ISSN 0967-859X
THE SOCIETY FOR EARTHQUAKE AND CIVIL ENGINEERING DYNAMICS

NEWSLETTER

Volume 20 No 2
May 2007

Folkestone Earthquake 28 April 2007

Roger Musson and **Alice Walker** provide a preliminary report.
British Geological Survey, West Mains Road, Edinburgh, EH9 3LA

British earthquakes are usually a minor affair so far as damage is concerned. Even in the largest earthquake in the last 50 years, the 1984 Lleyn Peninsula event (5.4 ML), damage was limited in the epicentral area, due to the depth of the event (18 km), and its location well away from urban areas (Turbitt et al. 1985). Typically, the only response required after a British earthquake is the making safe of a few damaged chimneys, and safety inspections on important facilities. Damage to plaster can be repaired at the householder's convenience and is by default covered in British home insurance policies.

It is therefore almost without precedent for emergency measures to be invoked as a result of an earthquake in Britain; however, this is exactly what occurred as a result of the Folkestone earthquake of 28 April 2007.

The main shock occurred at 08h 18m local time, at breakfast time on a Saturday morning. The magnitude was 4.2 ML (which has a recurrence interval of around five years in the UK overall) but the epicentre was directly adjacent to the town of Folkestone. Furthermore, the focus was shallow, at around 2 km. This combination of factors, aided perhaps by site amplification along the line of a culverted river, resulted in localised damage within Folkestone of a severity not seen at least since the East Midlands earthquake of 1957 (Neilson et al. 1984), and probably surpassing that. In the week following, a small number of aftershocks, with magnitudes up to 1.8ML were recorded but not reported felt. The record from the nearest BGS seismograph station (5km) indicated a peak ground acceleration of about 0.1g at 10Hz, with a very short duration (these are being verified). The parameters of the earthquake were

Contents

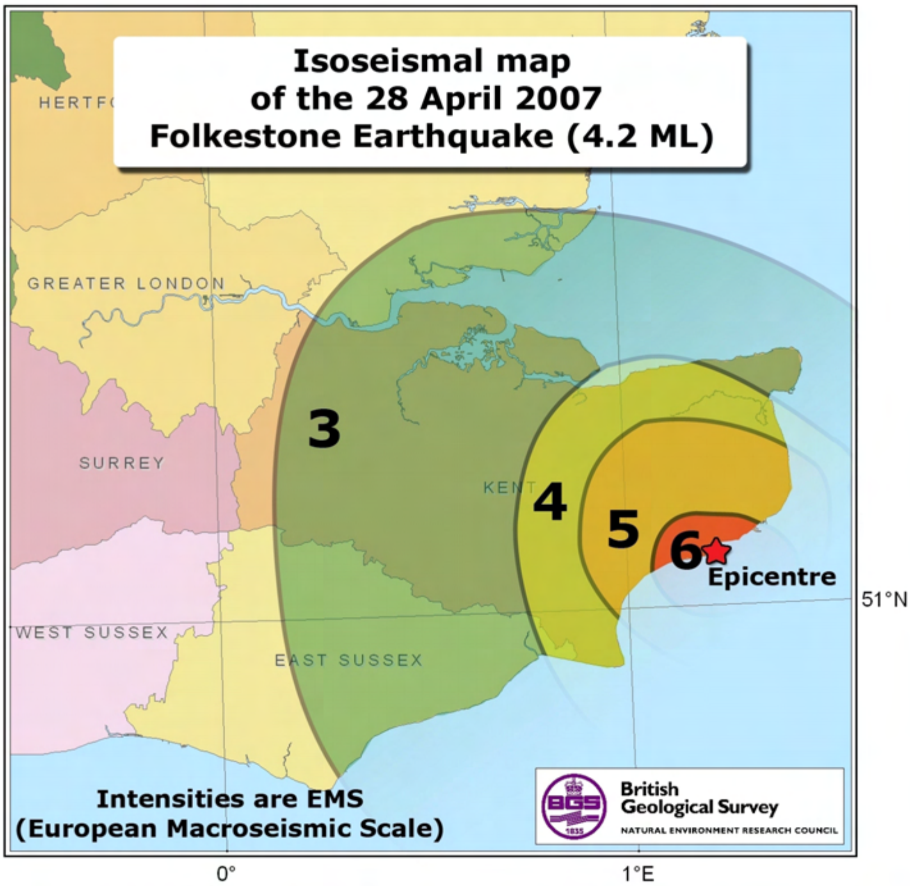


Figure 1 Folkestone Intensity Map

determined using data from the BGS UK seismic monitoring network supplemented with that from European neighbours.

The most visible damage was to the brickwork on the upper parts of chimney stacks, with the fall of bricks and chimney pots causing secondary damage to roofs on the way down. In the worst affected streets about one third of houses were so affected, and these houses often also had extensive cracks to plaster on the inside. In a few cases, chimney stacks were partly twisted, and some major cracks were observed in load-bearing walls, threatening the integrity of the building. At the time of writing, it appears that some houses will be demolished. In terms of intensity, the occurrence of many cases of damage of grade 2 leads to an assignment of a maximum intensity of 7 EMS in the area north of central Folkestone.

An online macroseismic questionnaire on the BGS web page attracted over 1000 responses within days, from which the isoseismal map shown in Figure 1 was compiled. Isoseismals are plotted for intensities 3, 4, 5 and 6 (though as with intensity questionnaires in general, there may be a bias towards positive responses that leads to slightly exaggerated values). Two things of particular note are the elongation of isoseismals to the north-west, and the fact that the bulk of the observations are restricted to Kent. Although replies were received from as far away as Norwich (175km) and Bognor (130km), the area of intensity 3 EMS was surprisingly restricted for an earthquake of this magnitude, and it is clear that in London the intensity was not more than 2 EMS. It seems likely that this is due to the shallow focal depth, which meant that the energy is more highly attenuated by the uppermost crustal layers. The earthquake was reported to be much less felt in France with some reports from Calais and Boulogne.

