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Framework for a Ground-Motion Model for Induced Seismic Hazard and Risk Analysis in the Groningen Gas Field, The Netherlands

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The potential for building damage and personal injury due to induced earthquakes in the Groningen gas field is being modeled in order to inform risk management decisions. To facilitate the quantitative estimation of the induced seismic hazard and risk, a ground motion prediction model has been developed for response spectral accelerations and duration due to these earthquakes that originate within the reservoir at 3 km depth. The model is consistent with the motions recorded from small-magnitude events and captures the epistemic uncertainty associated with extrapolation to larger magnitudes. In order to reflect the conditions in the field, the model first predicts accelerations at a rock horizon some 800 m below the surface and then convolves these motions with frequency-dependent nonlinear amplification factors assigned to zones across the study area. The variability of the ground motions is modeled in all of its constituent parts at the rock and surface levels.

INTRODUCTION

Gas production in the Groningen field in the northeast Netherlands is causing induced earthquakes, in response to which the field operator NAM (Nederlandse Aardolie Maatschappij) is developing seismic risk estimates as a basis for decisions regarding risk-mitigation measures (e.g., Bommer et al. 2015a). A key element of this risk estimation is a

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model for the prediction of surface ground motions due to these earthquakes and potential larger events that might occur as production continues.

The Groningen gas field, which is the 7th largest in world based on initial reserves, was discovered in 1959 and gas production began in 1963. The reservoir, located in the Rotliegend sandstone at a depth of 3 km, is now almost three-quarters depleted, which has led to compaction that has reactivated normal faults that traverse the reservoir layer. The first perceptible earthquakes occurred some 15 years and the largest event to date was the M_L 3.6 (**M** 3.4) Huizinge earthquake of 16 August 2012. In response to these induced earthquakes, NAM has initiated an intense data collection and study program to model the resulting hazard and risk. A key element of the hazard and risk assessments is the ground-motion prediction model described herein.

The development of the ground motion model has focused on reflecting the local conditions as accurately as possible, which has benefited from extensive efforts to collect new data both in terms of ground motion recordings and the characteristics of the near-surface materials over the field, which are dominated by deep layers of soft soil deposits. At the same time, the model attempts to capture the large uncertainty inevitably associated with extrapolation from the small-magnitude events recorded until now to the largest magnitude earthquakes considered in the hazard and risk calculations. The model is exclusively applicable to the Groningen field but the approach adopted for its development may provide an alternative to the use of more generic models for induced seismicity such as have been proposed by Douglas et al. (2013) and Atkinson (2015).

GROUND-MOTION RECORDING NETWORKS AND DATABASE

The development of a ground motion prediction model for the Groningen field has benefited greatly from pre-existing and expanded networks of accelerographs, which have yielded important recordings of ground shaking from all of the larger induced earthquakes.

The seismological service of the Royal Dutch Meteorological Institute (KNMI) has operated a network of digital accelerographs in the Groningen field for many years. In recent years, this network has been upgraded and expanded to 18 operational instruments (Fig. 1). As part of the response to the 2012 Huizinge earthquake, NAM has funded the installation of an additional ~70 accelerographs, each of which is collocated with a 200-meter borehole in which geophones are installed every 50 m (Fig. 1).

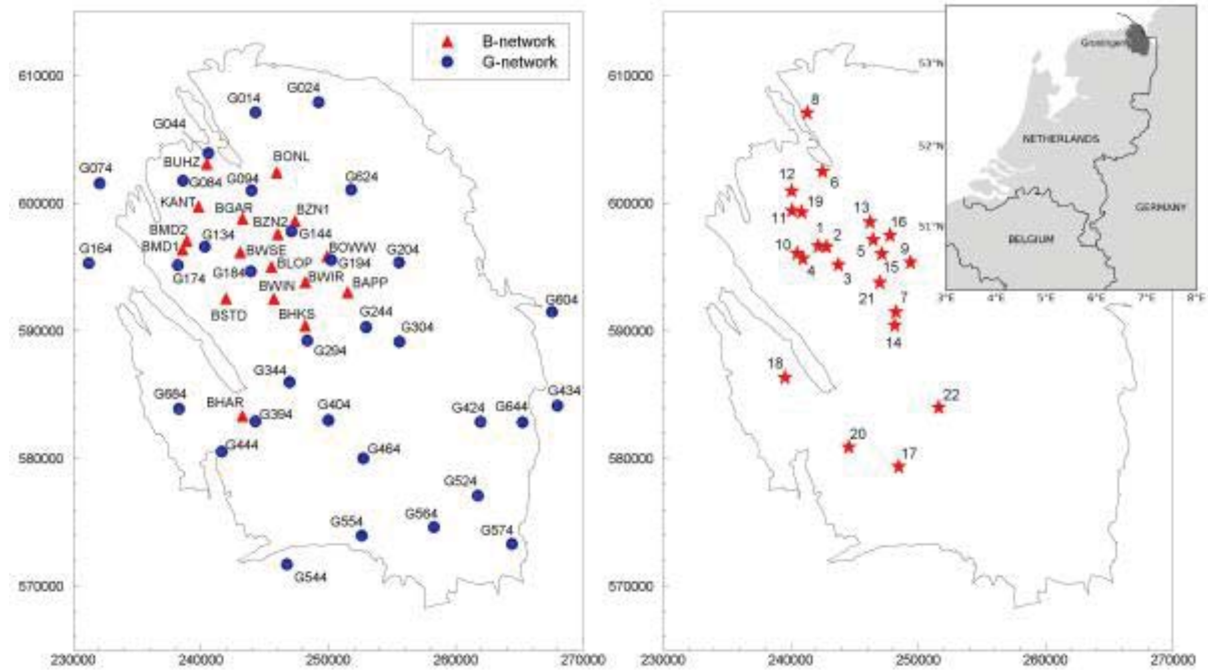

Figure 1. *Left*: KNMI permanent accelerograph network (red triangles) and new borehole instruments (blue circles) in the Groningen field that have contributed recordings to the current ground-motion database; *right*: epicenters of earthquakes of $M_L \geq 2.5$ contributing to the current database. Coordinates expressed in the Dutch RD (Rijks-Driehoek) system in meters. Inset shows location of the Groningen gas field.

Another network of accelerographs has been installed by the Dutch research organization TNO on behalf of NAM. These 200+ instruments have been installed in public buildings and private homes. A fourth network consists of accelerographs installed at the NAM gas production facilities for the purposes of triggering safe-shutdown in the event of strong shaking. Recordings from these two networks are being evaluated for incorporation into the ground-motion database for future model development, but the current model is based on recordings from the instruments depicted in Fig. 1. In order to reduce uncertainty in the model development, *in situ* measurements of the shear-wave velocity (V_S) profile over the upper ~30 m were performed at the KNMI surface accelerographs (B-stations in Fig. 1) using active MASW, seismic CPT and, in some cases, down-hole and cross-hole measurements of V_S.

For the purposes of deriving the Groningen ground motion model (GMM), only earthquakes of M_L 2.5 and greater have been considered since even for the exposed masonry dwellings in the field, it is very unlikely that smaller events could present a threat. The magnitude-distance distribution of the current database of 178 recordings from 22 earthquakes is shown in Fig. 2.

