Predicting and Monitoring Ground Motions Induced by Hydraulic Fracturing

OGA-commissioned paper by Dr Julian J Bommer, May 2017

1. Introduction

Hydraulic fracturing can sometimes generate earthquakes that may result in levels of ground shaking that are felt. Within the regulatory environment in the UK[1], operational guidelines for hydraulic fracturing specify the level of earthquake magnitude at which injection should be immediately suspended, followed by monitoring for seismicity. While magnitude is a useful parameter for defining such operational protocols, because it can be computed very rapidly and defines a unique value for each seismic event, it may be poor indicator of the resultant ground motion, due to the dependence on depth, distance and surface geology. It is suggested that ground-motion prediction to assess any potential risk to buildings form part of the plan and that monitoring during and after injection be conducted to assess the local surface response to any hydraulic-fracturing induced seismicity.

The potential for damage to buildings is controlled by the nature and intensity of the ground shaking entering the foundations. The characteristics of the shaking are controlled primary by the amount of seismic energy released at the earthquake source (which is measured by the magnitude), how far and through what kind of rocks the seismic waves travel from the earthquake source to the site, and the nature of the ground on which the building is founded. This document outlines methodologies to define, predict and monitor the possible ground motion resulting from hydraulic fracturing operations.

2. Ground-Motion Characterisation and Prediction

Since the degree of disturbance to individuals and the risk of potential damage to buildings caused by earthquakes is controlled by the shaking at the surface rather than by the magnitude of the earthquake, a key element of seismic hazard assessment is a model for the prediction of ground shaking. While the movement of the ground is a transitory displacement during the shaking episode, it is more generally characterised by the acceleration or velocity of the ground. The former is more closely related to the forces experienced by structures exposed to the shaking whereas the latter is more indicative of the energy content of the shaking; both acceleration and velocity of the ground actually provide better indicators of the way the shaking is felt by people, partly because they reflect the frequency of the vibrations. In this context, the frequency refers to the average number of cycles or reversals of shaking per second, as opposed to the

[1] Note that onshore licensing and management of induced seismicity is being devolved to the Scottish and Welsh Governments; either administration may choose to adopt a different approach to that of the UK Regulators.

frequency in terms of how often episodes of shaking occur. The latter, which may be counted in number of times shaking occurs per day or per week, for example, will also influence how people respond to the ground motion in terms of disturbance and tolerance.

2.1. Ground-motion parameters

Earthquake ground-motions are recorded on different types of instruments that produce traces of a quantity of the ground shaking against time. The instruments are greatest use for ground-motion modelling purposes are accelerographs, which produce records of ground acceleration against time, usually in three orthogonal directions along the vertical and two horizontal axes. Records obtained from seismographs or geophones that produce time-histories of velocity can also be useful provided the sampling rate is sufficiently high to allow accurate differentiation of the traces to obtain accelerations (Figure 1).

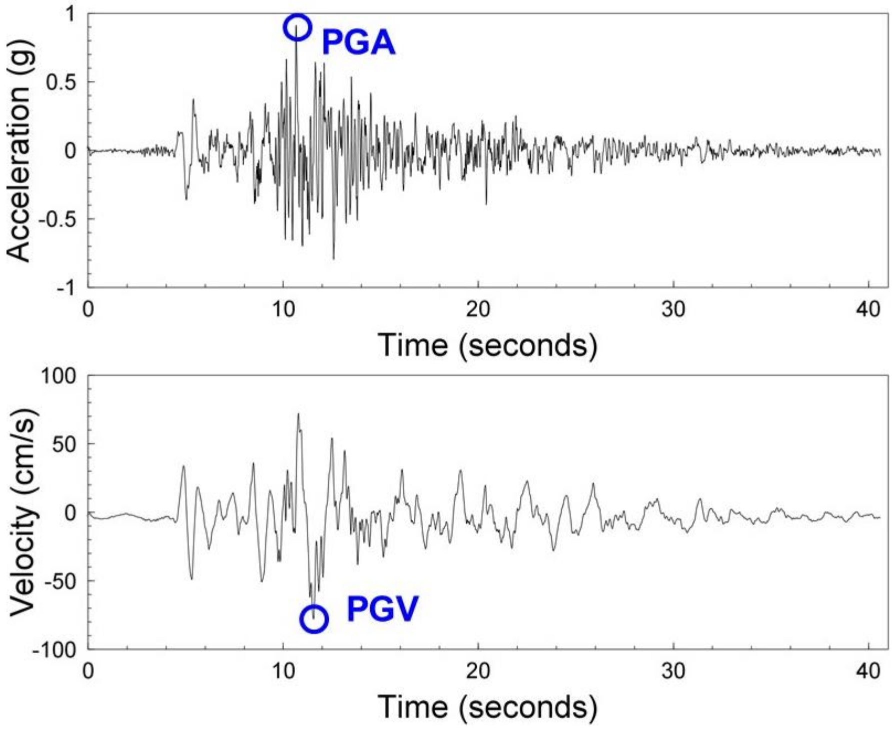


Figure 1. *Upper*: Single-component of an earthquake accelerogram indicating PGA as the absolute maximum amplitude. *Lower*: Velocity time-series obtained from integration of the accelerogram; PGV is the maximum absolute amplitude. There is no specific meaning associated with positive and negative values; the polarity is simply a convention to indicate direction, so positive may be north and negative south, for example.

Accelerograms are complex, 3D signals of the complete motion at a specific location associated with an episode of earthquake shaking. Several different parameters are used to characterise these recordings, usually treating the horizontal and vertical components separately. The simplest parameter is the maximum absolute value of acceleration, referred to as peak ground acceleration (PGA). There are several options for defining the horizontal PGA in terms of how the two horizontal components of each accelerogram are treated, including using the larger of the two, their resolved vector or their geometric mean, which is the mean of their logarithmic values (or the square root of their product). The most widely-used definition in current practice is the geometric mean or one of many subtle variations of this definition (*e.g*., Boore *et al.,* 2006). The same options for treatment of the two horizontal components of motion also apply to all other ground-motion parameters.

One of the more complete representations of the ground shaking is the response spectrum, which is a collection of parameters—the maximum responses at different natural frequencies of vibration—rather than a single parameter such as PGA. The response spectrum indicates the maximum absolute acceleration—obtained from the sum of the acceleration of the base and the acceleration of the mass relative to the base—of a single-degree-of-freedom (SDOF) oscillator with a specific natural oscillation frequency and damping level. The latter is usually modelled as an equivalent viscous damping expressed as a proportion of critical damping; for most engineering applications, ground-motion prediction models assume 5% of critical damping. A suite of models of SDOF oscillators with a common damping ratio and different vibration frequencies are subjected to a given accelerogram at their bases, and the maximum response of the mass is calculated. Plotting the maximum responses against the corresponding vibration period constructs a response spectrum (Figure 2).

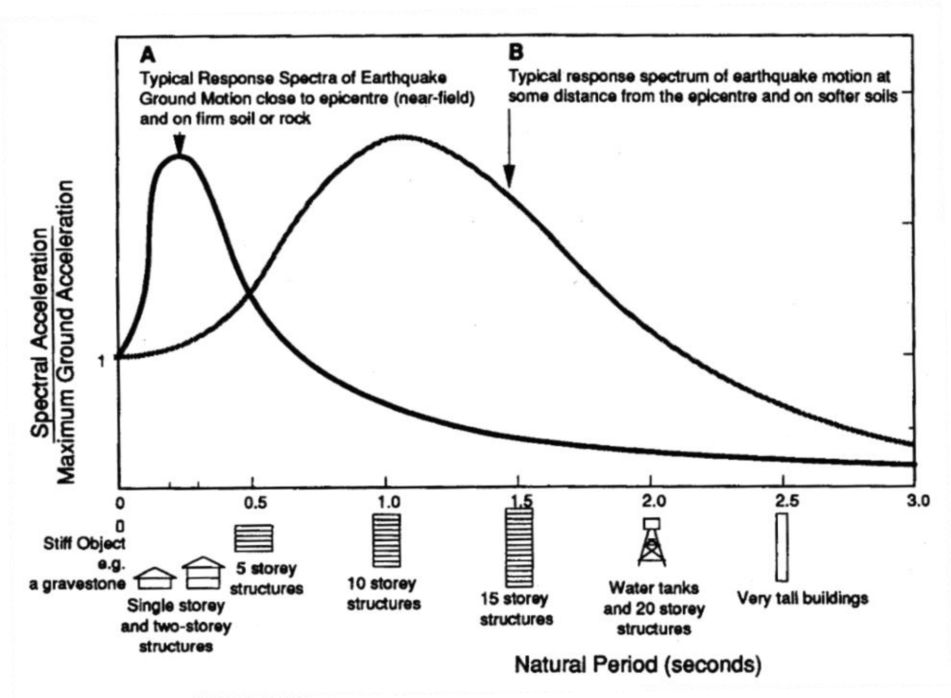


Figure 2. Response spectra of acceleration normalised to PGA. Diagrams below the *x*-axis indicate typical natural vibration periods of different structures (Coburn & Spence, 2002). The diagram illustrates the influence of distance and site conditions on the shape of the response spectrum, but it is also strongly dependent on earthquake magnitude, as shown in Fig. 3.