Relating British earthquakes to geological structure is always fraught with difficulty. The main cause of British seismicity is believed to be reactivation of favourably-oriented structures in response to the overall regional stress regime, and these can be minor basement faults with no surface expression. However, the shallowness of the Folkestone event suggests a possibility to identify the causative feature.

The regional tectonics of the Dover Straits area are dominated by features of Variscan age with a general ESE-WNW orientation. The North Artois Shear Zone is a major strike-slip feature running through Belgium and the Calais area into the Dover Straits, the line of which is continued by the northern boundary of the Weald Basin in Kent (Vandycke 2002, Lagarde et al. 2003). Investigations into the geology for the English part of the Channel Tunnel identified fold structures with a Variscan trend that were active in the Alpine period, intersected by antithetical, steeply-dipping wrench faults, also originally of Variscan age, with orientations predominantly NW-SE or NNW-SSE, defining a mosaic of structurally controlled depositional blocks within the Lower Chalk. The westernmost of the NNW-SSE bounding structures that has been identified, runs close to Folkestone (Warren and Harris 1996).

The preliminary focal mechanism for the Folkestone earthquake shows vertical strike-slip faulting with a strike of 152 or 61^{o} – this could be considered to be more or less compatible with this bounding structure, which may be the causative fault. It is also aligned with the isoseismal elongation, though the significance of this is open to debate. This earthquake is of particular interest because of past earthquakes in the Dover Straits area in 1382, 1580, 1776 and 1950. The earlier two of these were two of the largest earthquakes to have affected Britain (magnitudes approaching 6), a recurrence of which could have considerable economic consequences. Hitherto the relation of these earthquakes (if any) to seismogenic structures across the Channel has been a matter of debate, and it is to be hoped that further analysis of the Folkestone earthquake may shed some light on this difficult question. Several significant earthquakes (magnitude between 5.5 and 6) have occurred on fault systems between the Dover Straits and the Rhine; the strongest of these (1692 Verviers, 1938 Mons, 1992 Roermond) have been felt in SE England. The last of these caused around €100 million of damage close to its epicentre. Palaeoseismic evidence suggests that magnitudes in this area can even reach 6.5 (Camelbeeck and Meghraoui, 1996).

The BGS team, together with its collaborators, are continuing to work on data from this earthquake in order to refine our understanding of its characteristics in terms of location, mechanism, geological influences and damage impacts. More comprehensive reporting, therefore, will become available at a later date.

Acknowledgements

The authors wish to thank the following BGS Seismic Information team members for their contributions: Dr David Kerridge, Dr Brian Baptie, Dr David Booth, Dr Lars Ottemoller, Dr Susanne Sargeant, Mr Glenn Ford, Mr David Galloway, Mr Bennett Simpson, Mr Julian Bukits, Mr John Laughlin, Mr Heiko Buxel, Mr Anthony Swan and Mr Andrew Blythe; and Dr Peter Hobbs and P Witney (BGS Keyworth) who carried out a geological and damage walk-over of the area; and Dr Paul Burton of University of East Anglia who, with Dr Susanne Sargeant, carried out field observations of damage.

References

CAMELBEECK, T, and MEGHRAOUI, M. 1996. Large earthquakes in northern Europe more likely than once thought. Eos, Vol. 77, 405,409.

LAGARDE, J L, AMORESE, D, FONT, M, LAVILLE, E, and DUGUÉ, O. 2003. The structural evolution of the English Channel area. Journal of Quaternary Science, Vol. 18, 201-213.

NEILSON, G, MUSSON, R M W, and BURTON, P W. 1984. Macroseismic reports on historical British earthquakes V: Midlands. British Geological Survey Global Seismology Report, No 228.

TURBITT, T, BARKER, E J, BROWITT, C W A, HOWELLS, M, MARROW, P C, MUSSON, R M W,

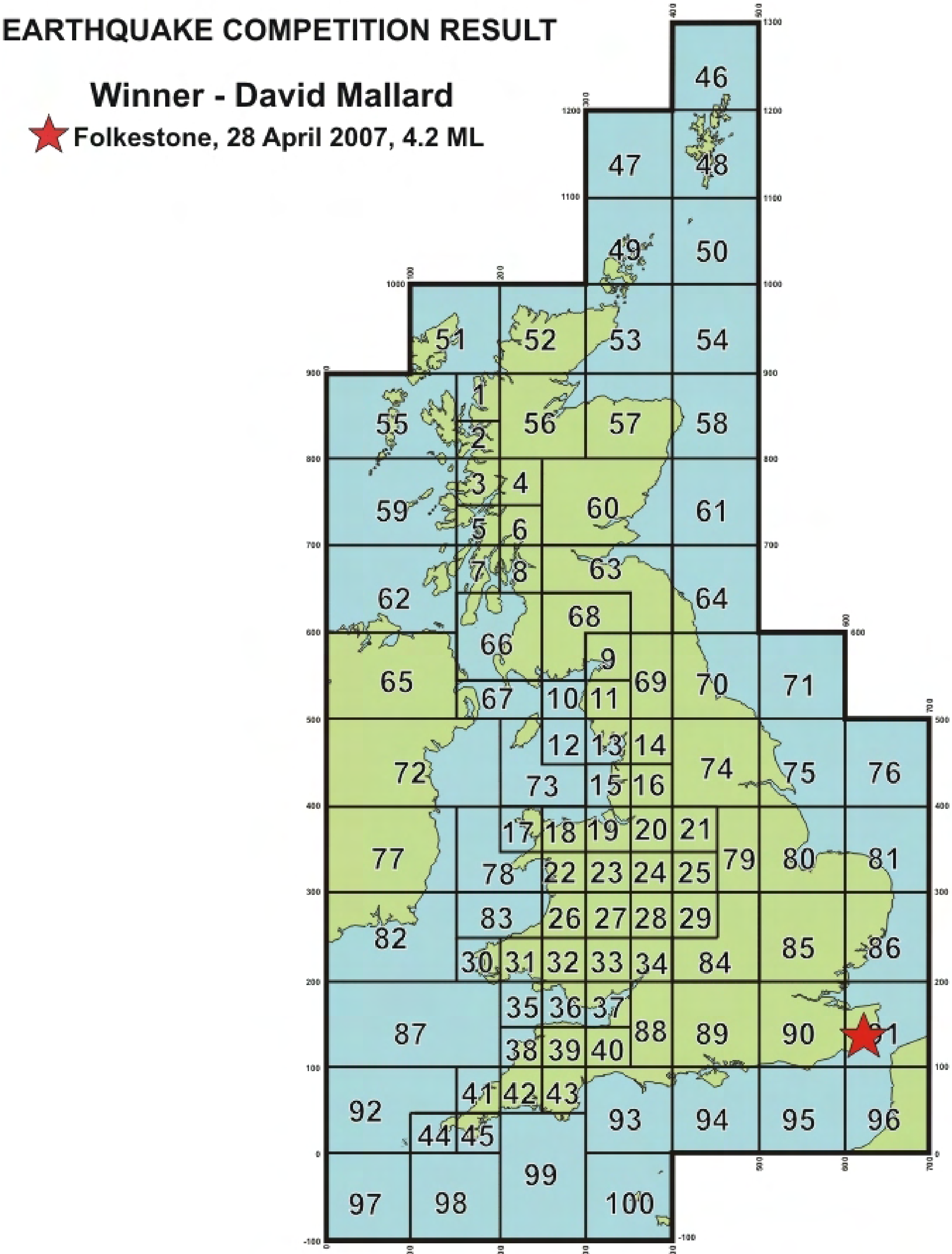
NEWMARK, R H, REDMAYNE, D W, WALKER, A B, JACOB, A W B, RYAN, E, and WARD, V. 1985. The North Wales earthquake of 19 July 1984. Journal of the Geological Society, Vol. 142, 567-571.