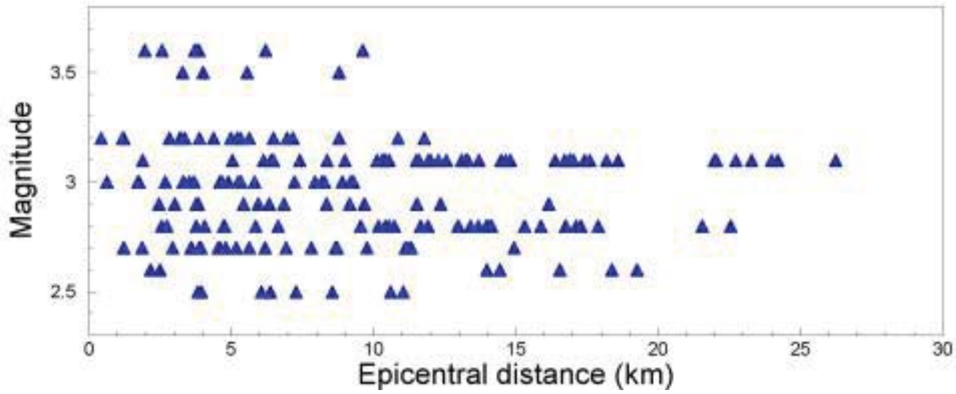

Figure 2. Distribution of ground-motion database in terms of local magnitude and epicentral distance

The number of available records for each earthquake has steadily increased over time: there are 7 records from the 2012 Huizinge earthquake, compared with 42 from the most recent event, an earthquake of M_L 3.1 that occurred in September 2015. The largest recorded value of horizontal peak ground acceleration (PGA) is the $0.08g$ obtained at an epicentral distance of 2 km from the 2012 Huizinge earthquake; the corresponding value of peak ground velocity (PGV) was 3.5 cm/s.

An important point to note is the limited useable bandwidth of the recordings, which is not unexpected in view of the small magnitudes of the earthquakes. After applying 8-order Butterworth high-pass filters to the horizontal components of motion, the number of available records drops off very rapidly beyond an oscillator period of about 1 second, with practically no useable data beyond 2.5 seconds.

FRAMEWORK FOR GRONINGEN GROUND-MOTION MODEL

As a result of the urgency to respond to the potential threat of induced earthquakes in the Groningen field, the development of the hazard and risk models—and hence each of their components also—has been evolutionary and incremental since approaches have been adopted to facilitate the need for robust estimates at several reporting stages.

EVOLUTION OF GRONINGEN GROUND MOTION MODELS

The GMMs for induced earthquakes in the Groningen field have undergone several stages of development and while ongoing refinements will be made (see Discussions and Conclusions), the basic framework of the model is now stable.

The first stop-gap model adopted for the initial seismic hazard assessment was based on the equations of Akkar et al. (2014b) derived from recordings of tectonic earthquakes in Europe and the Middle East. For magnitudes below about 4, magnitude-dependent adjustments were made to several coefficients in order for the model to fit the Groningen data at smaller magnitudes (Bourne et al. 2015).

The next stage of evolution of the Groningen GMM was developed using inversions of the recorded motions to obtain estimates of source, path and site parameters for the field. Stochastic simulations were then generated to obtain predictions over the full range of magnitudes considered in the hazard and risk calculations (up to at least 6.5), with alternative values of the stress parameter used to obtain alternative models that diverged at larger magnitudes, reflecting the epistemic uncertainty in the extrapolation from small to large magnitudes. This paper explains the incorporation of nonlinear site response effects into the model accounting for lateral variations in the near-surface soil profiles.

OVERVIEW OF MODELING APPROACH

The current GMM for Groningen is an adaptation of the approach followed by Bommer et al. (2016a) to invert the ground motions for source, path and site parameters, and then use stochastic simulations to estimate median motions over the full ranges of magnitude and distance considered in the hazard and risk analyses. The important difference is that the inversions and predictions are made at a reference rock horizon and these predicted motions are then combined with probabilistic frequency-dependent nonlinear site amplification factors to obtain the surface motions. Such a convolution of probabilistic estimates of ground shaking at a buried rock horizon with probabilistic site amplification factors results in correctly calculated probabilities of the surface motions (Bazzurro and Cornell 2004). In the nuclear industry, this is generally referred to as Approach 3 (McGuire et al. 2001); however, because of the implementation the Groningen GMM within a Monte Carlo framework (Bourne et al. 2015), this actually represents Approach 4, which is essentially the development of site-specific predictions incorporating nonlinear site response.

Figure 3 schematically illustrates the procedure followed to develop the model in terms of a ground motion prediction equation (GMPE) for accelerations at the NS_B rock horizon and probabilistic amplification factors to transfer the rock motions to the ground surface. The reference rock horizon is the base of the North Sea supergroup, located at an average depth of about 800 m. This marks a significant impedance contrast with the underlying limestones of the Cretaceous chalk (across which shear-wave velocities double to about 1.5 km/s), which in turn is underlain by the Zechstein salt layer that is immediately above the gas reservoir (Rodriguez-Marek et al. 2017). The stochastic ground motion simulations therefore model the propagation from the reservoir to the base of the North Sea supergroup, and these provide the basis for the rock GMPEs described in the next section. The propagation of seismic waves from this rock horizon to the ground surface is modeled by the site amplification zonation of the gas field as summarized in a later section.