The response quantity is generally the acceleration of the mass and at very high oscillator frequencies—which correspond to very stiff structures—the spectral acceleration is equivalent to PGA since there is no relative motion between the mass and the base. The response spectrum is widely used because it captures the interaction of buildings and ground motions as illustrated in Figure 2. As a rough rule-of-thumb, the natural period of vibration of a building (the time it takes to vibrate back and forth if displaced at its roof level and then released) is approximately equal to the number of storeys divided by 10; the natural frequency of the building is simply the reciprocal of the natural period. Buildings with different characteristics will be more or less sensitive to particular shaking scenarios depending on the dominant periods of the ground motion. For example, a high-rise structure of say 15 storeys will be more strongly affected by a ground motion that has a response spectrum with high amplitudes at around 1.5 seconds. The spectral accelerations at these longer periods are particularly sensitive to the magnitude of the earthquake, as shown in Figure 3. As the magnitude increases, for a given distance and site condition, the overall spectral amplitudes increase, but more so at longer periods. For example, as the magnitude increases from 4 to 7, the PGA value increases by a factor of 7.7 but the spectral acceleration at 1 second increases by a factor of 44.

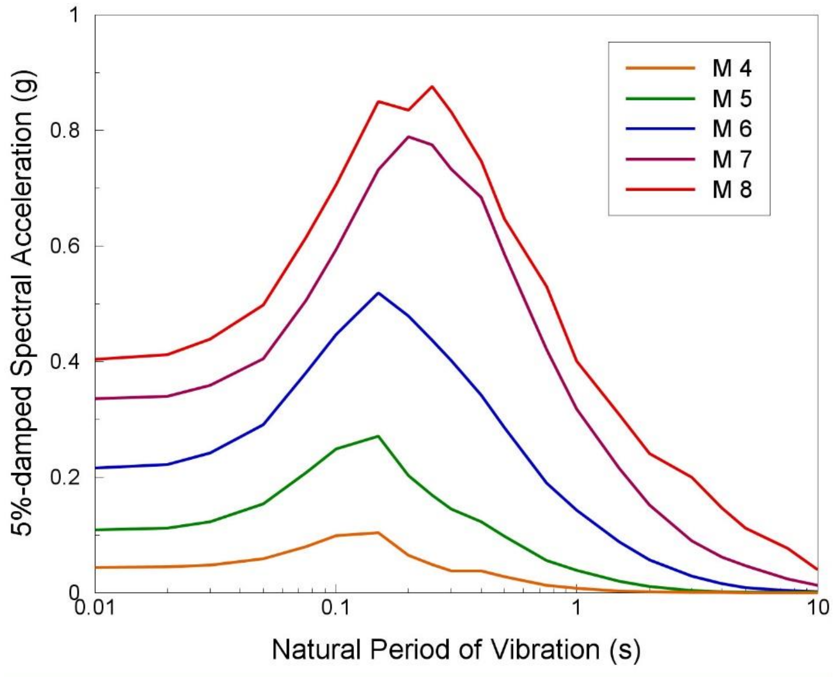


Figure 3. Predicted response spectra for a fixed distance and site condition due to earthquakes of five different magnitudes; the prediction are made using a GMPE from California.

A simple parameter that has many engineering applications is the peak ground velocity, or PGV. The velocity time-history is obtained by integration of the accelerogram and PGV is then defined in the same way as PGA is obtained from the acceleration time-history. In general, PGV is a better indicator of the damage potential of the motion than PGA since it is more closely related to the energy in the motion. Moreover, whereas

PGA is only indicative of the spectral response of very stiff structures that have very short response periods, PGV has been found to correlate well with spectral accelerations at frequencies in the range from about 1-3 Hz (*e.g.*, Bommer & Alarcón, 2006). The oscillator frequency at which peak velocity and spectral acceleration are correlated decreases as the magnitude of the earthquake increases. Peak velocity is very widely-used in guidelines for tolerable levels of shaking due to a variety of anthropogenic activities, as discussed in Section 4.

The impact of ground shaking on both people and the built environment depends not only on the amplitude of the motion but also its duration. There are many different ways to measure either the duration or the number of cycles of motion in an accelerogram (Bommer & Martinez-Pereira, 1999; Hancock & Bommer, 2005); the most widely-used measure of duration is the significant duration defined as the interval between the times at which 5% and 75% (or 95%) of the total Arias intensity is attained. Arias intensity is a measure of the energy in an accelerogram based on the integral of the acceleration squared over the full length of the record.

2.2. Ground-motion prediction equations

Ground-motion prediction equations (GMPEs) have been developed for all of the ground-motion parameters listed in Section 2.1, although the most abundant are those for PGA and response spectral acceleration, SA. These equations were previously referred to as attenuation relations but this is considered a misnomer since they model both the attenuation of the motion with distance and the scaling of the motion with magnitude.

A GMPE predicts values of a ground-motion parameter, such as PGA, PGV or the spectral acceleration at a particular oscillator period, T, as a function of independent variables that characterise the radiation and propagation of seismic energy from the earthquake source to the site of interest. As a minimum, a GMPE will include terms related to the earthquake magnitude, the distance from the earthquake source to the site, and the characteristics of the site itself. Other factors, such as the style-of-faulting (*i.e.*, normal, reverse or strike-slip), are often included as well. The influence on the ground motion of other factors is often implicit rather than explicitly modelled in the equations. For example, the crustal attenuation characteristics (as represented by the quality factor, Q) is generally reflected in the use of data from a particular region to derive the equations. Similarly, stress drop—which controls the strength of the high-frequency radiation from the source—does not usually appear as an explicit predictor variable.

For the basic predictor variables that are included in a GMPE, it is important to use a consistent and clearly-stated definition for each parameter (just as it is for the definition of the horizontal component of motion being predicted). The magnitudes should all be measured on the same scale (whether local or Richter magnitude, M_L, or a teleseismic scale such as moment magnitude, **M** or M_w). Similarly, a consistent distance metric should be selected from the various options that measure the distance between the site of interest and a defined location that represents the earthquake source: epicentre (R_{epi}), hypocentre (R_{hyp}), closest point on the fault rupture (R_{rup}) or closest point on the projection of the fault rupture on to the Earth's surface (R_{JB}, the Joyner-Boore distance). The first two distance definition treat the earthquake source as a point and are therefore only appropriate for application to small-magnitude earthquakes. The local site conditions are sometimes represented by dummy variables that represent site classes (*e.g.*, rock, stiff soil, soft soil) but it is now more common to use the parameter V_{S30}, which is the time-averaged shear-wave velocity over the uppermost 30 metres at the site. The use of 30 m is mainly the result of this being the maximum depth reached in the majority of geotechnical boreholes rather than any specific geophysical criteria. Figure 4 shows predicted PGV values as a function of distance for two magnitudes and three site classes.