VANDYCKE, S. 2002. Palaeostress records in Cretaceous formations in NW Europe: extensional and strike-slip events in relationships with Cretaceous-Tertiary inversion tectonics. Tectonophysics, Vol. 357, 119-136.

WARREN, S T, and HARRIS, C S. 1996. An interpretation of the structural geology. 421-435 in Engineering Geology of the Channel Tunnel. HARRIS, C S, HART, M B, VARLEY, P M, and WARREN, C D (editors). (London: Thomas Telford.)

SECED Earthquake Competition

The Folkestone April 2007 Earthquake came hot on the heels of SECED's earthquake competion, held in April at the SECED AGM. **David Mallard** succesfully predicted that square 91 would yield the first event over 2.5 ML.



Uncertainties in Site Response Analysis: Characterization of Input Motions and Site Properties

Ellen M. Rathje, P.E., Ph.D. University of Texas at Austin

Introduction

Understanding the influence of soil conditions on earthquake ground shaking is critical for prescribing appropriate ground motion levels for seismic design. To evaluate the effects of the site-specific soil conditions on the expected level of ground shaking, seismic site response analysis is typically performed. This analysis involves propagation of expected input rock motions through the soil deposit to evaluate the expected motion at the soil surface. The predominant uncertainties involved in this analysis are the input rock motions, the shear wave velocity profile of the site, and the nonlinear soil properties (as characterized by the shear modulus reduction and damping curves). Equivalent-linear, SHAKE-type seismic site response analyses were performed for a deep soil site to consider the effect of these uncertainties on the predicted soil motion at the ground surface. Implications for probabilistic seismic hazard analysis were also addressed.

Selection of Input Rock Motions

Any site response analysis (as well as any dynamic analysis for seismic design) requires a suite of input rock