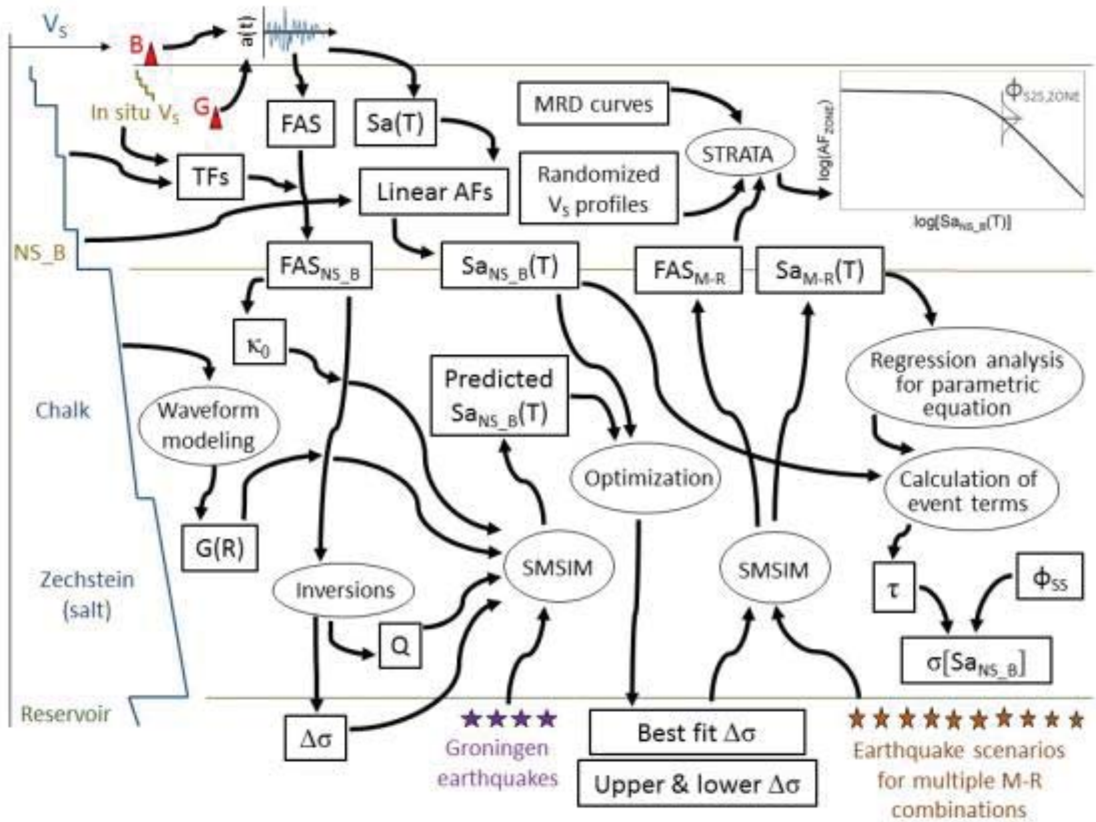

Figure 3. Schematic illustration of the derivation of the Groningen ground-motion model for response spectral accelerations at the surface, with quantities in rectangles and processes in ellipses. B and G refer to the surface and borehole stations (Fig. 1) and NS_B is the reference rock horizon. TF is transfer function, AF is amplification factor, FAS is Fourier amplitude spectra, Sa(T) is response spectral acceleration at period T; G(R) is the shape of the geometric spreading function; SMSIM is the software used for the stochastic simulations (Boore 2005); STRATA is the site response program by Kottke and Rathje (2008) used to conduct RVT-based 1D equivalent linear response analyses. MRD refers to modulus reduction and damping in the site response; M-R refers to magnitude-distance pairs, and the suffix ZONE refers to the zonation of the field for site amplification factors. The elements of the total aleatory variability at the rock horizon (σ) are the between-event (τ) and single-station within-event (φ_{SS}) standard deviations; the additional variability in the site amplification factors is the site-to-site standard deviation (φ_{S2S}).

GROUND-MOTION REQUIREMENTS FOR RISK CALCULATIONS

Before describing the model development, it is useful to clarify the requirements in terms of predicted parameters required as input to the risk calculations, which is determined by the ground-motion parameters incorporated into the fragility functions (Crowley et al. 2016). The main input required is predictions of the horizontal response spectral acceleration for a range of oscillator periods. The building typologies predominantly have natural vibration periods of 1 second or less, but there are a few with longer periods and the GMM was extended to 5 seconds to accommodate the possibility of seismically-isolated buildings. For hazard calculations, the geometric mean horizontal component was adopted in accordance with standard practice, but for the risk calculations the arbitrary horizontal component was used. The latter choice was simply to allow single-component accelerograms to be used in the derivation of the fragility functions (Baker and Cornell 2006). The median predictions for the two definitions of the horizontal component are identical, but for the arbitrary horizontal component the sigma value (logarithmic standard deviation) needs to be increased by the component-to-component variability (discussed in the next section).

Since many building types have different vibration periods in the two orthogonal directions, and also since the risk estimation involves calculating the expected damage for all buildings at a single location for each ground-motion realization, period-to-period spectral correlations were also required. The Groningen data are found to have period-to-period correlations broadly comparable to published relationships (in the range of useable data), so Baker and Jayaram (2008) was adopted as a suitable period-to-period correlation model that covers the full range of target periods.

Finally, for some building typologies it was found that the addition of duration made the fragility function more efficient. Consequently, the model was also required to predict vectors of spectral acceleration and strong-motion duration, as summarized later in the paper.

GMPE FOR REFERENCE ROCK HORIZON

The first part of the Groningen GMM is GMPEs for spectral accelerations at the selected reference rock horizon, which is located at the bottom of the North Sea supergroup some 800 m below the ground surface and is referred to as NS_B.

RECORDED MOTIONS AT ROCK HORIZON

The first stage in developing the GMPE for the NS_B is to transform the surface recordings to this reference horizon. A key assumption in the process is that because the motions recorded to date are very weak, the near-surface layers have responded essentially linearly to the excitations and therefore the deconvolution can be made assuming linear site response.

A key part of the Groningen GMM model is a field-wide V_S model from the surface down to the NS_B horizon, developed using a variety of data sources covering different depth ranges (Kruiver et al. 2017). As noted earlier, at the B-stations (Fig. 1) there are measured shallow V_S profiles, and these were used to modify the near-surface sections of field-wide profiles at these locations. For the borehole locations (G-stations in Fig. 1), where such *in situ* measurements have yet to be made, we instead opted to use the 200-m geophone recordings (velocity time-histories that were transformed to accelerations) and to thereby remove the influence of the near-surface profiles at these locations. The Fourier amplitude spectra (FAS) from the surface and from the 200-m boreholes were transformed to the NS_B horizon—which has a V_S close to 1.5 km/s and a unit weight of 21 kN/m^3—using a one-dimensional transfer function as implemented in STRATA (Kottke and Rathje 2008). Linear amplification factors are also calculated for the response spectra using the RVT procedure implemented in STRATA. The factors are calculated for the same V_S, damping and unit weight profiles, with input motions at the NS_B obtained from simulations—using an earlier version of the model—for magnitudes M_L 2.5 to 3.6 and distances from 0 to 20 km, consistent with distribution of the dataset (Fig. 2). Figure 4 shows examples of recorded horizontal response spectra and their appearance after transformation to the NS_B horizon.

SOURCE, PATH AND SITE PARAMETERS FOR GRONINGEN SEISMIC MOTIONS

The FAS at the NS_B horizon were then inverted, following the approach of Edwards et al. (2011), for source, path, and site parameters (Fig. 3). All FAS, deconvolved to the NS_B rock horizon, are fit with a parametric model. The spectra are first assessed for the useable bandwidth (Figure 5). The maximum analyzed frequency band of the FAS is 0.1 to 50 Hz, with a signal-to-noise (SNR) threshold of a factor of 3 used to define record-specific limits within this range. In practice most records show signal above the noise level over a broad range of frequencies due to the short hypocentral distance ($R < 25$ km) of recordings. Three parameters are then fit to each FAS: the event-specific source corner-frequency (f_0) of a parametric source spectrum (e.g., Brune 1970, Boatwright 1978) in addition to record-specific signal moment (long-period spectral displacement plateau) and κ. A least-squares penalty function is used in a combined grid-search (over event common f_0) and nonlinear Powell's direct search method (Press et al. 2007). Site-specific reference rock transfer functions are then obtained through stacking residual misfit functions.

