ERRATUM

Erratum to "The relationship between **M** and M_L – a review and application to induced seismicity in the Groningen gas field, the Netherlands" by Bernard Dost, Benjamin Edwards and Julian J Bommer, *Seismological Research Letters* **89**(3), 1062-1074, 2018.

by Bernard Dost, Benjamin Edwards and Julian J Bommer

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In response to induced earthquakes associated with conventional gas production in the Groningen gas field in the Netherlands, several networks of seismic monitoring instruments have been installed in the region (Dost *et al.*, 2017). The recordings recovered from these networks have been of fundamental importance to the development of ground-motion prediction models that underpin hazard and risk modeling to inform decision-making regarding mitigation measures (van Elk *et al.*, 2019). In late 2018 it was discovered that the surface accelerographs of the G-network had been installed with a calibration error such that the majority of the instruments were recording half of the correct ground-motion amplitudes. The error was swiftly corrected via the web site of KNMI (Royal Netherlands Meteorological Institute), which operates the networks. The calibration error explains, for example, the relatively low amplitudes observed in some of the KNMI network recordings in Fig. 3 of Bommer *et al.* (2017a).

Following discovery of the calibration error, work immediately began to assess the impact on the ground-motion models that have been developed as part of the induced seismic hazard and risk modeling effort in Groningen. The early ground-motion model of Bommer *et al.* (2016) was not affected because it was developed using only recordings from the KNMI B-network. The subsequent ground-motion models for the prediction of peak ground acceleration (PGA), peak ground velocity (PGV), and acceleration response spectra combined recordings from the B- and G-networks, but fortuitously did not use the surface accelerographs of the G-network. Rather, from these stations, recordings from the 200-meter geophones were used instead, a decision partly motivated by the improved signal-to-noise ratios of the deeper recordings. Another key consideration was the desire to by-pass uncertainty in the amplification factors relative to the buried reference rock horizon at ~800 m depth since the G-network stations had not benefited from the same *in situ* near-surface shear-wave velocity measurements as were conducted for the B-network accelerographs (Noorlandt *et al.*, 2018).

Two elements of the more recent ground-motion models did make use of the surface accelerograph recordings from both the B- and G-networks, but in neither case did the calibration error have any impact at all. The model for predicting ground-motion durations (Bommer *et al.*, 2017b) uses the significant duration definition, which is determined as the interval between accumulation of 5% and 75% of the total Arias intensity, a metric that is entirely insensitive to amplitude scaling of the record. The component-to-component variability model (Stafford *et al.*, 2019)—used to transform the geometric mean amplitudes predicted for the hazard into the arbitrary horizontal component used in the risk calculations—was derived from ratios of the two horizontal components of each accelerogram, which are also completely independent of amplitude scaling. The study of Stafford *et al.* (2019) additionally proposed a model for spatial correlations among response spectral ordinates in the Groningen field that made use of recordings from the G-network. The inclusion of these records will have influenced the results of that study, but most likely only by a small amount given that the results were obtained by averaging over multiple datasets and modelling approaches, and also that some of these analyses were entirely independent of the G-network. The seismic risk calculations for the Groningen field (van Elk *et al.*, 2019) currently approximate spatial correlation through rules for sampling variability within and between site response zones (Rodriguez-Marek *et al.*, 2017) rather than directly implementing the model of Stafford *et al.* (2019).

Another element of the ground-motion modeling that made use of the surface accelerograph recordings is the relationship between local and moment magnitudes in Groningen, as presented by Dost *et al*. (2018). This relationship—which in the magnitude range of relevance ($M_L \geq 2.5$) is one of equivalence between the two scales—is invoked for assigning seismic moments to events as part of the inversions of Fourier amplitude spectra for source, path and site parameters, as well as in calibrating the upper branches of the ground-motion logic-tree to match predictions from ground-motion prediction equations (GMPE) derived for tectonic earthquakes. Since recordings from surface accelerographs of the G-network were included in the calculation of seismic moments, many of the moment magnitude values have required correction: the changes in values are illustrated in Fig. 1 and a corrected version of the electronic supplement is now available (Table S1). As can be appreciated in Fig. 1, the impact has mainly affected smaller magnitudes since the larger earthquakes in the database were predominantly recorded by the accelerographs of the B-network. The correction of the data has resulted in a small change to the quadratic relationship between the two magnitude scales, as illustrated in Fig. 2. The corrected equation is:

$$\mathbf{M} = 0.0469\, M_L^2 + 0.6387\, M_L + 0.6375 \qquad (1)$$

As would be expected, the corrected relationship predicts slightly larger moment magnitudes for local magnitude smaller than M_L 2.5, but the conclusion of equivalence, on average, at higher magnitudes is unchanged. The quadratic form of equation (1) is only a convenient way to express the relationship in a single formula, and in practice it is probably appropriate to assume a linear relationship ($M_W = M_L$) for larger magnitudes; consequently, the apparent divergence from this model that would be implied by extrapolation of the cyan curve in Fig. 2 to larger magnitudes can be safely ignored.

In light of this finding, it may be concluded that the Groningen ground-motion models have been entirely unaffected by the unfortunate calibration error. However, for any application involving smaller magnitude induced earthquakes in the Groningen field, the updated model presented herein should now be used.

Data and Resources

The data used in this work are available at the Royal Netherlands Meteorological Institute (KNMI) Seismic and Acoustic Data Portal (http://rdsa.knmi.nl/dataportal/, last accessed March 2019).

Acknowledgments

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References

Bommer, J.J., B. Dost, B. Edwards, P.J. Stafford, J. van Elk, D. Doornhof, and M. Ntinalexis (2016). Developing an application-specific ground-motion model for induced seismicity, *Bulletin of the Seismological Society of America* **106**, no. 1, 158-173.

Bommer, J. J., B. Dost, B. Edwards, P. P. Kruiver, M. Ntinalexis, A. Rodriguez-Marek, P. J. Stafford, and J. van Elk (2017a). Developing a model for the prediction of ground motions due to earthquakes in the Groningen gas field, *Netherlands Journal of Geoscience* **96**, no. 5, s203–s213, doi: 10.1017/njg.2017.28.

Bommer, J. J., P. J. Stafford, B. Edwards, B. Dost, E. van Dedem, A. Rodriguez-Marek, P. Kruiver, J. van Elk, D. Doornhof, and M. Ntinalexis (2017b). Framework for a ground-motion model for induced seismic hazard and risk analysis in the Groningen gas field, the Netherlands, *Earthquake Spectra* **33**, no. 2, 481–498.

Dost, B., B. Edwards, and J.J. Bommer (2018). The relationship between **M** and M_L – a review and application to induced seismicity in the Groningen gas field, the Netherlands, *Seismological Research Letters* **89**, no. 3, 1062-1074.

Dost, B., E. Ruigrok, and J. Spetzler (2017). Development of seismicity and probabilistic seismic hazard assessment for the Groningen gas field, *Netherlands Journal of Geoscience* **96**, no. 5, s235–s245, doi: 10.1017/njg.2017.20.

Noorlandt, R.P., P.P. Kruiver, M.P.E. de Kleine, M. Karaoulis, G. de Lange, A. Di Matteo, J. von Ketelhodt, E. Ruigrok, B. Edwards, A. Rodriguez-Marek, J.J. Bommer, J. van Elk, and D. Doornhof (2018). Characterisation of ground-motion recording stations in the Groningen gas field. *Journal of Seismology* **22**, no. 3, 605-623.

Rodriguez-Marek, A., P.P. Kruiver, P. Meijers, J.J. Bommer, B. Dost, J. van Elk, and D. Doornhof (2017). A regional site-response model for the Groningen gas field. *Bulletin of the Seismological Society of America* **107**, no. 5, 2067-2077.

Stafford, P.J., B.D. Zurek, M. Ntinalexis, and J.J. Bommer (2019). Extensions to the Groningen ground-motion model for seismic risk calculations: component-to-component variability and spatial correlation, *Bulletin of Earthquake Engineering*, doi: 10.1007/s10518-018-0425-6.

van Elk, J., S.J. Bourne, S.J. Oates, J.J. Bommer, R. Pinho, and H. Crowley (2019). A probabilistic model to evaluate options for mitigating induced seismic risk, *Earthquake Spectra*, doi: 10.1193/050918EQS118M.