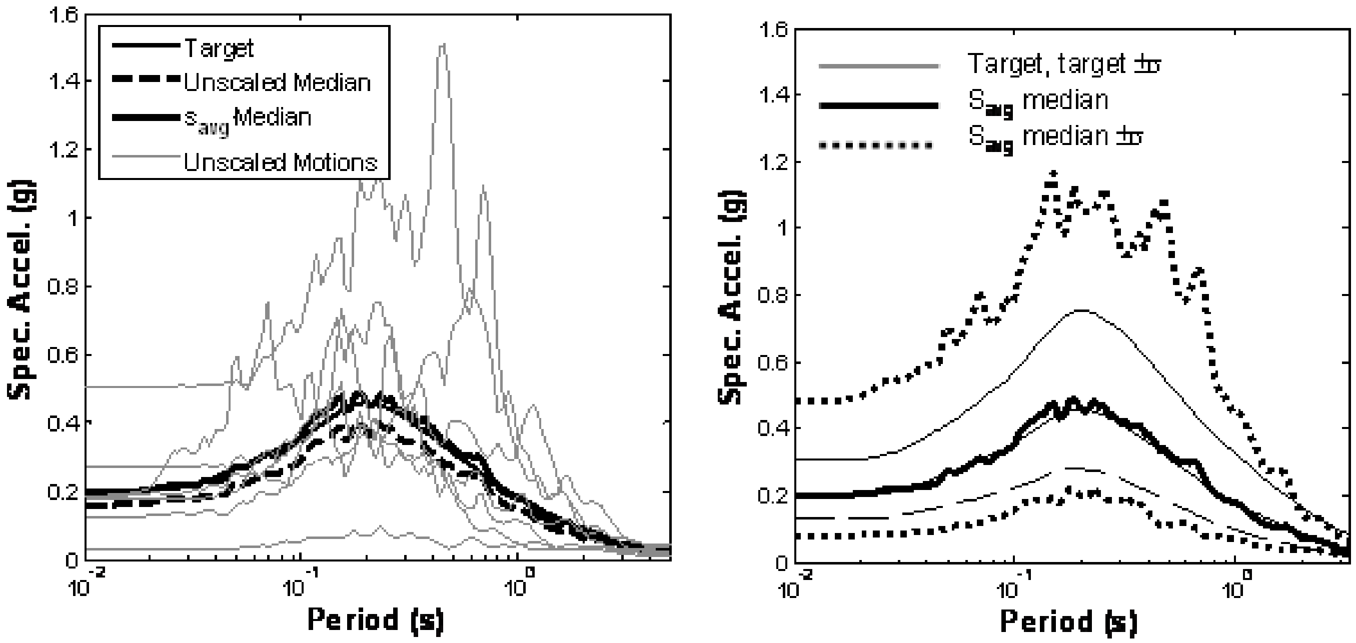


Figure 1. Suite of motions selected to fit the median target response spectrum

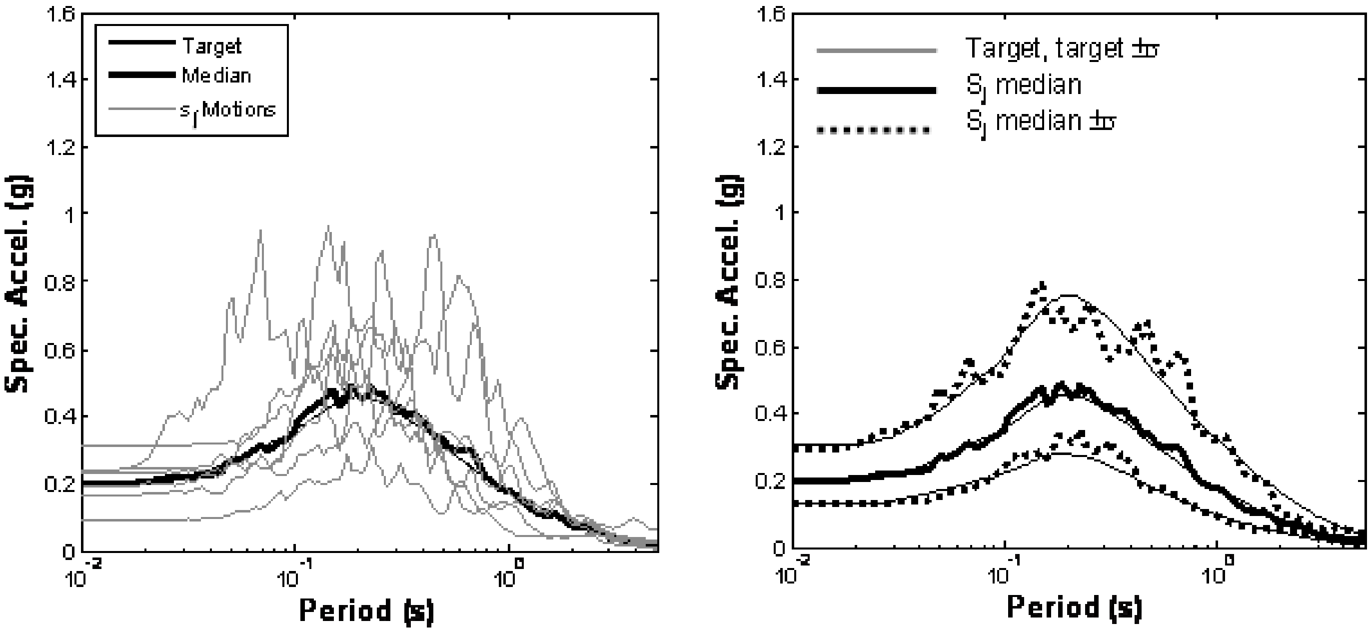


Figure 2. Suite of motions selected and scaled to fit the median target response spectrum and a given variability (σ)

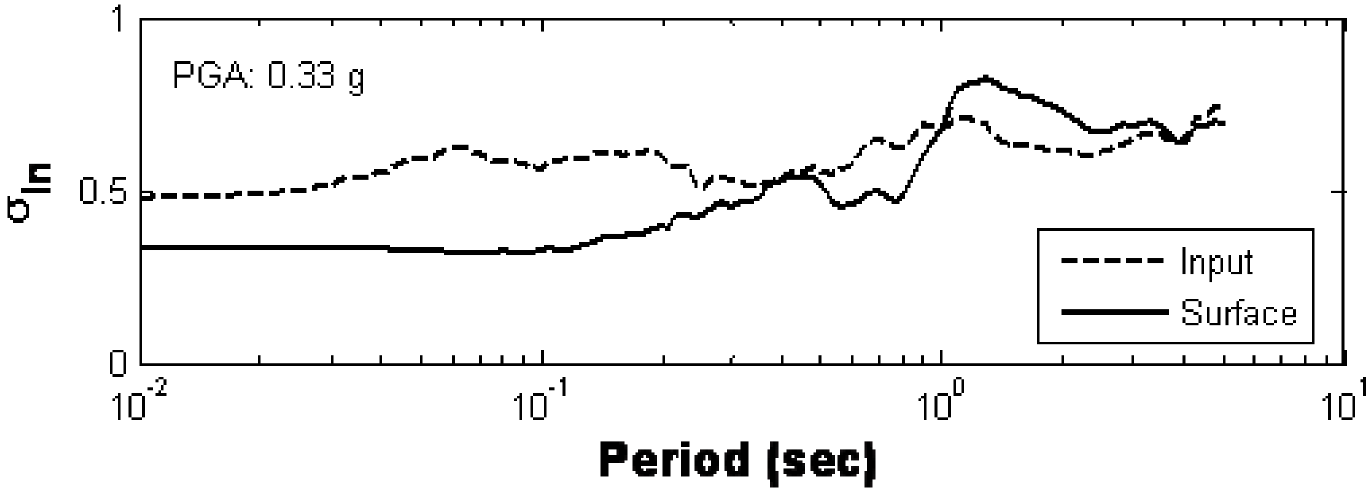


Figure 3. Change in standard deviation (σ_{ln}) of a suite of motions due to site response

motions to adequately capture the expected frequency content of the rock motion over the frequency range of engineering interest. A suite also allows for some variability about the target response spectrum. A semi-automated selection procedure for earthquake motions has been developed (Kottke and Rathje 2007) that selects suites of motions that best-match a target response spectrum. In addition to generating suites of motions that match the target spectrum, the algorithm also includes a scaling procedure that scales individual motions within the suite to best-match a desired level of variability (standard deviation).