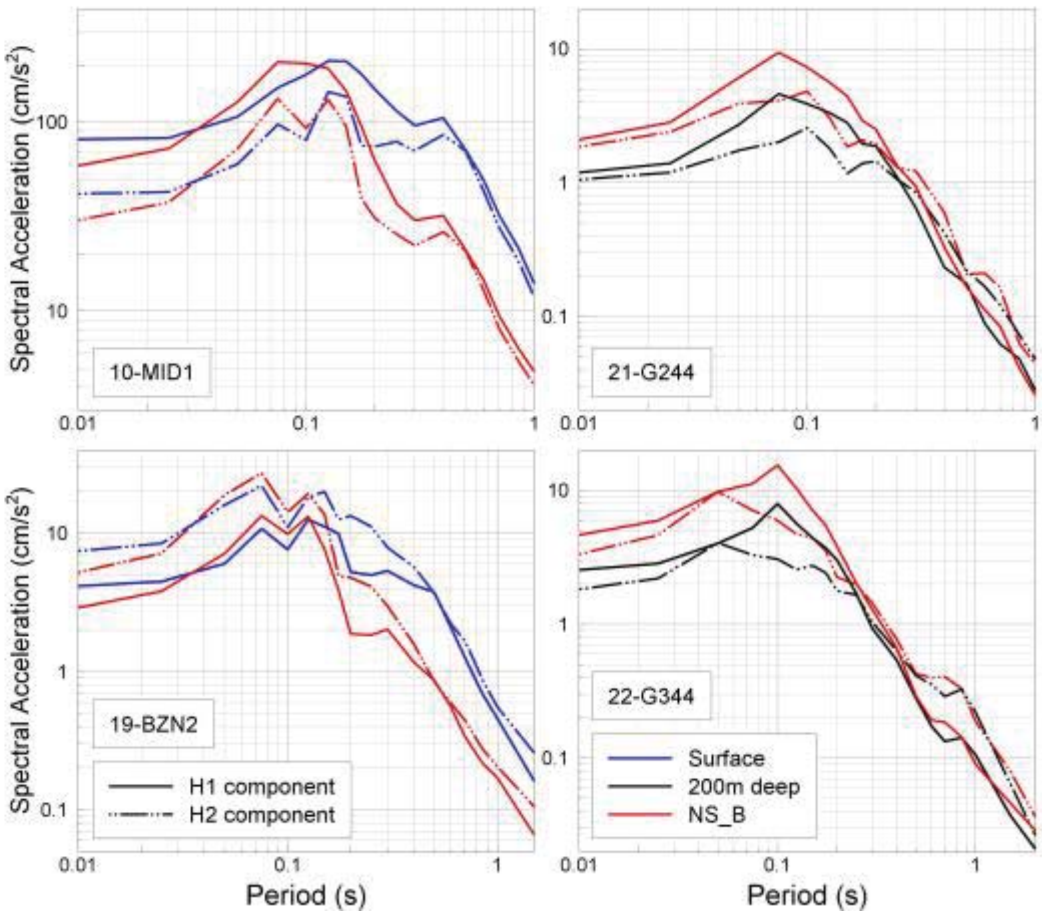

Figure 4. Horizontal response spectra from surface accelerograph (*left*) and 200-m geophone (*right*) recordings, and their transformation to the reference rock horizon (shown in red)

As a result of the relatively small dataset available for these inversions, some elements were constrained independently. Firstly, the high-frequency attenuation term, kappa (κ), was estimated from individual FAS plotted on log-linear axes following Anderson and Hough (1984). Secondly, the geometric spreading—and in particular the distances at which this transitions from near-source to the region of constructive interference due of direct and reflected/refracted waves to far-field decay—were obtained from full waveform finite difference simulations performed using a 3D velocity model for the field. This includes the high-velocity Zechstein salt layer directly above the gas reservoir, which exerts a pronounced effect on seismic wave propagation (Kraaijpoel and Dost 2013). The inversions were then used to estimate the stress parameter ($\Delta\sigma$), the decay rates in each segment, the Q value, and the amplification factor at the NS_B (which was found to be very close to 1). For the inversions, the use of both the Brune (1970) and Boatwright (1978) spectra was explored, with neither found to perform consistently better hence the former was used. A trade-off exists between the parameters hence we determine the range of covariate model parameters that lead to a comparable (±5%) misfit to represent this uncertainty.

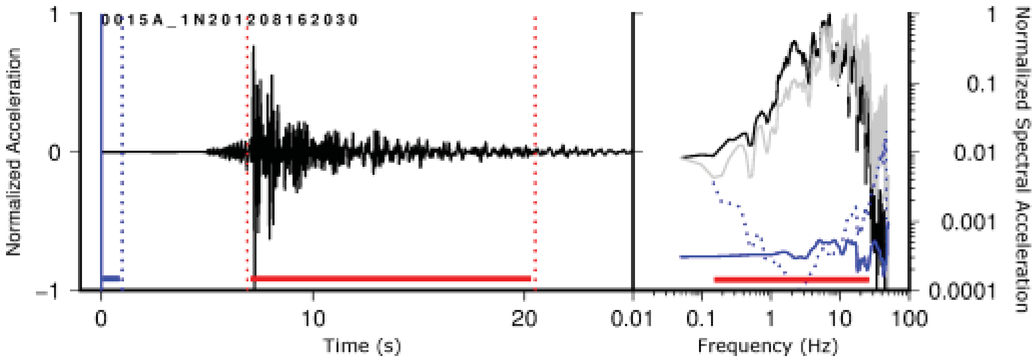

Figure 5. *Left panel*: example acceleration time series of the 2012 M_L3.6 Huizinge earthquake recorded at station 15 (GARST), 14 km from the epicenter. The period highlighted in red indicates the signal and in blue the noise. *Right panel*: Fourier amplitude spectrum of the acceleration time series. Black: as recorded at the surface; grey: deconvolved to the NS_B; solid blue: recorded noise; dotted blue: noise after deconvolution to the NS_B and low frequency adjustment; the frequency range highlighted in red shows the FAS used in inversions (SNR > 3).

The geometric spreading model was found to be proportional to $R^{-1.71}$ up to hypocentral distances of 7 km, $R^{0.69}$ from 7 to 12 km, and then to decay as $R^{-1.67}$ beyond 12 km; spherical decay (R^{-1}) was assumed beyond 25 km, as supported by the full waveform simulations. Using this spreading model and the results of the inversions of the FAS, many combinations of $\Delta\sigma$, Q and site kappa (κ_0) were explored to identify the combination of parameters that best fit the response spectral ordinates at the NS_B horizon (Fig. 6). Based on the RMS bias (root-mean-square bias of response spectra—ln[observed/predicted]—over the 23 analyzed response periods) and the sigma of this bias (calculated as the standard deviation of the bias measurements—one per period—over the range of available period), the final best fitting model for the motions at the NS_B horizon were a stress parameter of 70 bar, a frequency-independent Q of 200, and a site kappa of 0.015 s, which is consistent with the hard rock conditions at the NS_B.

STOCHASTIC GROUND-MOTION SIMULATIONS

The forward simulations for response spectral accelerations at the 23 selected oscillator periods for magnitudes from 2.5 to 6.5 and for distances up to 60 km were performed using SMSIM (Boore, 2005). In extrapolating to magnitudes so much larger than the range covered by the data, account needs to be made for the inevitable epistemic uncertainty in the predictions at larger magnitudes. This was done by both introducing magnitude-dependence of the stress parameter into the model and also creating alternative (higher and lower) models based on different values of the stress parameter inferred from Fig. 6, as had been done previously (Bommer et al. 2016); the stress parameter models are shown in Fig. 7 together with the individual estimates for the 22 earthquakes. The weights assigned to these branches are 0.2 for the lower branch, since it is unclear whether low stress drop values would persist at larger magnitudes, and 0.4 each to the central and upper models.