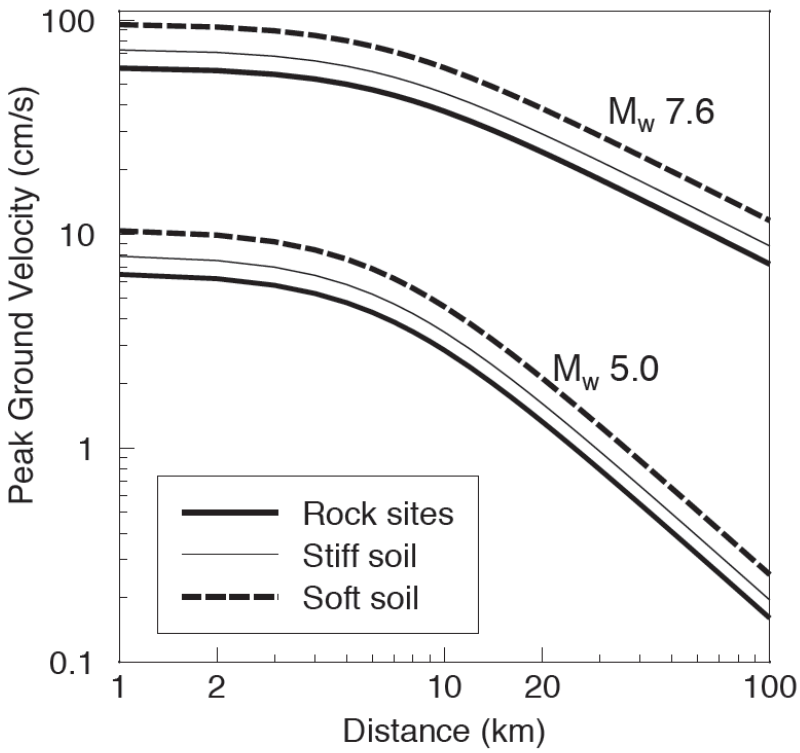


Figure 4. Predicted PGV values (in cm/s) as a function of magnitude, distance and site classification (Akkar & Bommer, 2010)

The functional form of a GMPE is defined to predict logarithmic values of the chosen ground-motion parameter as a function of the selected explanatory variables. In recent years it has been recognised that the scaling of ground motions with earthquake can display non-linearity for both small and large magnitude (Douglas & Jousset, 2011; Baltay & Hanks, 2014) and that the geometric spreading of ground motions is magnitude-dependent (*e.g.*, Cotton *et al.,* 2008).

For a chosen ground-motion parameter and for a given target region of application, there are essentially two ways that a GMPE can be developed: empirical and stochastic. An empirical model means that is derived from observations, in this case recorded values of the ground-motion parameter. The first step in deriving an empirical GMPE is to assemble large databases of recorded motions and perform regression analyses to obtain the coefficients of a chosen functional form for the equation (*e.g*., Douglas, 2003). This approach works well wherever there are abundant ground-motion recordings representing a range of magnitude-distance combinations that covers the earthquake scenarios to be considered in the seismic hazard or risk calculations. A suitable functional form will facilitate some degree of extrapolation beyond the limits of the database—to larger magnitudes, in particular—but extending such empirical equations far beyond the range covered by the underlying data involves great uncertainty and is to be avoided. For this reason, it is common in regions of lower seismicity—such as the central and eastern United States—to a stochastic approach to generate GMPEs (Boore, 2003). Stochastic simulations effectively treat earthquake ground motion as a random process and is controlled by a small number of parameters. Rather than using recorded values of ground-motion parameters, values of the parameter are estimated from a theoretical model. The starting point is a simple model of the Fourier spectrum of the seismic radiation at the earthquake source, which is then modified for path and site effects. The earthquake source is generally characterised by seismic moment (M_0) and stress drop ($\Delta\sigma$), the path effects by intrinsic attenuation (related to Q) and geometric spreading patterns, and the site by a linear amplification function and the high-frequency damping parameter, κ. Values of these parameters are estimated from inversion of the Fourier amplitude spectra (FAS) of weak-motion recordings, generally from small-magnitude earthquakes (*e.g*., Edwards *et al*., 2008). While there is a physical basis for the forward modelling ground motions for larger earthquakes, there is inevitably uncertainty in how some of the parameters scale with magnitude, particularly the stress drop. A stochastic GMPE for the UK is presented by Rietbrock *et al*. (2013), who also discuss the influence of such uncertainty on the model.

These can be combined by developing GMPEs for a specific region and this is referred to as the hybrid-empirical method (Campbell, 2003). This approach aims to benefit from the physical constraint providing by robust empirical models while using stochastic simulations to adjust the predictions for differences between the host and target regions.

2.3. Variability and uncertainty in GMPEs

To determine the relationship between variables where change is dependent on independent variables requires the analysis of a large database of ground-motion recordings, and will generally result in an equation that models the expected patterns of increasing amplitudes of motion with increasing magnitude and decreasing source-to-site distance. However, the data will also invariably display very considerable scatter around the predictive curve (Figure 5). This scatter, which appears to be random with respect to the model, is referred to as aleatory variability or simply randomness. The introduction of additional independent variables and the use of more complex definitions of the variables—such as using V_{S30} values rather than just distinguishing between ‘rock’ and ‘soil’ sites—have led to only modest reductions of the scatter, which is therefore interpreted to be the result of either inherent randomness in ground-motion fields or due to the use of very simple models to represent very complex processes (or some combination of the two).

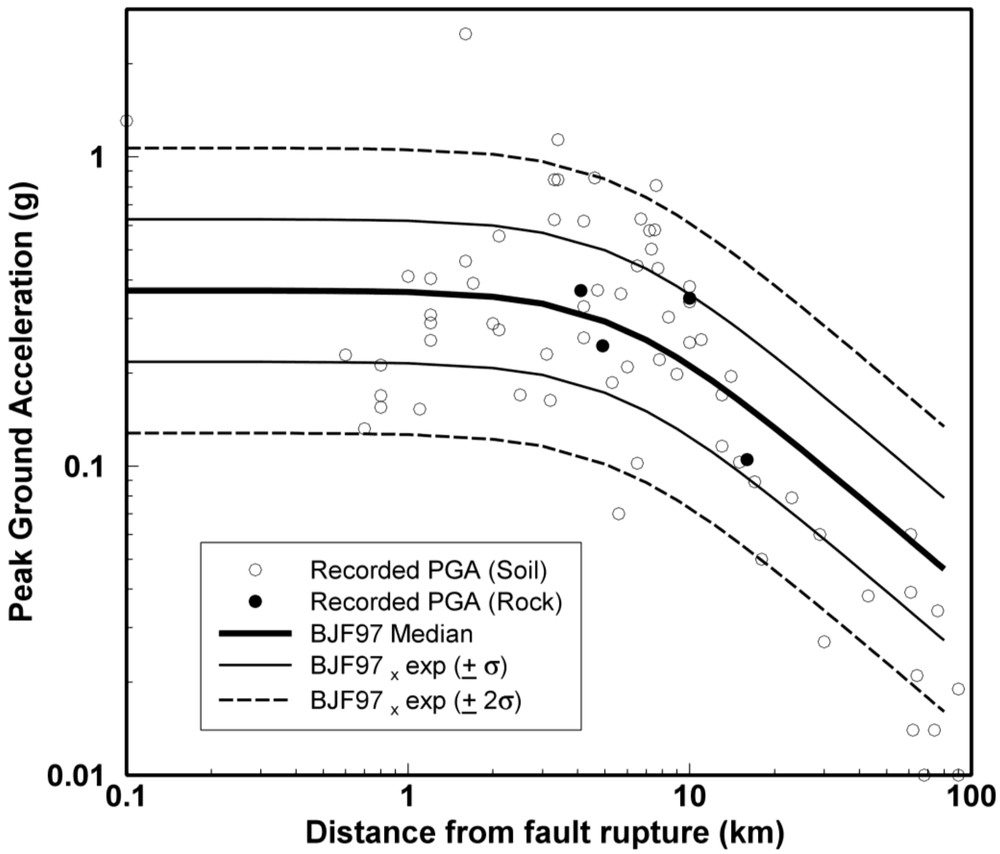


Figure 5. Recorded PGA values from an earthquake in California compared with predicted values from a Californian GMPE. The thick solid line is the median prediction for soil sites; the thin solid lines represent plus/minus one standard deviation and the dashed lines plus/minus two standard deviations (Bommer & Abrahamson, 2006)

The logarithmic residuals of observed ground-motion amplitudes with respect to the predicted values from GMPEs are generally found to conform to a Gaussian distribution (*e.g.*, Strasser *et al*., 2009). The log-normal scatter is therefore fully represented by the standard deviation, represented by σ (sigma), which is as important as the coefficients of the equation since GMPEs do not predict unique values of ground-motion parameters but probabilistic distributions of these values. Any application of the GMPE includes selection of the number (ε, epsilon) of standard deviations to be considered: if ε is set to zero, then the median values of motion are predicted, having a 50% probability of being exceeded. If ε is set to two, then the predicted motions—likely to be at least 3.5 times greater than the median–will have only a 1-in-40 chance of being exceeded.

The random variability in ground-motion fields can be broken down into various elements, the first distinction being earthquake-to-earthquake variability and within-earthquake variability (*e.g*., Al Atik *et al*., 2010). The former reflects variation in source properties—such as stress drop and the rupture propagation history—not explicitly modelled in most GMPEs, whereas the latter reflects several factors including the azimuth of the travel path and variations in the deeper profiles from one site to another. The elements of variability in ground-motion predictions can be reliably estimated from empirical datasets provided that appropriate regression techniques are used (Boore & Joyner, 1997). The variability in stochastic simulations of ground motions will often be an underestimation of the true variability in ground-motion fields since it reflects the influence of the variations in the parameters considered in the model. Some researchers have attempted to estimate the complete variability associated with such models (*e.g*., Toro *et al*., 1997).