An example of a suite of motions selected and scaled using the semi-automated procedure is shown in Figures 1 and 2. For this example, seven motions were selected from a catalog of 44 motions, and the target response spectrum and its variability (σ_{ln}) were defined using the Abrahamson and Silva (1997) ground-motion prediction equation for $M_w = 6.5$ and R = 20 km. The selection procedure, and its initial average scaling, provides an excellent fit with the target spectrum, but the variability of the suite is very large (Figure 1). Individual scale factor are then derived that maintain the excellent fit to the target response spectrum, but also fit the target variability (Figure 2). This second scaling process can also be used to minimize the variability, if one is predominantly interested in the median response.

Using the procedure outlined above, multiple suites of 5, 10, and 20 motions were developed that fit the target response spectrum and its variability. These suites were used as input into site response analysis to consider how many motions are required to predict a stable estimate of the median surface response and its variability. These results showed that as few as 5 well-selected motions can provide a stable estimate of the median surface motion, but as many as 20 motions are required to characterize the standard deviation of the surface motion (Kottke 2006).

While site response analysis is typically used to predict the change in the median ground motion due to soil response (i.e., soil amplification/ deamplification), little information is available regarding the effect of soil response on the standard deviation of expected motion. Site response analyses were performed using a 20 motion suite of input motions, fit to the target variability, to address this issue. Results show that site response significantly changes the standard deviation of the ground motions. Figure 3 displays the standard deviation (σ_{ln}) versus period for the suite of input motions and surface motions, and reveals that at periods less than the initial site period (about 0.9 s in this case) the standard deviation is reduced by as much as 30%. However, at periods larger than the site period the standard deviation is increased. These results are due to soil nonlinearity, which causes site amplification to be intensity dependent, as well as the different effects of soil nonlinearity at long and short periods.

Uncertainties in Site Properties

Site properties are uncertain for various reasons, including measurement uncertainty, sample disturbance, and true spatial variability at a site. Monte Carlo simulations can be used to account for these uncertainties in a seismic site response analysis. In a Monte Carlo simulation, the input properties for the site response analysis (shear wave velocity, Vs, and nonlinear soil properties) are randomly selected from a defined probability distribution. The site response is calculated for each realization of site properties and the results from all analyses are used to define the statistical properties of the surface motion. Analyses were performed with shear wave velocity randomized, nonlinear properties (i.e., shear modulus reduction, G/G_{max}, and damping, D, curves) randomized, and both shear wave velocity and nonlinear properties randomized. The effects of these randomizations on the median surface response and its standard deviation were investigated.

Figure 4 shows the median response spectra for the surface motions computed for the different randomization schemes, including the analyses with no randomization. The input target response spectrum had a median peak ground acceleration (PGA) of 0.33 g, representing a

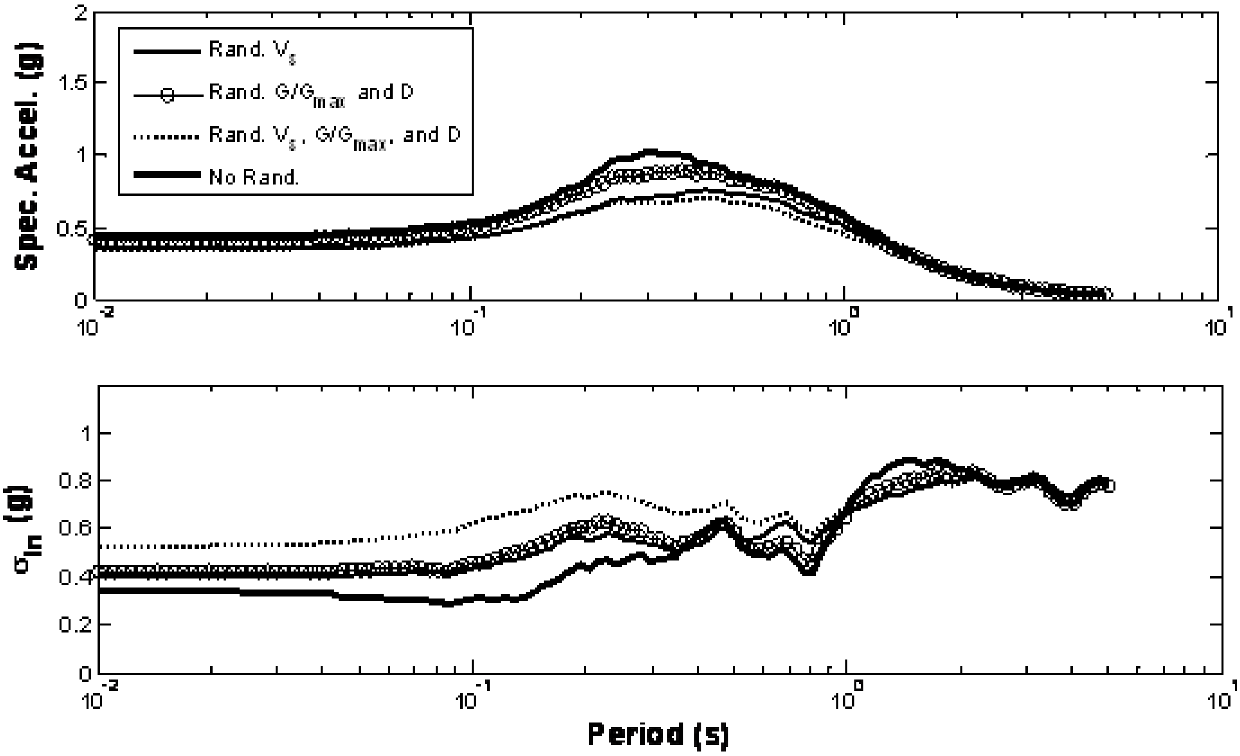


Figure 4. Effect of randomization of shear wave velocity and nonlinear properties on the predicted median surface response spectra and its standard deviation.