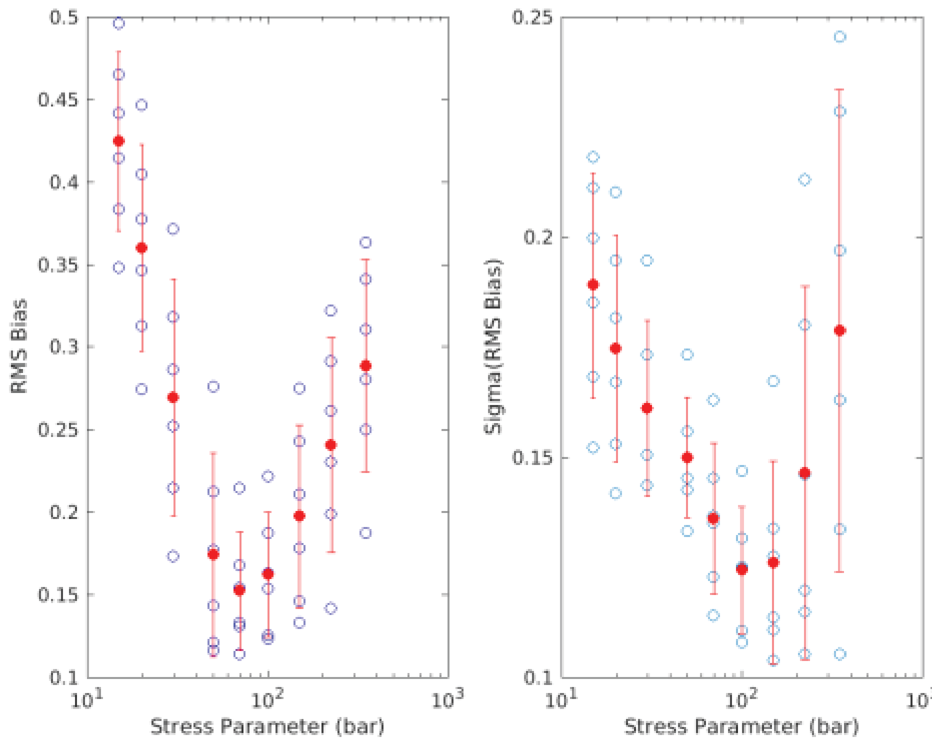

Figure 6. RMS bias (*left*) and sigma (*right*) with respect to the recordings as a function of Δσ for the Q = 200 models. Open circles indicate individual simulations. Red circles indicate the average of all relevant simulations at a given Δσ

Both the inversions and forward simulations were performed including the magnitude-dependent near-source distance saturation term determined for earlier versions of the model (Bommer et al. 2016). This term was obtained from regression on the Groningen data but found to agree closely with the alternative saturation term proposed by Atkinson (2015) when extrapolated to larger magnitudes.

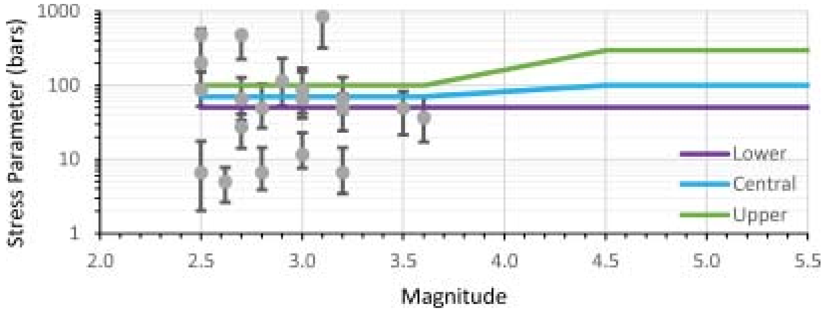

Figure 7. Stress parameter estimates from inversion of the Groningen data (grey circles with error bars) and the stress parameter values used in forward simulations

FUNCTIONAL FORM OF GMPE

In order to facilitate the implementation of the model, regressions were performed to fit a functional form to the results of the stochastic simulations. The functional form of the equation is the same as that adopted by Bommer et al. (2016) for direct predictions at the ground surface, except for the inclusion of segmented geometric spreading. Since the model predicts motions at a rock horizon—assumed uniform across the field—due to normal-faulting earthquakes initiating in the gas reservoir, there are only two independent variables, magnitude and distance. The magnitudes are local magnitudes, which is internally consistent since the same scale is used for the earthquake catalog on which the seismic source model is based (Bourne et al. 2015).

As in the earlier model, epicentral distance is used for convenience to allow point-source simulations of earthquakes in the hazard and risk calculations; since all the earthquakes initiate in the gas reservoir, a horizontal distance metric is sufficient. Clearly for the larger earthquakes considered, the point-source approximation is unrealistic but sensitivity analyses have shown that it is conservative for risk calculations in terms of both individual and aggregate measures (Bommer et al. 2015b). However, future developments will incorporate finite fault ruptures (see Discussion and Conclusions).

SIGMA MODEL

A potential weakness of stochastically-derived GMPEs is the lack of a robust basis for the sigma values. In the development of this model, as in the earlier version presented by Bommer et al. (2016), the components of sigma can be informed by calculation of 'residuals' of the motions at the NS_B horizon since the model is essentially unbiased in the range of useable data (see next section). The between-event sigmas are maintained constant across magnitudes, even though many models indicate higher variability at small magnitudes, and extrapolated to longer response periods by maintaining the last reliably-determined value constant.

Within-event variability can be measured from the NS_B data, after removal of the event terms, but slightly smaller values are adopted for the model since the site-to-site variability, accounted for in the site amplification factors, must be removed. Non-ergodic values of within-event variability were adopted from the model of Rodriguez-Marek et al. (2014) with a modest increase at short periods (< 0.1 s) to reflect the recent findings of Al Atik (2015). As in Bommer et al. (2016), an additional adjustment is applied to the within-event variability for the point-source approximation.

As noted in earlier, in order to transform the predictions of geometric mean horizontal accelerations into the arbitrary horizontal component for the risk calculations, an estimate is needed of the component-to-component variability. The Groningen recordings, which are often observed to be strongly polarized, even on the as-recorded components, display unusually high component-to-component variability compared to values obtained from tectonic databases (e.g. Campbell and Bozorgnia 2007) as can be seen in Fig. 8.

In order to explore whether the large component-to-component variability might be a result of the small-magnitude range of the Groningen data, records were compiled from small-to-moderate magnitude tectonic earthquakes, including the European (Akkar et al., 2014a), NGA-West2 (Ancheta et al., 2016) and KiK-net (Dawood et al. 2016) databases. A weak dependence on magnitude was found, with the component-to-component variability increasing as magnitude decreases, but even restricting the data to magnitude 4 and lower did not result in variances close to those found for Groningen. However, considering only recordings of events of magnitude 6 or smaller and restricting the data to successively shorter maximum distance results in pronounced increases in the component-to-component variability (Fig. 8). This is interpreted as possibly being the result of the radiation pattern from the double-couple source being preserved at short distances, and led to the decision to retain the Groningen values for the modeling. In order to overcome the absence of data at longer periods, however, the variances were replaced by those of Campbell and Bozorgnia (2007) multiplied by factor of 2.25, which were found to be a good approximation to the Groningen values (Fig. 8).

