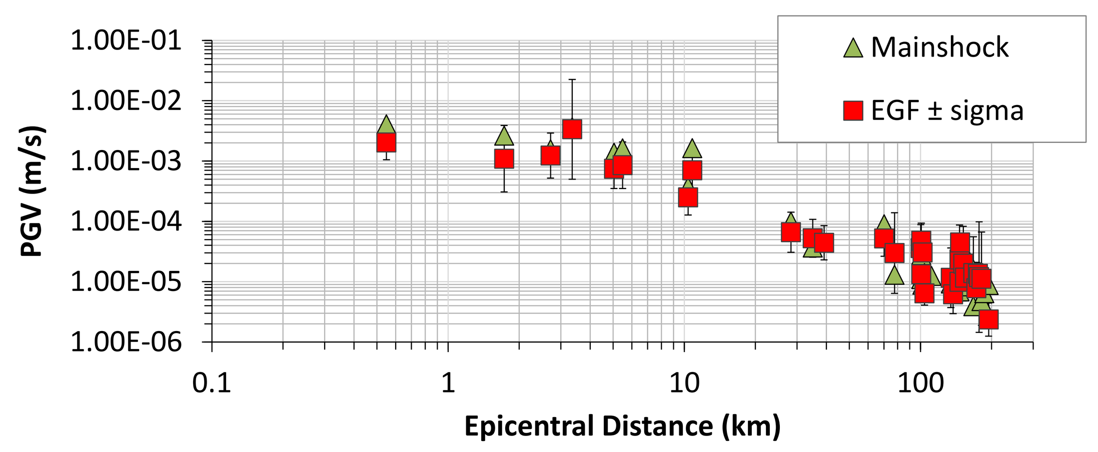


Figure 4. *PGV (geometrical mean horizontal) from the Basel **M** = 3.2 event along with the prediction (and plus/minus one standard deviation) from the EGF predictions.*