moderate level of shaking that induced moderate soil nonlinearity. The randomization of nonlinear properties resulted in only a minor decrease in the median response, while randomization of the shear wave velocity caused up to a 30% reduction in the median surface response. This reduction is attributed to the fact that randomization of the shear wave velocity essentially randomizes the initial site period, causing the peak responses to occur at different periods for each Vs realization. Averaging these dissimilar responses results in a reduction in the surface response as compared with analyses that use only the baseline soil properties. Figure 4 also shows the standard deviation of the surface motions for each of the randomization schemes. The additional uncertainty in the input properties results in an increase in the standard deviation at short periods and a slight decrease at longer periods, as compared to the baseline (no randomization) case. When both Vs and nonlinear properties are randomized, the change in standard deviation is most significant.

These analyses show that randomizing input properties for *equivalent-linear* site response analysis results in a reduction in the surface response. This consequence may be non-intuitive, as engineers often feel that by including more uncertainty one obtains a more conservative result. Therefore, it is important for engineers to understand the impact of including site uncertainty when performing site response analysis.

Site Response and Probabilistic Seismic Hazard Analysis

Probabilistic seismic hazard analysis (PSHA) has become almost ubiquitous for defining design level ground motions based on an expected probability of exceedance. Most hazard curves generated by PSHA are developed for rock site conditions, using a rock ground-motion prediction equation, or for generic soil conditions, using a soil ground-motion prediction equation. However, soil ground motion prediction equations are based on general soil classes and many do not model soil nonlinearity. If site-specific site response analysis is desired, currently the most common approach is to perform the site response analysis outside of the PSHA framework using the hazard curves for rock to derive the input motions for the analysis (Figure 5). The uniform hazard spectrum typically is used to select the input rock motions, although more recently engineering seismologists have suggested developing scenario spectra that acknowledge the fact that different earthquake scenarios control the hazard at different periods. Scenario spectra can be derived from the uniform hazard spectrum using deaggregation information at different periods (Figure 5). For either specification of the input spectra, performing the site response after the hazard calculation results in an unknown hazard level for the soil surface motion, and studies have shown that the resulting soil motion may be unconservative (Cramer 2003, Bazzurro and Cornell 2004), particularly at long return periods. This approach may be unconservative because it ignores contributions to the hazard of small rock motions magnified by large amplification factors.

A more rigorous approach incorporates the site-specific site response into the hazard calculation directly (Figure 6). Here, a suite of site response calculations are performed to quantify

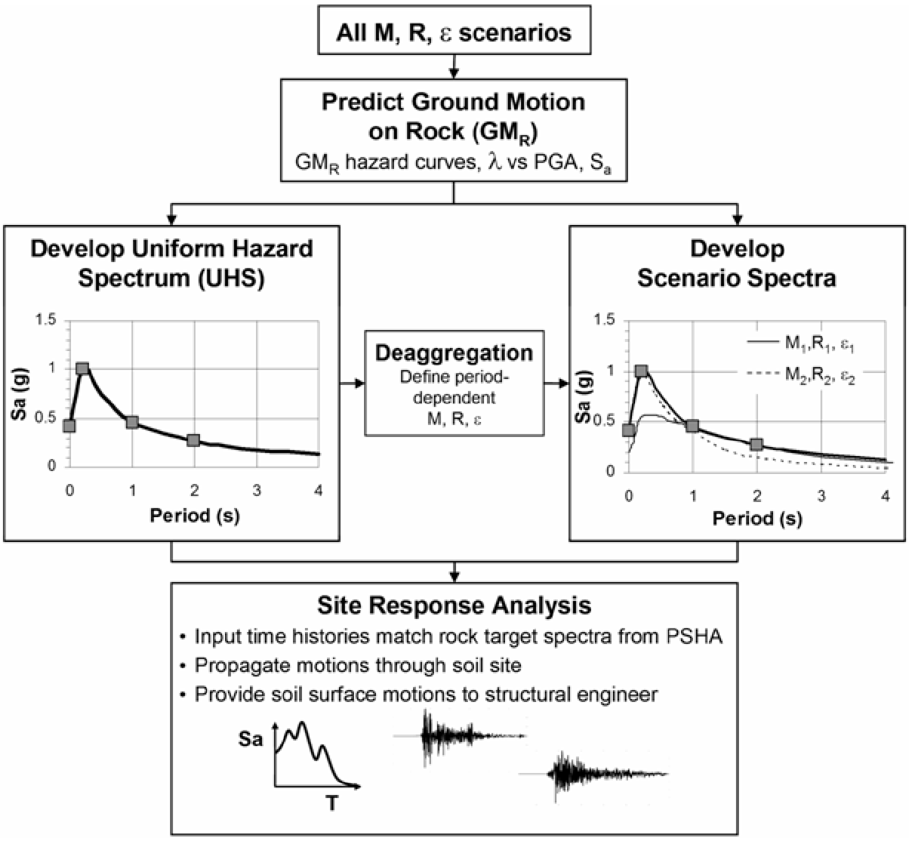


Figure 5. Framework for performing seismic site response outside of the PSHA calculation