All GMPEs include a sigma term to represent the randomly distributed residuals, which is interpreted as inherent variability in ground motions. Another type of uncertainty is encountered in selecting the most appropriate GMPE for application in a given region or for a specific project, especially in the absence of locally-recorded data. The fact that the most appropriate model is generally not unambiguously defined is the result of what is known as epistemic uncertainty. Epistemic uncertainty reflects a lack of knowledge and, unlike random variability, it is theoretical reducible through the acquisition of more and/or better data. Even in regions with abundant databases of ground-motion recordings, the data may not have sufficiently sampled all combinations of magnitude, stress drop, distance and other variables to be totally unbiased, for which reason it is common to consider alternative GMPEs in seismic hazard assessment—using logic-trees that assigned relative weights to alternative models—even where there are multiple GMPEs derived from local data (*e.g*., Al Atik & Youngs, 2014). When the GMPEs are applied to magnitude-distance scenarios outside the range of data from which they are derived, the epistemic uncertainty is larger. In cases where there are no local or regional recordings and the GMPEs are imported from another region, there is even greater epistemic uncertainty because of the lack of constraint to prove the applicability of the equations to the target region and site. Recommendations for the selection and adjustment of GMPEs is addressed in Section 4.1

3. Mitigating seismic risk associated with ground motion (PGV)

The ultimate objective of any protocol related to induced earthquakes is to limit or control the consequent seismic risk, which in very broad terms can be considered as the possibility of undesirable consequences of earthquakes, such as disturbance to the public or potential damage. For informed decision-making, it is usual to treat risk in a probabilistic framework, in which case seismic risk is more specifically defined as the probability (within a specified time frame) of particular undesirable consequences occurring due to induced earthquakes. This section discusses limiting values on ground-motion amplitudes as the basis for risk mitigation. In view of its relationship with the energy contained in ground shaking, its correlation with the maximum response of intermediate-period structures, and its widespread use in guidelines related to tolerable shaking levels, the chosen parameter for quantifying the ground motion is the peak ground velocity (PGV).

3.1. Elements of seismic risk

The phenomena of induced and triggered seismicity, which include all earthquakes whose time and location are related to some anthropogenic activity, have been recognised for many decades. Well-known examples have included earthquakes associated with the impounding of deep reservoirs (*e.g.*, Simpson *et al*., 1988) and with mining (*e.g*., Klose, 2013), waste-water disposal (Ellsworth, 2013), enhanced geothermal systems (Majer *et al*., 2007), and hydrocarbon production from a conventional reservoir at the Groningen field in The Netherlands (Nepveu *et al*., 2016). Engineering studies related to earthquake-resistant design consider seismic risk, but are generally applicable only to larger earthquakes (M ≥ 4).

Seismic risk is the result of combining three factors: seismic hazard, exposure, and fragility. Seismic hazard is the probability of different levels of shaking (PGV) occurring or being exceeded at the site of interest within a specified time period. The exposure refers to elements of the built environment in the area where ground shaking could be expected. The fragility of each element of exposure defines the probability of it reaching a specific performance level or ‘failure’ under different levels of PGV (Figure 6). Convolution of the hazard and fragility defines the total probability of ‘failure’ of that specific element.

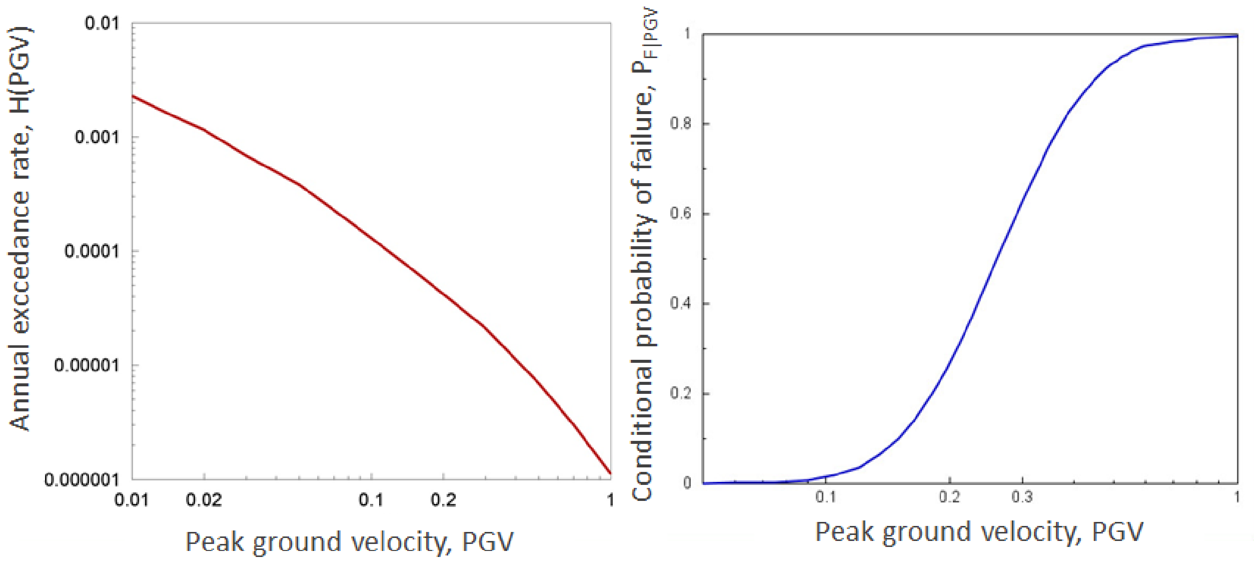


Figure 6. Examples of a seismic hazard curve (*left*) and fragility curve (*right*)

The fragility curve depends on a definition of failure, which can be related to the consequences that the protocol aims to prevent. In an engineering assessment of building damage, it is common to define different damage states (DS), where DS1 corresponds to hairline cracks in walls and DS5 indicates total collapse (Figure 7). Fragility curves may then be defined for different damage states, with the higher levels of damage requiring greater amplitudes of PGV (Figure 8).

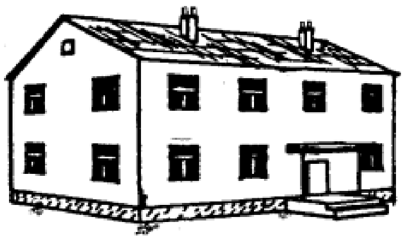
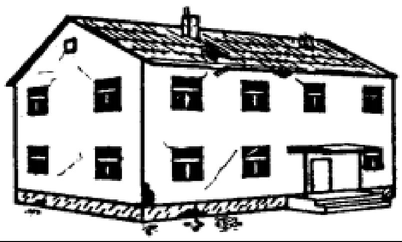
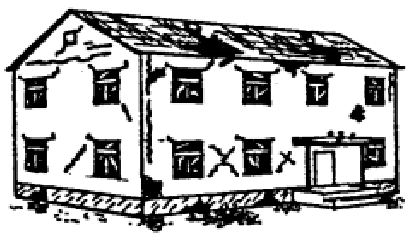
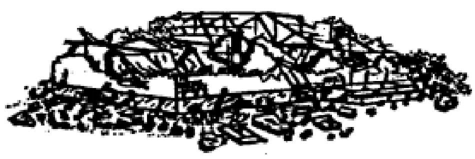
Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction (very heavy structural damage)** Total or near total collapse.