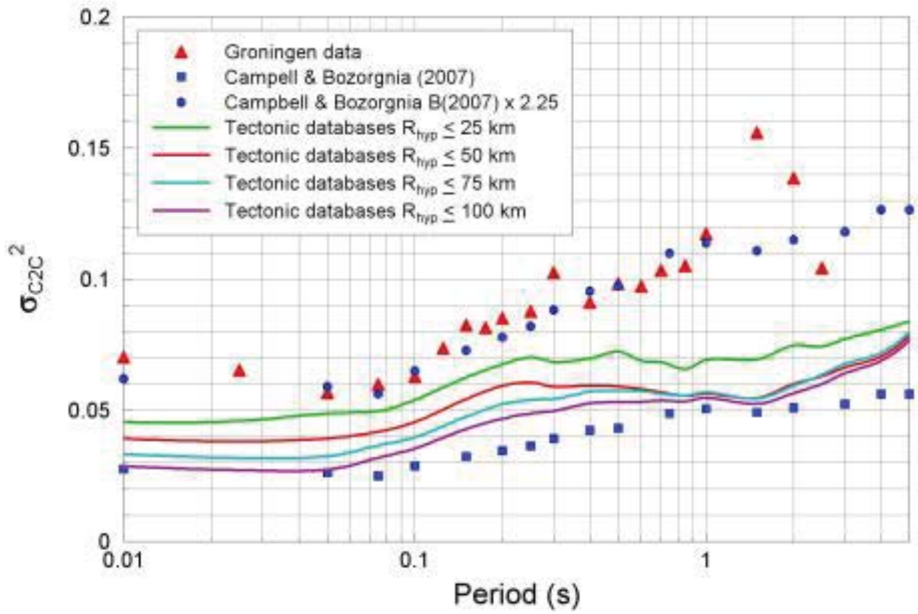

Figure 8. Component-to-component variance (calculated from individual pairs of horizontal components) as a function of period from the Groningen data, the model of Campbell and Bozorgnia (2007), and from a database of tectonic strong-motion earthquake recordings limited to different maximum distances

MODEL FOR SURFACE GROUND MOTIONS

CONVOLUTION OF ROCK HAZARD AND SITE RESPONSE

The predicted motions are transformed to the ground-surface through convolution with site amplification factors. In the Monte Carlo framework in which the hazard and risk model for Groningen has been developed, for each earthquake the between-event variability is randomly sampled and then the ground shaking field generated including random sampling from the within-event variability. This realization of the NS_B spectral acceleration is then used to define the nonlinear amplification factor assigned to the zone in which the site is located. The study area is divided into 161 zones, initially based on near-surface geology (Kruiver et al. 2017) and then refined through extensive site response analyses (Rodriguez-Marek et al. 2017). To generate the final surface motions, the amplification factor is calculated as a function of the NS_B spectral acceleration, randomly sampling from the site-to-site variability (φ_{S2S} in Fig. 3), and then this factor is applied to the same NS_B acceleration. The result is a fully probabilistic estimate of the surface motions.

Although the surface recordings are deconvolved to the NS_B using location-specific measured near-surface V_S profiles and the predictions are made convolving the NS_B motions with zonation-based amplification factors calculated using generic velocity profiles, the model provides a reasonable fit to the recorded motions (Fig. 9).

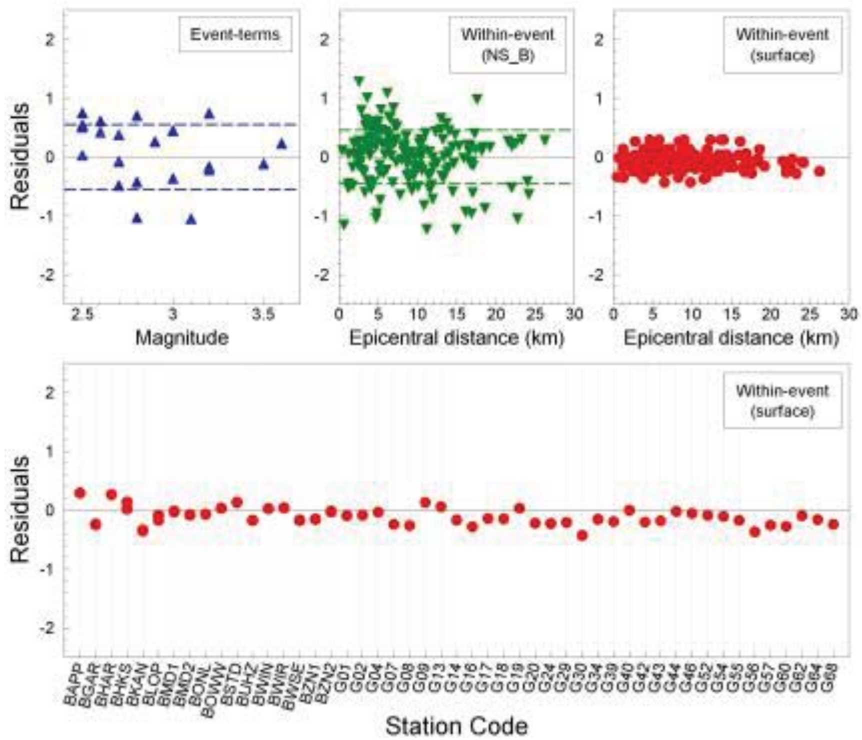

Figure 9. Residuals of recorded motions in terms of spectral acceleration at 0.7 s

The site-response component of the ‘residuals’ are calculated by subtracting the residuals at the NS_B horizon (duly decomposed into between-event and within-event components) from the total residuals estimated at the ground surface. In passing it may be noted that the few cases of large absolute values of the event term all correspond to sparsely-recorded earthquakes. The lower plot, in each case, shows the site-response component of the residuals for each station, from which it may be inferred that there are no pronounced and consistent trends for motions at individual stations to be over- or under-predicted.

Figure 10 shows median predicted response spectra in one of the zones for an earthquake of M_L 5.5 at two distances. The plots show the predicted accelerations at the reference rock horizon and their transform to the surface using the nonlinear amplification factors and also only the linear amplification, to illustrate the contributions from different elements of the model. Note that at longer response periods, the period elongation due to nonlinear response causes slight amplification of the rock motions.

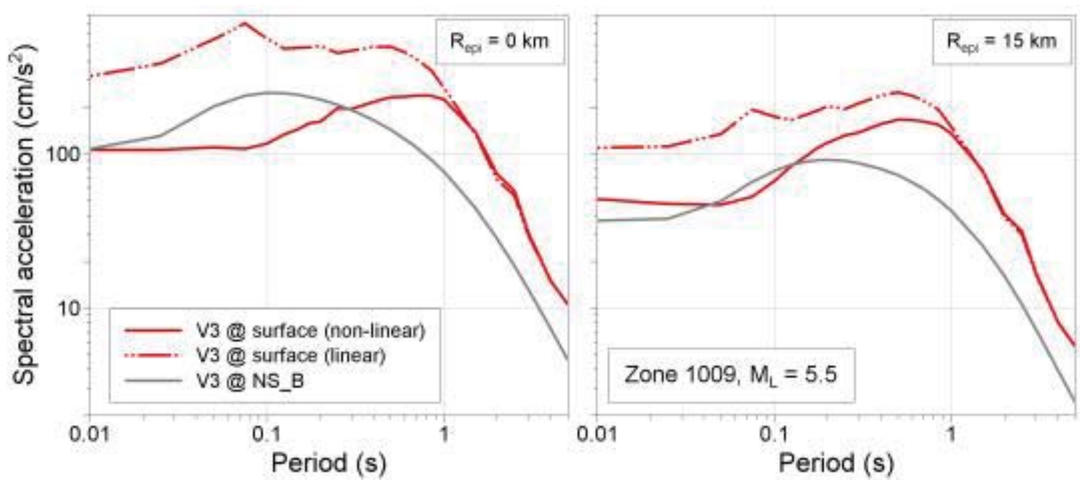

Figure 10. Predicted median response spectra at from a magnitude 5.5 earthquake at two distances (in one zone) at the reference rock horizon and at the surface using both linear and nonlinear amplification factors

VECTORS OF SPECTRAL ACCELERATION AND DURATION

Since the Groningen data are insufficient to derive a location-specific GMPE for duration (using the 5-75% Arias intensity significant duration), the approach adopted was to adjust the state-of-the-art model of Afshari and Stewart (2016) to better match the Groningen data at small magnitudes and short distances. The Afshari and Stewart (2016) model is based on physical considerations, including earthquake stress drop, and is parameterized in terms of magnitude, style-of-faulting, rupture distance, V_{S30} and depth to V_S = 1 km/s. The model is found to over-predict durations at short distances—where the Groningen motions are very short (Bommer et al. 2016)—and it also predicts no magnitude-dependence below **M** 5.35. The adjustments result in a model that is consistent with Groningen data at small magnitudes while retaining the physical basis of the predictions at larger magnitude, also accommodating the alternative stress parameter values adopted for the ground-motion logic-tree (Fig. 11). The durations invoke the median value V_{S30} calculated for each zone (Fig. 12). The correlation function of Bradley (2011) between residuals of durations and spectral accelerations was found to fit the Groningen data.