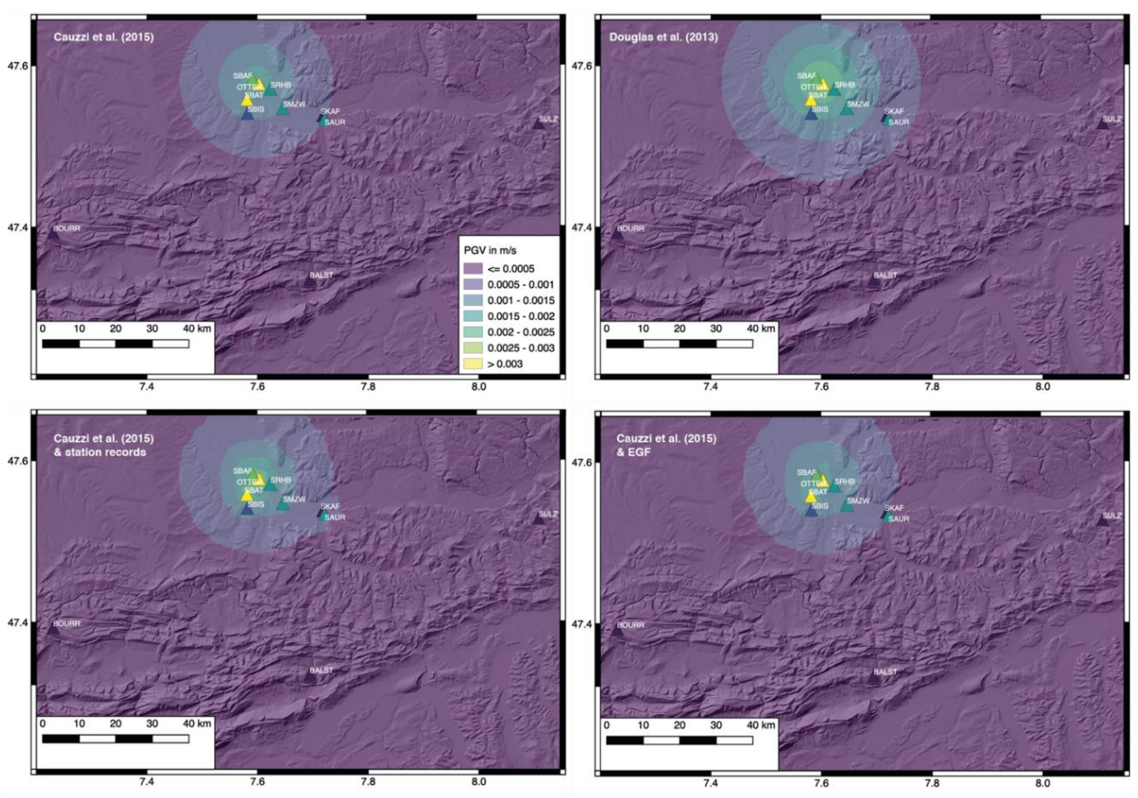


Figure 5. *PGV maps (background) and **M** = 3.2 mainshock amplitude (triangles) for the Basel event. The background maps: the predictions of the Cauzzi et al. GMPE – top left; the predictions of the Douglas et al. GMPE – top right; the interpolation of station records and Cauzzi et al. – bottom left; the interpolation of EGF predictions and Cauzzi et al. – bottom right. The triangles in each map are coloured according to the recorded PGV at each station.*

Uncertainty and Limitations

It is desirable to predict the likely shaking using the smallest possible events, e.g. so that hazard can be updated as close as possible to real-time. Unfortunately, however, upscaling smaller and smaller events amplifies uncertainties or bias. This is shown by comparing the predictions made using only events with M_L ≤ 2 (46 events) and only M_L ≤ 1.5 (20 events) (Figure 4).

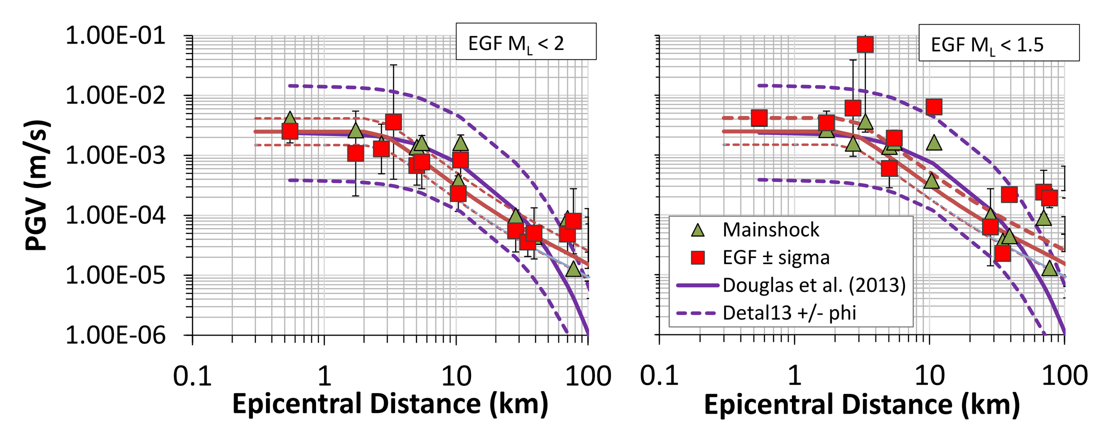
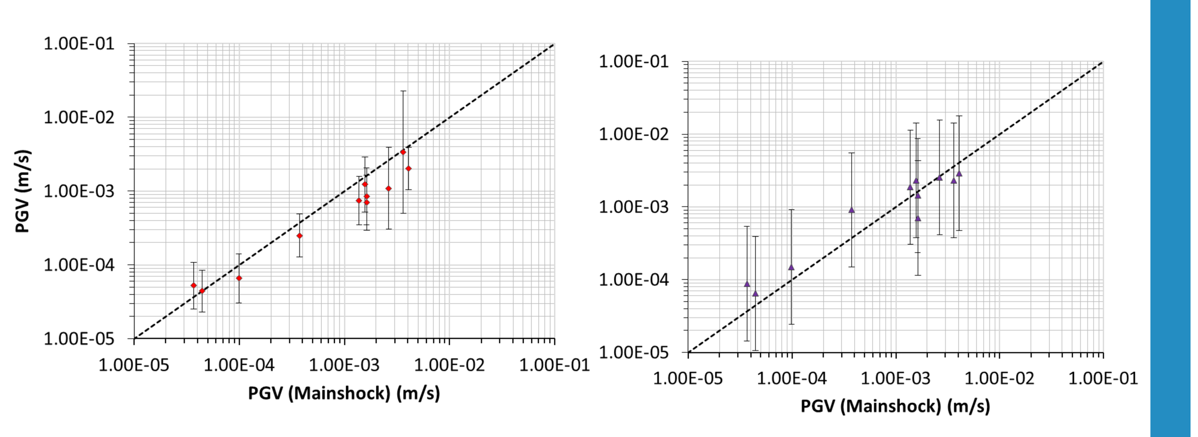