Figure 8. Damage states defined in the EMS-98 intensity scale (Grünthal, 1998)

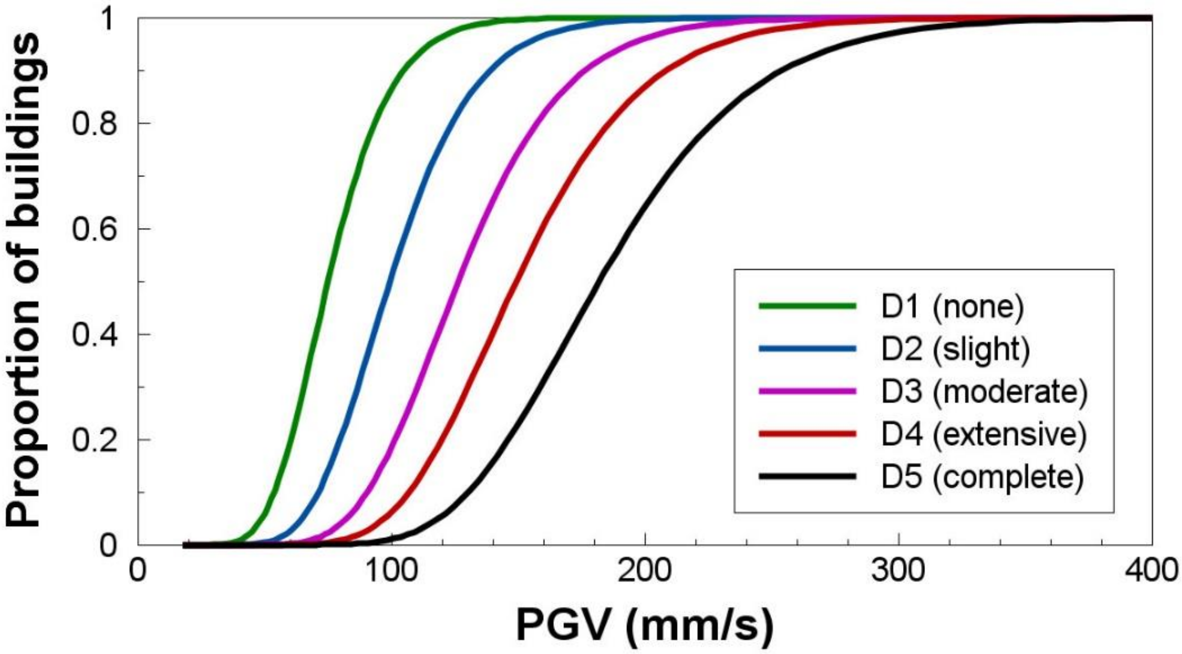


Figure 8. Examples of fragility curves for a particular building category and five different damage states, defined as a function of PGV (Bommer *et a*l., 2006)

3.2. Risk metrics and performance targets

In light of the discussion in Section 3.1, use of fragility functions to define acceptable PGV for an operational protocol for hydraulic fracturing, assessing all the building typologies in the exposed area (height, construction material, load-resisting system, age, *etc*.) is not likely to be practicable. In addition, fragility curves derived for standard earthquake engineering applications are generally derived considering destructive earthquakes, which means that most of the ground motions conditioning the horizontal axis of the fragility curves will correspond to earthquakes with magnitude of 4 and greater, often up to 7 or 7.5. If such curves are to be applied to motions from smaller magnitude events, then it would be necessary—particularly for the higher damage states—to make adjustments for the much shorter duration of shaking from the smaller events, The use of fragility curves conditioned on the long duration motions from larger earthquakes without such adjustments could lead to significant over-estimation of the impact of the motions.

3.3. Adopting generic guidelines on vibrations

An alternative to deriving or adopting fragility curves specifically derived for earthquake ground motions, is to infer PGV thresholds defined for other types of ground-borne vibrations (Figure 9). Another example is shown in Figure 10, which is taken from BS 7385-2 (BSI, 1993). This guide to vibrations in buildings deals with a variety of sources that "*include blasting (carried out during mineral extraction or construction excavation),* *demolition, piling, ground treatments (e.g. compaction), construction equipment, tunnelling, road and rail traffic and industrial machinery*". In terms of the bullet points listed in Section 3.2, the first point is addressed by defining two groups of buildings: Reinforced and framed structures, industrial and heavy commercial buildings (Line 1), and unreinforced or light framed structures, residential or light commercial type buildings (Line 2), the latter being more fragile. The second bullet point is addressed by the specification of "*cosmetic damage*", which would probably correspond to damage states DS1 but is not explicitly defined.

An issue to be aware of when using thresholds such as those shown in Figure 8 is that PGV in this context means the largest of the three orthogonal components; analysis of tectonic earthquake recordings suggests that, on average, the larger horizontal component of PGV is 15% greater than the geometric mean value (Beyer & Bommer, 2006). In structural engineering, the vertical component is generally considered separately because of the very different load resisting systems of buildings to loads in the horizontal and vertical directions. The human body, however, can be more sensitive to vertical ground motions in the higher frequency range above about 5 Hz (*e.g.*, BSI, 2008a).

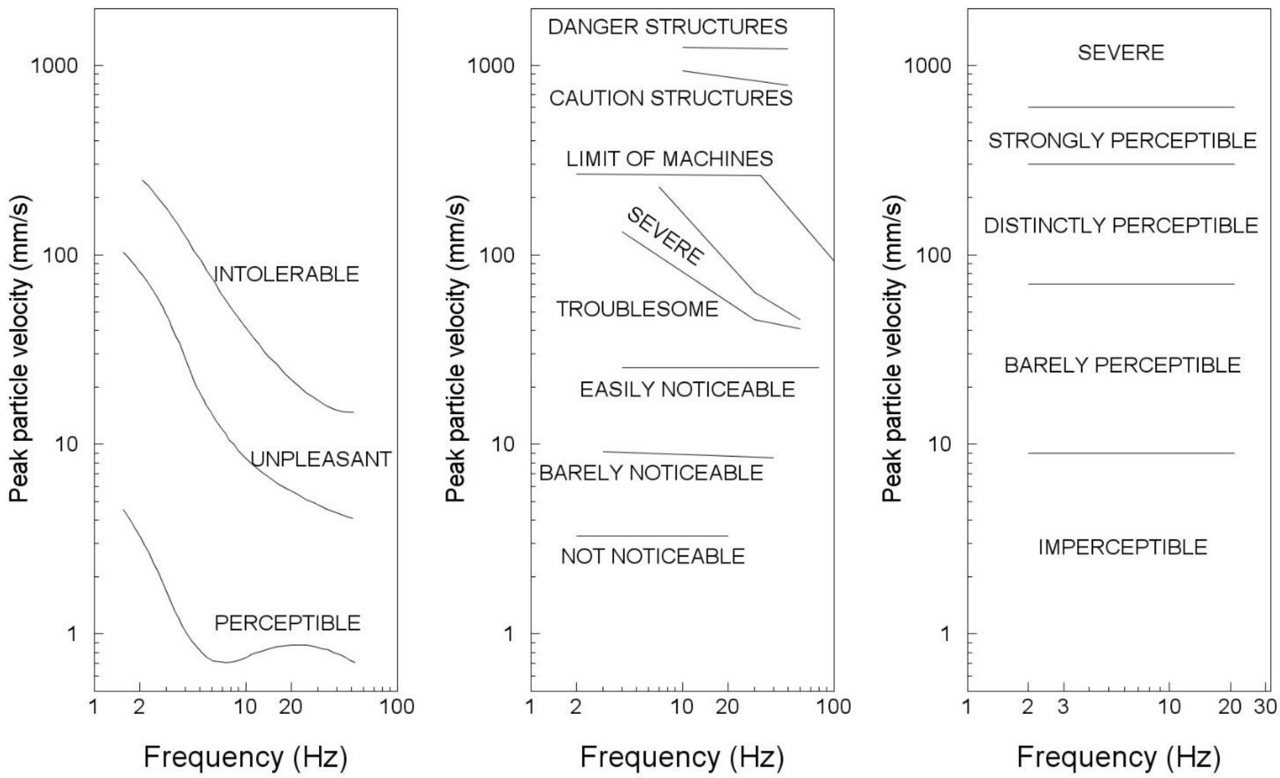


Figure 9. Examples of thresholds for tolerable motions defined in terms of PGV and the dominant frequency of the shaking due to blasting (*left*), traffic (*middle*) and pile-driving (*right*). Modified from Bommer *et al*. (2006)

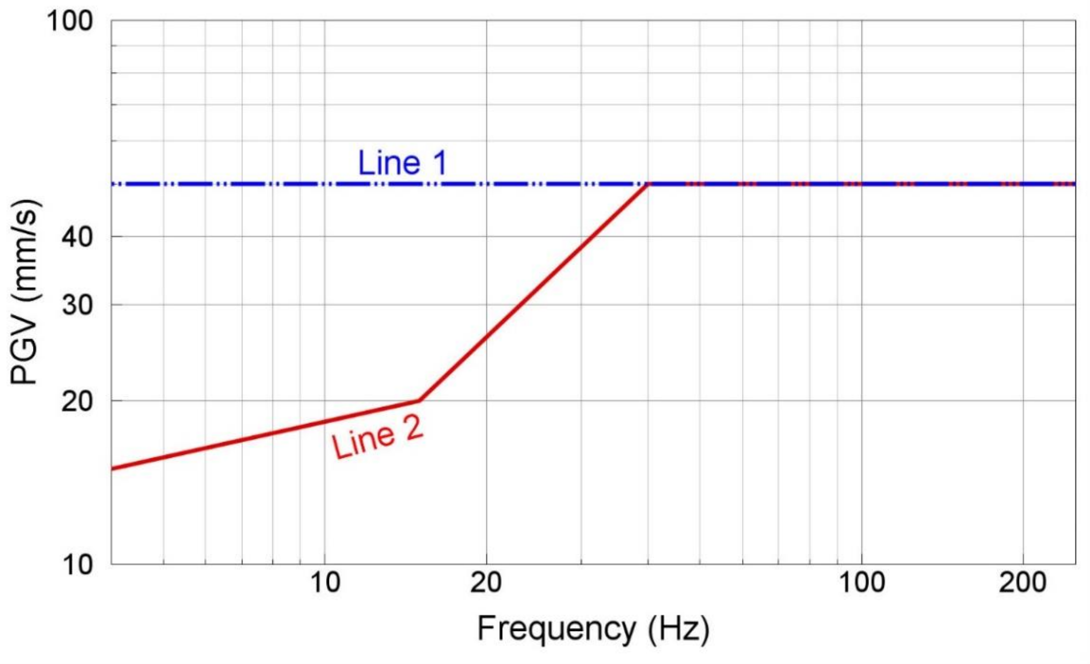


Figure 10. Tolerable PGV thresholds—related to cosmetic damage—as a function of frequency for stronger (Line 1) and weaker (Line 2) types of buildings from BS 7385-2 (BSI, 1993)