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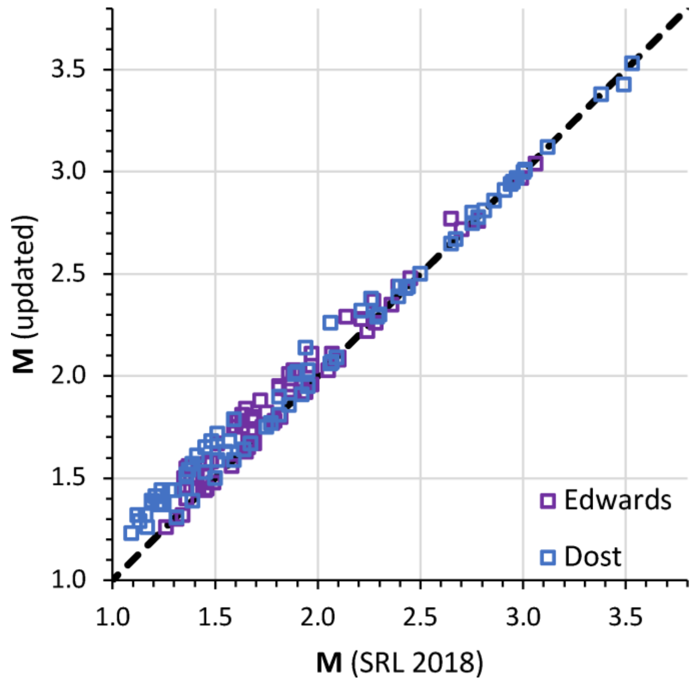
Figure 1. Original (Dost et al., 2018) versus modified (this Erratum) moment magnitude values following application of the calibration correction. Two sets of values are presented: (i) using the method proposed by Dost et al. (2018), as provided in the Electronic Supplement of Dost et al. (2018) and this Erratum (Table S1) and (ii) using the method of Edwards et al. (2010) applied to a sub-set of the events for comparison, as shown in Figure 6 of Dost et al. (2018).

Figure 2. Corrected magnitude data, the original relationship (green) and corrected equation (cyan).

Figures



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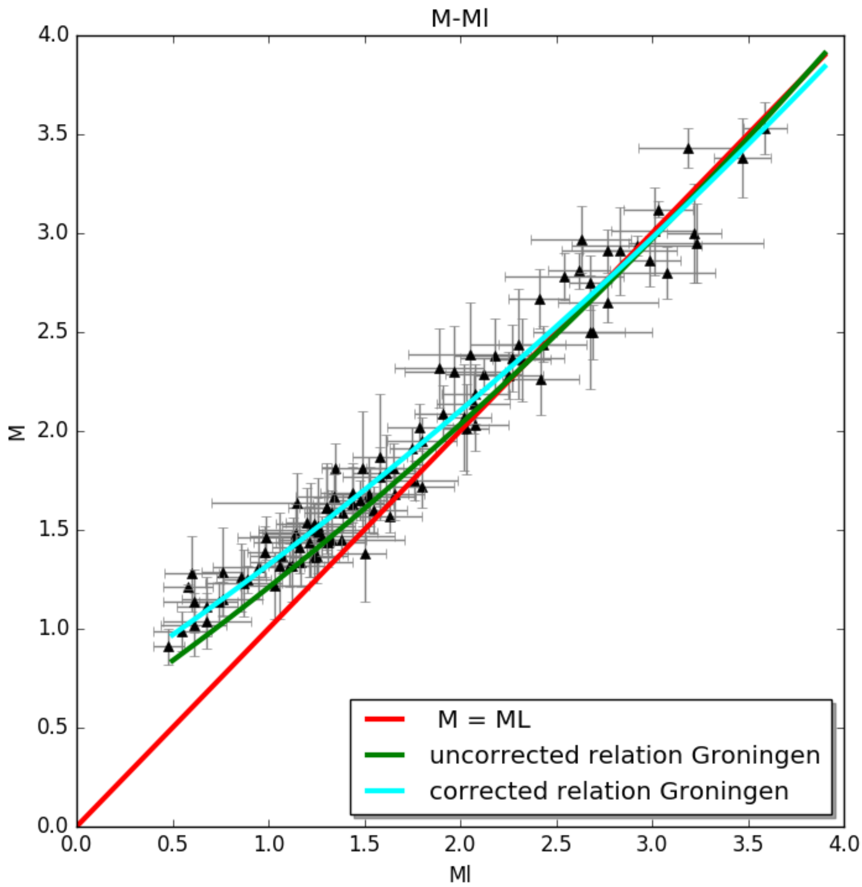

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