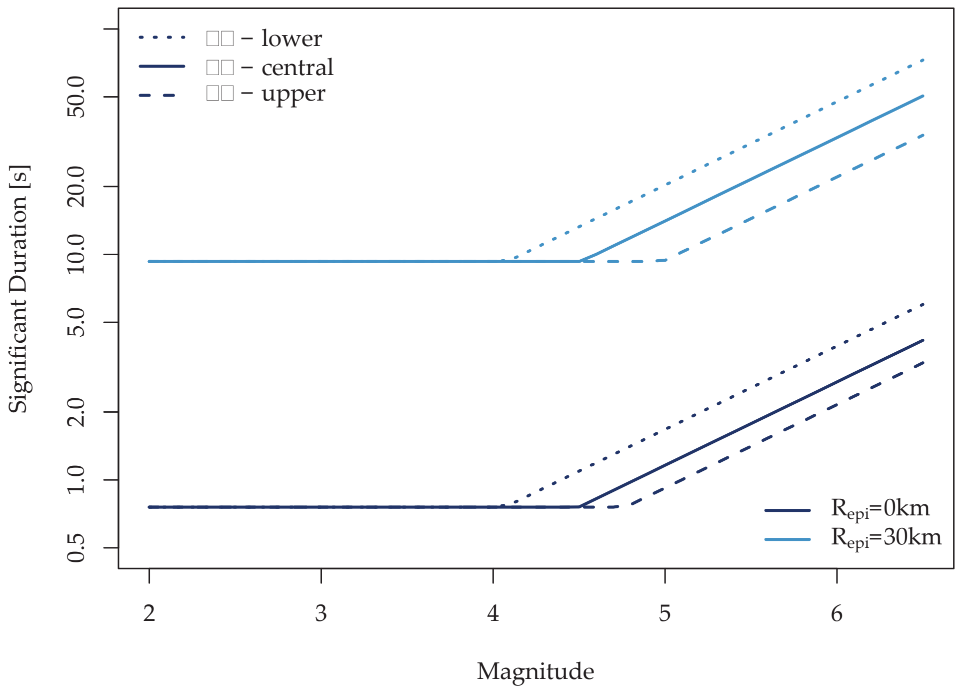

Figure 11. Median predicted values of duration from three Groningen-specific equations as a function of magnitude for two distances

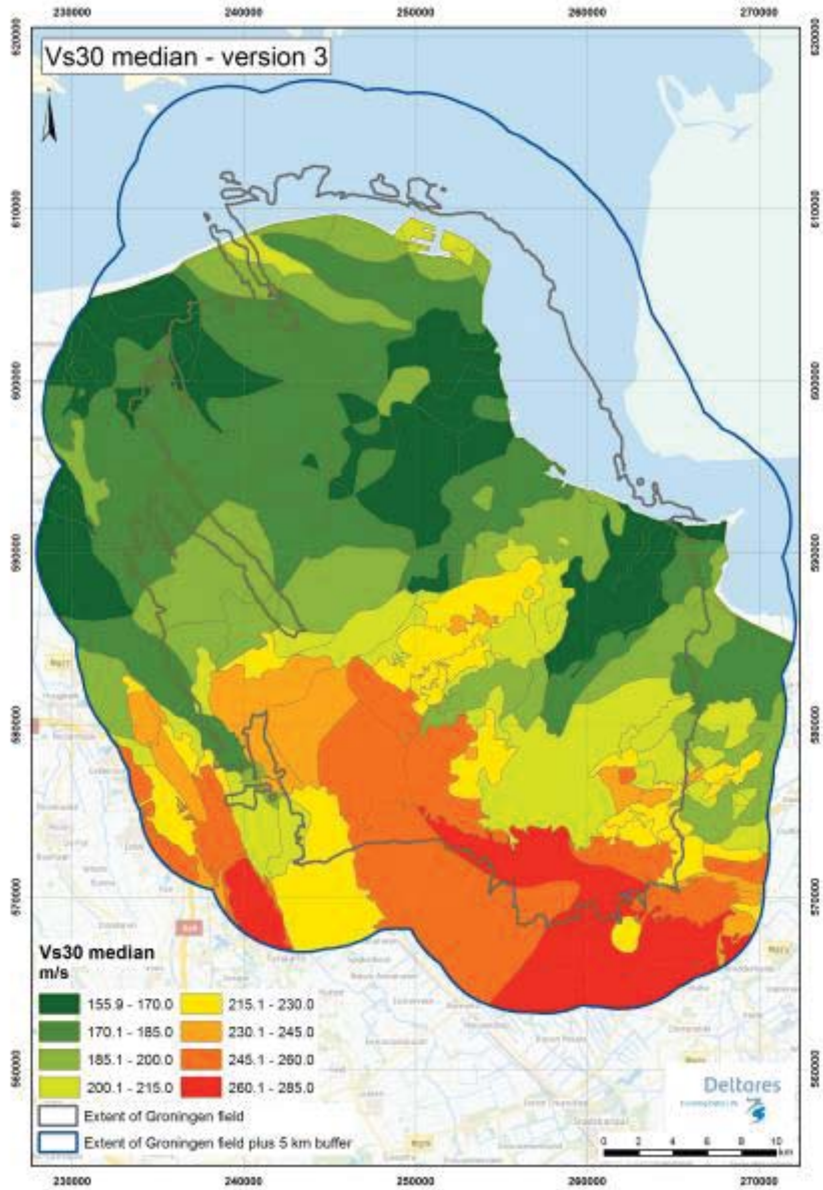

Figure 12. Median V_{S30} values for the 161 site amplification zones (Rodriguez-Marek et al. 2017)

DISCUSSION AND CONCLUSIONS

We have developed a ground-motion model for shallow-focus induced earthquakes in the Groningen gas field that relies neither on recordings of tectonic earthquakes occurring at greater depth nor on recordings of induced seismicity in environments where the upper crustal structure is very different from that encountered above the Groningen gas reservoir. The model is calibrated to the source characteristics of Groningen earthquakes, with a logic-tree structure to accommodate potential differences in the stress drops of larger earthquakes than those observed to date. The model is calibrated to the specific path characteristics of the Groningen field and also to the near-surface profiles, including the nonlinear response expected under higher levels of acceleration.

The model is a snapshot of ongoing refinement within the general framework presented herein. An area that will receive particular attention in the next phase of development being the incorporation of finite fault rupture characteristics. However, the basic framework of the model in terms of modeling motions at the reference rock horizon and convolving these with nonlinear site amplification factors is essentially stable. Although the model itself has no application outside the Groningen field (hence the absence of some specific details of the model), we believe that the approach may be informative for others faced with the challenge of modeling the attendant hazard and risk due to induced earthquakes.