As can be appreciated from Figures 9 and 10, the PGV thresholds often vary with the frequency of the motion. Their application to earthquake shaking therefore requires definition of the dominant frequency of the ground motion, which can be interpreted in several ways. For example, it might be assumed equal to the frequency at which the peak of the response spectrum of relative velocity occurs (Alarcón *et al*., 2006); as noted earlier, this will vary with the magnitude of the earthquake. Alternative measures, and empirical equations for their prediction, are discussed by Rathje *et al*. (2004) and Du (2017).

An advantage of using guidelines such as those illustrated in Figures 9 and 10 is that they are based on published standards and their application has precedent for non-seismic sources of vibration. There are issues to be addressed, however, since the performance targets underlying the PGV limits are often vaguely, or even ambiguously, defined, and the nature of the vibrations due to anthropogenic sources such as blasting, traffic and demolition may be different in duration, frequency content and frequency of occurrence from the shaking associated with induced earthquakes.

By way of illustration, Figure 11 shows an indication of PGV levels, in mm/s, and their possible consequences (as described in the EMS-98 intensity scale) and the 15 mm/s the lowest level that could possibly cause cosmetic damage in weak structures (BSI, 1993; see Figure 8).

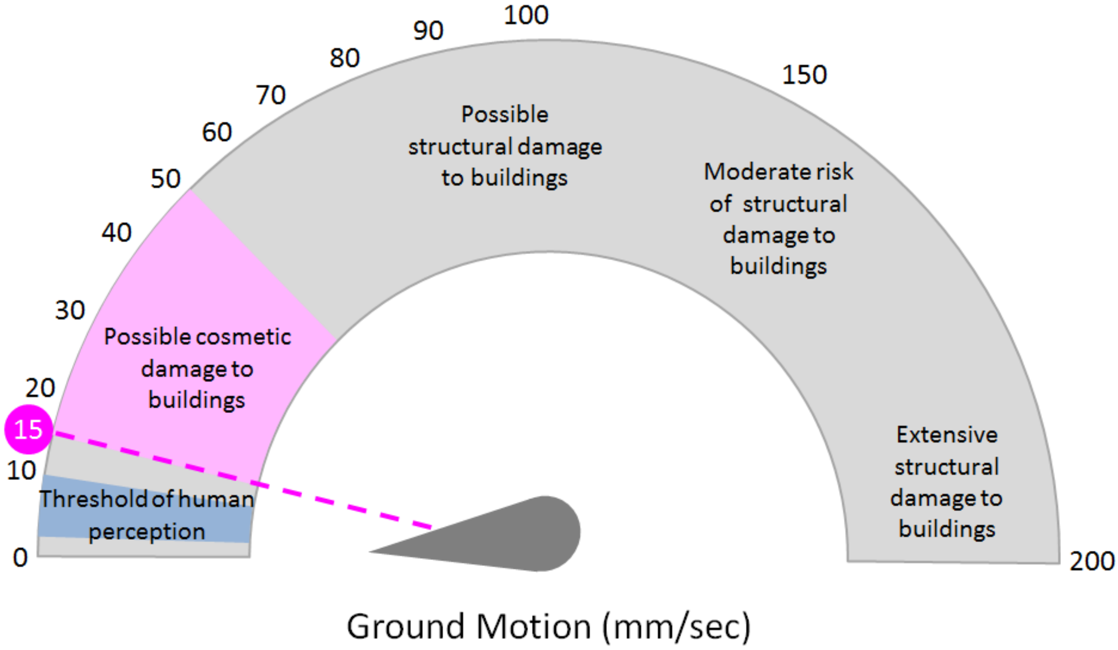


Figure 11. PGV levels and their potential impacts

3.4. Establishing background levels of vibration

There are several sources of ground-borne vibrations in most environment, including rail and road traffic, construction activities, and the operation of large machinery, whether in factories or other facilities. As well as being informed by established guidelines on tolerable vibration levels, it is useful to also establish the background levels of ground vibration, which may be presumed tolerable. These existing levels of ground vibration can be easily established through the operation of sensitive seismic recording instruments prior to the initiation of any hydraulic fracturing activities.

Equally valuable is to establish the vibration levels against which any special structures in the affected area have been designed, whether these are due to external sources or internally generated vibrations.

4. Prediction of PGV

In order to implement any decision criteria conditioned on pre-defined thresholds of PGV, a model is required to enable the estimation of values of this ground-motion parameter for any combination of magnitude and distance considered. This section discusses criteria for selecting suitable GMPEs and briefly discusses considerations regarding their implementation in practice.

4.1. Selection and adjustment of GMPEs

Recent papers presenting GMPEs to include PGA, SA for a wide range of response periods, and PGV as well, but in general there are far fewer GMPEs available for PGV than for the other parameters (Douglas, 2012), which partly explains why there have been proposals to scale PGV from response spectral ordinates (*e.g.*, Bommer & Alarcón, 2006). An excellent global compendium of GMPEs, based initially on Douglas (2003), is maintained at the web site www.gmpe.org.uk.

For natural (tectonic) earthquakes, it is generally advisable to first establish criteria for the pre-selection of GMPEs—related to their inherent quality, their capacity to be extrapolated beyond the limits of the underlying data, and their relevance to the region and site under consideration—and apply these to all known equations to obtain a reduced list of candidate equations (*e.g.*, Bommer *et al*., 2010). Given how few existing GMPEs are likely to be even potentially applicable to cases of induced seismicity, any selection criteria applied in this way will generally need to be rather lenient. A few GMPEs have been proposed specifically for application to induced seismicity, some being intended for generic application (Douglas *et al*., 2013; Atkinson, 2015) and some for specific locations (Bommer *et al*., 2016; Yenier *et al*., 2017). Much larger numbers of GMPEs have been derived for application to natural (tectonic) earthquakes, but there are two major challenges to be addressed in applying such equations to induced earthquakes. The first issue is that GMPEs have generally been derived for applications related, ultimately, to earthquake-resistant design and have therefore tended to be applicable only to larger earthquakes (*e.g.*, **M** ≥ 4). Extrapolation of these equations to smaller magnitudes will generally lead to gross over-estimation of the motions (Bommer *et al*., 2007; Atkinson & Morrison, 2009; Chiou *et al*., 2010). Consequently, many recent GMPEs have been derived to extend to smaller magnitudes: for example, some of the models for active tectonic regions such as California (NGA-West2) are applicable to earthquakes as small as magnitude 3.0 (Abrahamson *et al*., 2014; Boore *et al*., 2014). The second challenge associated with applying standard GMPEs to induced seismicity is related to focal depth since induced earthquakes are generally much shallower than most tectonic earthquakes. The shallower depths of induced earthquakes can have two counteracting effects in terms of the resulting ground motions at the surface. On the one hand, the shallow foci lead to shorter travel paths between the earthquake source and locations close to the epicentre, which will tend to lead to relatively higher motions. On the other hand, there is considerable evidence that stress drop decreases with focal depth (*e.g.*, Allen, 2012; Hough, 2014) and the waves from shallow earthquakes will travel through rocks of low Q and thus experience greater attenuation with distance; both of these effects will tend to diminish the surface motions. All of these factors should be considered in relation to the distance metric used in the GMPEs: for example, if a horizontal distance, like R_{epi} or R_{JB}, is used, then there is an implicit assumption that focal depth distributions in the host and target regions are comparable.

An alternative to selecting an empirical GMPE for application to a particular case of induced seismicity is to derive a new application-specific model, using either stochastic simulations directly or using such simulations to create a hybrid-empirical model more closely matched to local conditions.