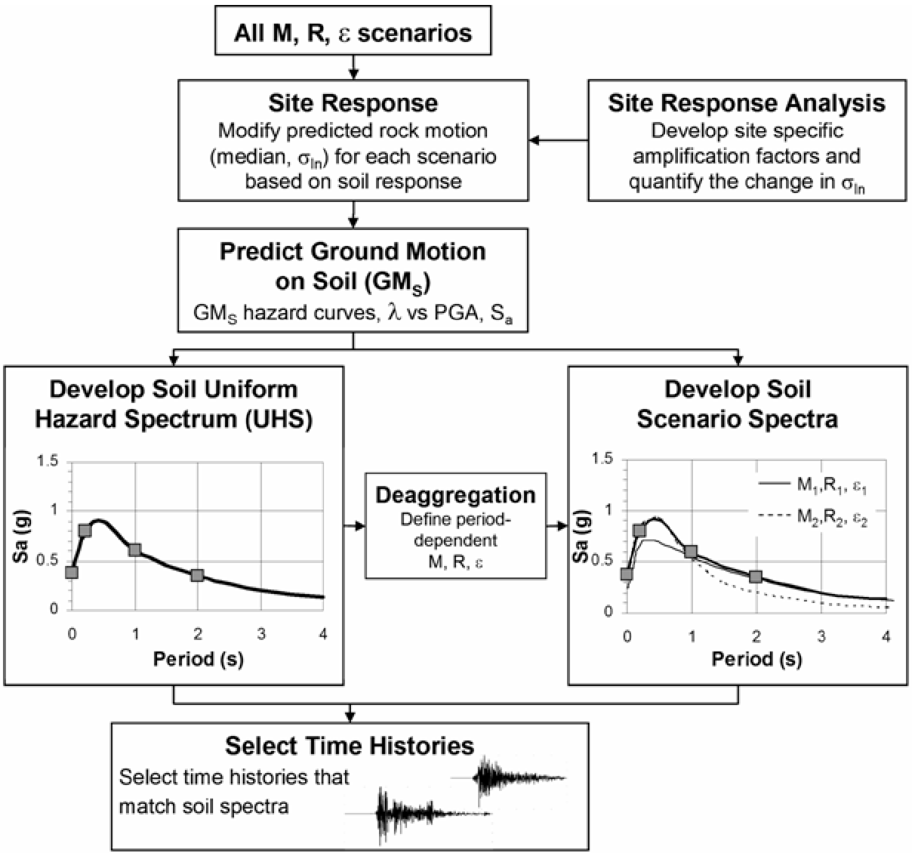


Figure 6. Framework for incorporating seismic site response within the PSHA calculation

the amplification/deamplification of motion at different periods and different input intensities, as well as to describe the standard deviation of the soil surface motion. The work described previously in this article addresses these issues. This information is then used to modify the predicted rock motion (median and σ_{ln}) for each earthquake scenario, such that soil amplification is taken into account for all levels of shaking and the hazard curves are developed for the soil surface motion. The resulting uniform hazard spectrum or scenario spectra are used as target spectra to select appropriate time histories that can be used in subsequent structural analysis. The main benefit of this approach is that the hazard for the soil surface motion is specified, such that the input motions used in the subsequent structural analysis have a known hazard level.

References

Abrahamson, N.A. and Silva, W.J. 1997. "Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes," *Seismological Research Letters*, 68(1), 94–127.

Bazzurro, P. and Cornell, C.A. 2004. "Nonlinear Soil-Site Effects in Probabilistic Seismic-Hazard Analysis," *Bulletin of the Seismological Society of America*, 94(6), 2110-2123.

Cramer, C.H. 2003. "Site Specific Seismic Hazard Analysis That is Completely Probabilistic," *Bulletin of the Seismological Society of America*, 93, 1841-1846.

Kottke, A.R. 2006. "Impact of Input Ground Motions and Site Variability on Seismic Site Response," M.S. Thesis, Department of Civil, Architectural, and Environmental Engineering

Kottke, A.R. and Rathje, E.M. 2007. "Semi-Automated Selection and Scaling of Earthquake Ground Motions," Proceedings, *4th International Conference on Earthquake Geotechnical Engineering*, Paper No. 1248, Thessaloniki, Greece, June (CD-ROM).

Long-Range Guided Wave Inspection: Rapid Screening of Large Structures

Tiziana Rossetto reports on the January 2007 SECED meeting, where **Peter Cawley** provided a fascinating and honest presentation of the practical benefits and limitations of this technique, and explained the research behind its development.

In the January SECED evening meeting **Professor Peter Cawley** of the Department of Mechanical Engineering at Imperial College London presented research on long-range guided wave inspection. Research into this method has evolved over the past 15 years and is now in routine commercial use worldwide.