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REFERENCES

Afshari, K., and Stewart, J.P., 2016. Physically parameterized prediction equations for significant duration in active crustal regions, *Earthquake Spectra* **32**(4), 2057-2081.

Akkar, S., Sandıkkaya, M. A., Senyurt, M., Azari Sisi, A., Ay, B. Ö., Traversa, P., Douglas, J., Cotton, F., Luzi, L., Hernandez, B., and Godey, S., 2014a. Reference database for seismic ground-motion in Europe (RESORCE), *Bulletin of Earthquake Engineering* **12**(1), 311-339.

Akkar, S., Sandıkkaya, M. A., and Bommer, J. J., 2014b. Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East, *Bulletin of Earthquake Engineering* **12**(1), 359-387.

Al Atik, L., 2015. *NGA-East: Ground-Motion Standard Deviation Models for Central and Eastern United States, PEER Report 2015/07, Pacific Earthquake Engineering Research Center,* University of California at Berkeley.

Ancheta, R. D., Darragh, R. B. , Stewart, J. P., Seyhan, E., Silva, W. J., Chiou, B. S.-J., Wooddell, K. E., Graves, R. W., Kottke, A. R., Boore, D. M., Kishida, T., and Donahue, J. L., 2014. NGA-West2 database, *Earthquake Spectra* **30**(3), 989-1005.

Anderson, J. G., and Hough, S. E., 1984. A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies, *Bulletin of the Seismological Society of America* **74**, 1969-1993.

Atkinson, G. M., 2015. Ground-motion prediction equation for small-to-moderate events at short hypocentral distances, with applications to induced-seismicity hazard, *Bulletin of the Seismological Society of America* **105**(2A), 981-992.

Baker, J. W., and Cornell, C. A., 2006. Which spectral acceleration are you using?, *Earthquake Spectra* **22**(2), 293-312.

Baker, J. W., and Jayaram, N., 2008. Correlation of spectral acceleration values from NGA ground motion models, *Earthquake Spectra* **24**(1), 299-317.

Bazzurro, P., and Cornell, C. A., 2004. Nonlinear soil-site effects in probabilistic seismic hazard analysis, *Bulletin of the Seismological Society of America* **94**, 2110-2123.

Boatwright, J., 1978."Detailed spectral analysis of two small New York state earthquakes," *Bulletin of the Seismological Society of America* **68**, 1117-1131.

Bommer, J. J., Crowley, H., and Pinho, R., 2015a. A risk-mitigation approach to the management of induced seismicity, *Journal of Seismology* **19**(2), 623-646.

Bommer, J. J., Dost, B., Edwards, B., Kruiver, P. P., Meijers, P., Ntinalexis, M., Polidoro, B., Rodriguez-Marek, A., and Stafford, P.J., 2015b. *Development of Version 2 GMPEs for Response Spectral Accelerations and Significant Durations from Induced Earthquakes in the Groningen Field*, http://www.namplatform.nl/feiten-en-cijfers/feiten-en-cijfers-onderzoeksrapporten.html#iframe-L2VtYmVkL2NvbXBvbmVudC8/aWQ9b25kZXJ6b2Vrc3JhcHBvcnRlbg.

Bommer, J. J., Dost, B., Edwards, B., Stafford, P. J., van Elk, J., Doornhof, D. and Ntinalexis, M., 2016. Developing an application-specific ground-motion model for induced seismicity, *Bulletin of the Seismological Society of America* **106**(1), 158-173.

Boore, D. M., 2005. *SMSIM – Fortran programs for simulating ground motions from earthquakes: Version 2.3 – A Revision of OFR 96-80*, *USGS Open-File Report 00-509, US Geological Survey*, Reston VA.

Bourne, S. J., Oates, S. J., Bommer, J. J., Dost, B., van Elk, J., and Doornhof, D., 2015. A Monte Carlo method for probabilistic seismic hazard assessment of induced seismicity due to conventional gas production, *Bulletin of the Seismological Society of America* **105**(3), 1721-1738.

Bradley, B. A., 2011. Correlation of significant duration with amplitude and cumulative intensity measures and its use in ground motion selection, *Journal of Earthquake Engineering* **15**(6), 951-978.

Brune, J. N., 1970. Tectonic stress and the spectra of seismic shear waves from earthquakes," *Journal of Geophysical Research* **75**(26), 4997-5009. 1971. Correction **76**(20), 5002.

Campbell, K. W., and Bozorgnia, Y., 2007. *Campbell-Bozorgnia NGA Ground Motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameters, PEER Report 2007/02, Pacific Earthquake Engineering Research Center*, University of California at Berkeley.

Crowley, H., Polidoro, B., Pinho, R., and van Elk, J., 2016. Framework for developing fragility and consequence models for inside local personal risk, *Submitted to Earthquake Spectra*.

Dawood, H., Rodriguez-Marek, A., Bayless, J., and Thompson, E. M., 2016. A flatfile for the KiK-net database processed using an automatic protocol, *Earthquake Spectra* **32**(2), 1281-1302.

Douglas, J., Edwards, B., Convertito, V., Sharma, N., Tramelli, A., Kraaijpoel, D., Mena Cabrera, B., Maercklin, N., and Troise, C., 2013. Predicting ground motions from induced earthquakes in geothermal areas, *Bulletin of the Seismological Society of America* **103**(3), 1875-1897.

Edwards, B., Fäh, D., and Giardini, D., 2011. Attenuation of seismic wave energy in Switzerland, *Geophysical Journal International* **185**, 967-984.

Kottke, A. R., and Rathje, E. M., 2008. *Technical Manual for STRATA, PEER Report 2008/10, Pacific Earthquake Engineering Center*, University of California at Berkeley.

Kraaijpoel, D., and Dost, B., 2013. Implications of salt-related propagation and mode conversion effects on the analysis of induced seismicity, *Journal of Seismology* **17**(1), 95-107.

Kruiver, P. P., van Dedem, E., Romijn, R., de Lange, G., Korff, M., Stafleu, J., Gunnink., J. L., Rodriguez-Marek, A., Bommer, J. J., van Elk, J., and Doornhof, D., 2017. An integrated shear-wave velocity model for the Groningen gas field, The Netherlands," *Accepted for publication in Bulletin of Earthquake Engineering*.

McGuire, R. K., Silva, W. J., and Costantino, C. J., 2001. *Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines, NUREG/CR-6728, US Nuclear Regulatory Commission*, Washington DC.

Press, W. H., Teukolsky, S. A., Vetterling, W. T., and Flannery, B. P., 2007. *Numerical Recipes: The Art of Scientific Computing*. Cambridge University Press, Cambridge; New York.

Rodriguez-Marek, A., Kruiver, P. P., Meijers, P., Bommer, J. J., Dost, B., van Elk, J., and Doornhof, D., 2017. A regional site-response model for the Groningen gas field, *Re-submitted to Bulletin of the Seismological Society of America following revision*.

Rodriguez-Marek, A., Rathje, E. M., Bommer, J. J., Scherbaum, F., and Stafford, P. J., 2014. Application of single-station sigma and site response characterization in a probabilistic seismic hazard analysis for a new nuclear site, *Bulletin of the Seismological Society of America* **104**(4), 1601-1619.