When applying the selected GMPE to a particular area, the definition of explanatory variables in the model must be used consistently. For example, the magnitude scale used to quantify any induced seismicity and the magnitude scale employed in the GMPE should be the same; if different scales are used, suitable adjustments should be made and the errors associated with such adjustments propagated into the final predictions. Equally important is ensuring that the near-surface characteristics at the site of interest are correctly reflected in the GMPE; if the GMPE is calibrated only for hard rock sites, for example, its application to a site covered by soft soils will require appropriate adjustments.

4.2. Confidence levels

As noted in Section 2.3, GMPEs are not deterministic models that predict unique values of PGV for a given magnitude-distance scenario but rather probabilistic models that predict a distribution characterised by the median value of PGV and the logarithmic standard deviation, σ[*log*(PGV)]. In estimating PGV at any particular location due to a specific earthquake event, a decision needs to be made regarding the treatment of the residual distribution. One option is to select a confidence level, which will then determine the value of ε: for 90% confidence, ε is 1.28; for 95%, 1.65; and for 99%, 2.32.

At the same time, it is important to note that in some applications the randomness in the spatial variability of ground motions is not explicitly accounted for except through consideration of the location, orientation and dimensions of the fault rupture, and the surface geology at each location, the latter influencing the degree of amplification of the ground motion. ShakeMaps are produced by the US Geological Survey within a short time after earthquakes (Wald *et al*., 2006). In California, where the system is directly informed by recordings of the shaking, the contours of estimated motion are adjusted to match the recorded values of PGA and PGV (Wald *et al*., 1999).

As discussed in Section 2.3, there is epistemic uncertainty associated with the GMPE. Prior to the occurrence of any induced earthquakes associated with a particular hydraulic fracturing operation and in the absence of any local recordings, the initial epistemic uncertainty may be large, so selecting the most conservative model in terms of leading to the highest estimates of PGV is desirable.

If recordings of natural (tectonic) events in the area are available, or data from induced events become available during operations, the GMPE can be refined and it should be possible to significantly reduce the epistemic uncertainty and this potentially obviates the need for logic-trees or conservative model choices, (see 5.3. Updating GMPEs using recorded motions).

5. Monitoring PGV Values and Updating Predictive Models

The effective implementation of an operational protocol based on PGV thresholds cannot rely exclusively on model predictions both because of the epistemic uncertainty regarding the most appropriate model for the application and because of the large variability inherent in the predictive models. Therefore, it is necessary to make *in situ* observations of the motions induced by all significant earthquakes related to a hydraulic fracturing operation. The use of macroseismic intensity—which assigns degrees reflecting the strength of shaking at a given location based on how the motions are felt by people and the effects of the motions on objects and buildings (*e.g*., Grünthal, 1998)—is not a feasible option for many reasons. One reason is the subjective nature of intensity assessment and the difficulty is separating the effects of seismic events that are spaced closely in time. Another is the large variability in empirical relationships between intensity and PGV, and the epistemic uncertainty regarding which relationship would be applicable (*e.g*., Atkinson & Kaka, 2007; Faneza & Michelini, 2010; Worden *et al*., 2012). Installing seismic instruments circumvents these problems and allows for refinement of both the PGV prediction equation and potentially also of the PGV thresholds.

5.1. Microseismic networks and strong-motion instruments

The installation of micro-seismic arrays is standard practice for hydraulic fracturing operations. Seismographs installed around the injection well, and often including some in boreholes, enable rapid and accurate location of micro-earthquakes, which indicate the progress of fracture development. The recording also enable the estimation of earthquake magnitude although for larger events in the UK, magnitudes will also be reported by the British Geological Survey (BGS).

Accurate determination of the origin time, location (in terms of epicentral coordinates and focal depth), and magnitude are essential for characterisation of induced earthquakes and for application of predictive models to estimate PGV at locations of interest. To verify the actual PGV levels realised at different locations in the area surrounding the injection well, it is necessary to install strong-motion recording instruments. A number of such instruments should be installed and their locations should take into account the following considerations:

- Proximity to key elements of exposure, particularly the more vulnerable buildings; there is obvious value is knowing the levels of shaking close to dwellings and other structures, particularly those more likely to be susceptible to damage
- Proximity to the injection well and likely location of induced earthquakes; in general, shaking will be strongest close to the epicentre and it is therefore advisable that at least on instrument be located at a short distance from potential seismicity

- Azimuthal coverage; the radiation from the earthquake source may not be uniform in all directions, and therefore it is advisable to distribute the instruments around the potential earthquake sources
- Nature of the surface geology; soft soils will tend to amplify the motions and therefore if there are buildings location on such ground, at least some of the instruments should also be installed where the same ground conditions are encountered

5.2. Complete ground-motion fields

After an earthquake, the PGV values will be known at the locations of all recording instruments. However, regardless of the density of the installed strong-motion network, there will be locations at which the motions are not known. Provided there are sufficient instruments and they are adequately distributed in distance and azimuth, the average offset of the recorded PGV values can be subtracted from the median prediction from the GMPE to yield an event-specific curve. Possible ground-motion fields can then be contoured by sampling from the remaining within-event variability, anchoring to the PGV values at the recording stations, and invoking a model for spatial correlation of the motions. Such contours should also reflect the influence of surface geology if this varies over the area of interest.

In the ShakeMaps discussed earlier, the near-real-time predictions of the ground motion levels following an earthquake are made using a single GMPE but an adjustment is applied to remove the bias of the recordings with respect to the median predictions (Wald *et al*., 2006). In other words, the median predictions are adjusted to fit, in an average sense, the recorded motions. This is equivalent to assuming that the average difference between the recordings and median prediction is the event-term or the specific sample of the earthquake-to-earthquake variability associated with this particular earthquake (see http://earthquake.usgs.gov/shakemap).

5.3. Updating GMPEs using recorded motions

As recordings are obtained from a number of earthquakes of known magnitude, an application-specific database can be developed, including consistent distance measures for all recordings and, if possible, site classification of the recording locations. Should a very abundant database become available, it may be feasible to use the recordings to derive a new GMPE. However, a simpler approach that does not require such an extensive local data set is to use analysis of the residuals of the data with respect to the original GMPE to make adjustments to the latter in order to improve its applicability. An example of such a process of selecting a preliminary equation and then subsequently modifying it using project-specific recordings from induced earthquakes associated with an enhanced geothermal system is described by Bommer *et al*. (2006). The results of using local data to modify an existing GMPE have since been formalised as what is now referred to as referenced-empirical models (Atkinson, 2008).

In ShakeMap, such an adjustment is made to the GMPE for each earthquake, as noted in the previous section.

5.4. Updating risk criteria

As discussed in Section 3, the PGV defining the operational protocol will be based on relating particular consequences to different levels of PGV. Combining field observations following an earthquake with known amplitudes of PGV allows the basis for these thresholds in a decision tree to be checked and potentially modified in the light of the evidence. The confidence with which any adjustments can be made will depend on the proximity of the nearest strong-motion recorded (which determines how well the site-specific PGV is constrained) and the knowledge of the pre-earthquake state of the building being inspected (in order to know the degree to which any observed damage is directly attributable to this specific episode of shaking).

6. References

Abrahamson, N.A., W.J. Silva & R. Kamai (2014). Summary of ASK14 ground motion relation for active crustal regions. *Earthquake Spectra* **30**(3), 1025-1055.

Akkar, S. & J.J. Bommer (2010). Empirical equations for the prediction of PGA, PGV and spectral accelerations in Europe, the Mediterranean and the Middle East. *Seismological Research Letters* **81**(2), 195-206.

Al Atik, L., N.A. Abrahamson, J.J. Bommer, F. Scherbaum, F. Cotton & N. Kuehn (2010). The variability of ground-motion prediction models and its components. *Seismological Research Letters* **81**(5), 783-793.

Al Atik, L. & R.R. Youngs (2014). Epistemic uncertainty for NGA-West2 models. *Earthquake Spectra* **30**(3), 1301-1318.

Alarcón, J.E., E. Booth & J.J. Bommer (2006). Relationships between PGV and response spectral ordinates. *Proceedings of 1st European Conference on Earthquake Engineering & Seismology*, Geneva, 3-8 September, paper no. 093.

Allen, T.I. (2012). *Stochastic ground motion prediction equations for southeastern Australian earthquakes using updated source and attenuation parameters*. Record 2012/69, Geoscience Australia, Canberra, Australia.

Atkinson, G.M. (2008). Ground-motion prediction equations for Eastern North America from a referenced empirical approach: Implications for epistemic uncertainty. *Bulletin of Seismological Society of America* **98**(3), 1304-1318.