Figure 6. *As Figure 4,* using only events with M_L < 2 (left, 46 EGF events) and M_L < 1.5 (right, 20 EGF events) and showing the GMPEs of Cauzzi et al. (2015) and Douglas et al. (2013).



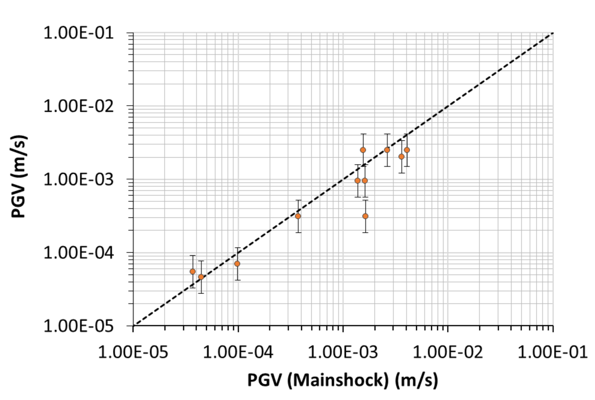


Figure 6. *Comparison of predicted PGV versus mainshock PGV for: the EGF (top left); the Douglas et al. (2013) GMPE (top right) and the Cauzzi et al. (2015) GMPE (bottom left).*

Conclusions

- Hybrid EGF predictions provide unbiased estimates of PGV (and by extension, PGA, PSA) using records of microseismic events prior to (or during) episodes of induced seismicity.
- Predictions implicitly include characteristic source, path and site effects (similar to a locally derived GMPE), hence reducing uncertainty (consistent with the single-station sigma model) and providing spatial distribution of predictions.
- Using a limited number of events (or events with too low magnitude or high noise levels) may lead to overestimation of predicted PGV. This could be refined in future applications by implementing a EGF filtering and/or QA steps.
- We suggest that the individual EGF predictions (i.e. a single upscaled micro-seismic event) are used to form a statistical distribution of possible motions (i.e. Figure 4: mean and standard deviation). This probabilistic prediction may then form part of a weighted mean (e.g. including GMPE predictions) in the early stages of episodes of induced seismicity. As local data becomes more readily available, we can move to fully EGF-based predictions, reducing uncertainty and potential bias due to the use of inappropriate GMPEs.

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This Article: Edwards, B., Staudenmaier, N., Cauzzi, C. and Wiemer, S., (2018). A Hybrid Empirical Green's Function Technique for Predicting Ground Motion from Induced Seismicity: Application to the Basel Enhanced Geothermal System. *Geosciences*, *8*(5), p.180.