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.

Atkinson, G.M. & S.I. Kaka (2007). Relationships between felt intensity and instrumental ground motion in the Central United States and California. *Bulletin of the Seismological Society of America* **97**(2), 497-510.

Atkinson, G.M. & M. Morrison (2009). Observations on regional variability in ground-motion amplitude for small-to-moderate magnitude earthquakes in North America. *Bulletin of the Seismological Society of America* **99**(4), 2393-2409.

Baltay, A.S. & T.C. Hanks (2014). Understanding the magnitude dependence of PGA and PGV in NGA-West 2 data. *Bulletin of the Seismological Society of America* **104**(6), 2851-2865.

Beyer, K. & J.J. Bommer (2006). Relationships between median values and aleatory variabilities for different definitions of the horizontal component of motion. *Bulletin of the Seismological Society of America* **94**(4A), 1512-1522.

Bommer, J.J. & N.A. Abrahamson (2006). Why do modern probabilistic seismic hazard analyses lead to increased hazard estimates? *Bulletin of Seismological Society of America* **96**(6), 1967-1977.

Bommer, J.J. & J.E. Alarcón (2006). The prediction and use of peak ground velocity. *Journal of Earthquake Engineering* **10**(1), 1-31.

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

Bommer, J.J., J. Douglas, F. Scherbaum, F. Cotton, H. Bungum & D. Fäh (2010). On the selection of ground-motion prediction equations for seismic hazard analysis. *Seismological Research Letters* **81**(5), 794-801.

Bommer, J.J., S. Oates, J.M. Cepeda, C. Lindholm, J.F. Bird, R. Torres, G. Marroquín & J. Rivas (2006). Control of hazard due to seismicity induced by a hot fractured rock geothermal project. *Engineering Geology* **83**(4), 287-306.

Bommer, J.J. & A. Martinez-Pereira (1999). The effective duration of earthquake strong motion. *Journal of Earthquake Engineering* **3**, 2, 127-172.

Bommer, J.J., P.J. Stafford, J.E. Alarcón & S. Akkar (2007). The influence of magnitude range on empirical ground-motion prediction. *Bulletin of the Seismological Society of America* **97**(6), 2152-2170.

Boore, D.M. (2003). Simulation of ground motion using the stochastic method. *Pure & Applied Geophysics* **160**, 635-676.

Boore, D.M. & W.B. Joyner (1997). Site amplifications for generic rock sites. *Bulletin of the Seismological Society of America* **87**, 327–341.

Boore, D.M., J.P. Stewart, E. Seyhan & G.M. Atkinson (2014). NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes. *Earthquake Spectra* **30**(3), 1057-1085.

Boore, D.M., J. Watson-Lamprey & N.A. Abrahamson, N.A. (2006). Orientation-independent measures of ground motion. *Bulletin of the Seismological Society of America* **94**(4A), 1502-1511.

BSI (1993). *Evaluation and measurements for vibration in buildings – Part 2: Guide to damage levels due to groundborne vibrations*. BS 7385-2, British Standards Institute.

BSI (2008a). *Guide to evaluation of human response to vibration in buildings – Part 1: Vibration sources other than blasting*. BS 6472-1, British Standards Institute.

BSI (2008b). *Guide to evaluation of human response to vibration in buildings – Part 1: Blast-induced vibration*. BS 6472-2, British Standards Institute.

Campbell, K.W. (2003). Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America. *Bulletin of the Seismological Society of America* **93**(3), 1012-1033.

Chiou, B., R. Youngs, N. Abrahamson & K. Addo (2010). Ground-motion attenuation model for small-to-moderatCe shallow crustal earthquakes in California and its implications on regionalization of ground-motion prediction models. *Earthquake Spectra* **26**(4), 907-926.

Coburn, A. & R. Spence (2002). *Earthquake Protection*. Second edition, Wiley.

Cotton, F., Pousse, G., Bonilla, F. & Scherbaum, F. (2008). On the discrepancy of recent European ground- motion observations and predictions from empirical models: Analysis of KiK-net accelerometric data and point-sources stochastic simulations*. Bulletin of the Seismological Society of America* **98**(5), 2244-2261.

Douglas, J. (2003). Earthquake ground motion estimation using strong-motion records: a review of equations for the estimation of peak ground acceleration and response spectral ordinates. *Earth-Science Reviews* **61**(1-2), 43–104.

Douglas, J. (2012). Consistency of ground-motion predictions from the past four decades: peak ground velocity and displacement, Arias intensity and relative significant duration. *Bulletin of Earthquake Engineering* **10**(5), 1339-1356.

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

Douglas, J. & P. Jousset (2011). Modeling the difference in ground-motion magnitude-scaling in small and large earthquakes. *Seismological Research Letters* **82**(4), 504-508.

Du, W. (2017). An empirical model for mean period (T_m) of ground motions using the NGA-West2 database. *Bulletin of Earthquake Engineering, in press*, DOI 10.1007/s10518-017-0088-8.

Edwards, B., A. Rietbrock, J.J. Bommer & B. Baptie (2008). The acquisition of source, path and site effects from micro-earthquake recordings using Q tomography: applications to the UK. *Bulletin of the Seismological Society of America* **98**(4), 1915-1935.

Ellsworth, W.L. (2013). Injection-induced earthquakes. *Science* **341**, doi: 10.1126/science.1225942.

Faenza, L. & A. Michelini (2010). Regression analysis of MCS intensity and ground motion parameters in Italy and its application in ShapeMap*. Geophysical Journal International* **180**, 1138-1152.

Grünthal, G. *ed*. (1998). *European Macroseismic Scale 1998*. Cahiers du Centre Européen de Géodynamique et de Séismologie Vol. 15, Conseil de L'Europe, Luxembourg.

Hancock, J. & J.J. Bommer (2005). The effective number of cycles of earthquake ground motion. *Earthquake Engineering & Structural Dynamics* **34**(6), 637-664.

Hough, S.E. (2014). Shaking from injection-induced earthquakes in the Central and Eastern United States. *Bulletin of the Seismological Society of America* **104**(5), 2619-2626.

Klose, C.D. (2013). Mechanical and statistical evidence of the causality of human-made mass shifts on the Earth's upper crust and the occurrence of earthquakes. *Journal of Seismology* **17**(1), 109-135.

Majer, E.L., R. Baria, M. Stark, S. Oates, J. Bommer, B. Smith & H. Asanuma (2007). Induced seismicity associated with Enhanced Geothermal Systems. *Geothermics* **36**, 185-222

Nepveu, M., K. van Thienen-Visser & D. Sijacic (2016). Statistics of seismic events at the Groningen field. *Bulletin of Earthquake Engineering* **14**, 3343-3362.

Rathje, E., F. Faraj, S. Russell & J.D. Bray (2004). Empirical relationships for frequency content parameters of earthquake ground motions. *Earthquake Spectra* **20**(1), 119-144.

Rietbrock, A., F. Strasser & B. Edwards (2013). A stochastic earthquake ground-motion model for the United Kingdom. *Bulletin of the Seismological Society of America* **103**(1), 57-77.

Simpson, D.W., W.S. Leith & C.H. Scholz (1988). Two types of reservoir-induced seismicity. *Bulletin of the Seismological Society of America* **78**(6), 2025-2040.

Strasser, F.O., N.A. Abrahamson & J.J. Bommer (2009). Sigma: issues, insights, and challenges. *Seismological Research Letters* **80**(1), 40-56.

Toro, G.R., N.A. Abrahamson & J.F. Schneider (1997). Model of strong ground motions from earthquakes in central and eastern North America: Best estimates and uncertainties. *Seismological Research Letters* **68**(1), 41-57.

Wald, D.J., V. Quitoriano, T.H. Heaton, H. Kanamori, C.W. Scrivner & C.B. Worden (1999). TriNet "Shake Maps": Rapid generation of peak ground motion and intensity maps for earthquakes in Southern California. *Earthquake Spectra* **15**(3), 537-555.

Wald, D.J., B.C. Worden, V. Quitoriano & K.L. Pankow (2006). *ShakeMap® Manual: Technical Manual, User Guide and Software Guide*, Version 1.0, 19th June.

Worden, C.B., M.C. Gerstenberger, D.A. Rhoades & D.J. Wald (2012) Probabilistic relationships between ground-motion parameters and Modified Mercalli Intensity in California. *Bulletin of the Seismological Society of America* **102**(1), 204-221.

Yenier, E., G.M. Atkinson & D.F. Sumy (2017). Ground motions for induced earthquakes in Oklahoma. *Bulletin of the Seismological Society of America* **107**(1), *in press*.