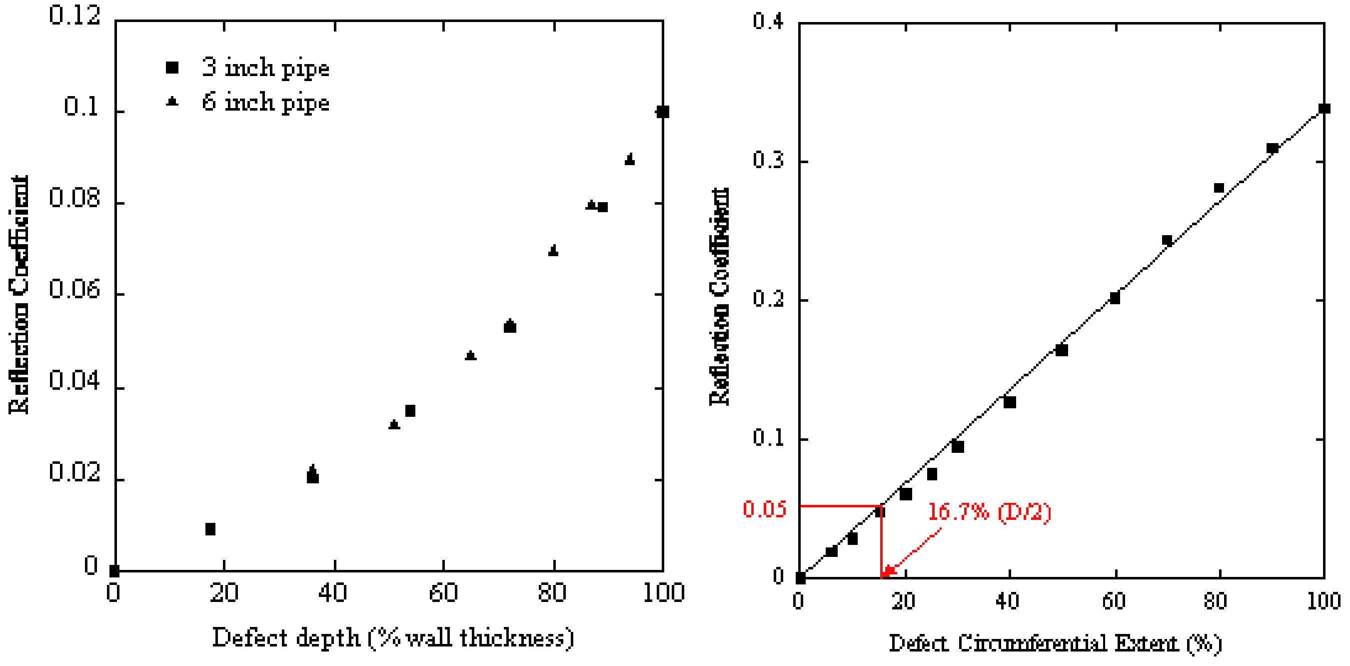
Long-range guided wave inspection involves the excitation of low frequency ultrasonic waves in a structure and the recording of the response signal. The same transducer can be used to both excite the wave and record the response. The wave travels along the structure (i.e. is a guided wave), and can be partially reflected by defects present along the structure length. Thus the defect is represented by the presence of a reflected wave in the response signal. The great advantage of the long-range guided wave method is the possibility of detecting defects over large sections of structures with a single measurement, and the ability to look at defects in locations that are inaccessible for visual inspection (e.g. buried, offshore or subsea).

In early trials, the response signal was found to be significantly affected by coherent noise of similar strength to the reflected waves caused by the defect. The coherent noise posed a real limitation to the reliability of long-range guided waves for defect detection. It was realised that the coherent noise was caused by the simultaneous excitation of several modes in the structure, each travelling at different speeds (dispersion). Key to the solution of coherent noise was the ability to control which mode was excited in the structure. Hence, a new generation of long-range guided wave excitation devices were developed that used an array of transducers to send and receive selected modes (e.g. Figure 1a).

Guided Ultrasonics Ltd., a spin off company of Imperial College London, has patented a device that induces torsional modes in pipelines. This allows the detection of defects in the pipe walls to be carried out without the signal being disturbed by the presence of fluid or gas in the pipe. The bigger the defect size in terms of percentage of the pipe wall depth and pipe circumference, the greater the reflection coefficient and hence the amplitude of the reflected signal (see figure 2).

In this application, features such as butt welds are also detected by the method as these cause reflection of the guided waves. Figure 4 shows the typical output obtained when adopting long-range guided waves to assess a pipeline. An attenuation of the wave with distance from the source is seen, which poses a limitation to the inspected length possible with one shot. As would be expected, this attenuation is greater in the case of buried pipelines than for those surrounded only by air. Typical ranges of applicability for the detection of defects in pipelines with current long-range guided wave technologies are given in Table 1, (note: these ranges can be doubled using low-frequency transducers).

Figure 1: **(a)** View of the transducers placed in an array for inspection of a pipeline. **(b)** Photo of application in the inspection of a buried pipeline (Photos care of Guided Ultrasonics Ltd.).



(a) (b)

Figure 2: Relationships between wave reflection coefficient and defect size in terms of defect depth (a) and defect circumferential extent (b).

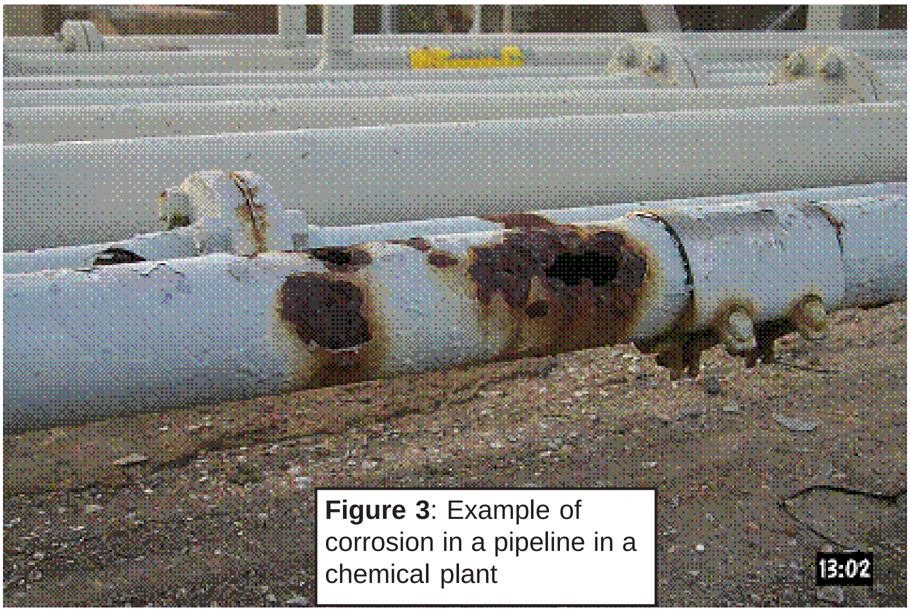


Figure 3: Example of corrosion in a pipeline in a chemical plant

Table 1: Typical ranges of applicability of long-range guided wave inspection method for pipes	
Pipe Condition	**Range**
Good pipe condition, surrounded by air	80m, 6 weld lengths, the first flange, the second bend or branch
Typical 30 year old pipe with little internal or external corrosion	40m
Typical 30 year old pipe with some general corrosion	20m
Typical pipe wrapped in factory applied foam	15m
Heavily corroded pipe or pipe that is bitumen wrapped	5m

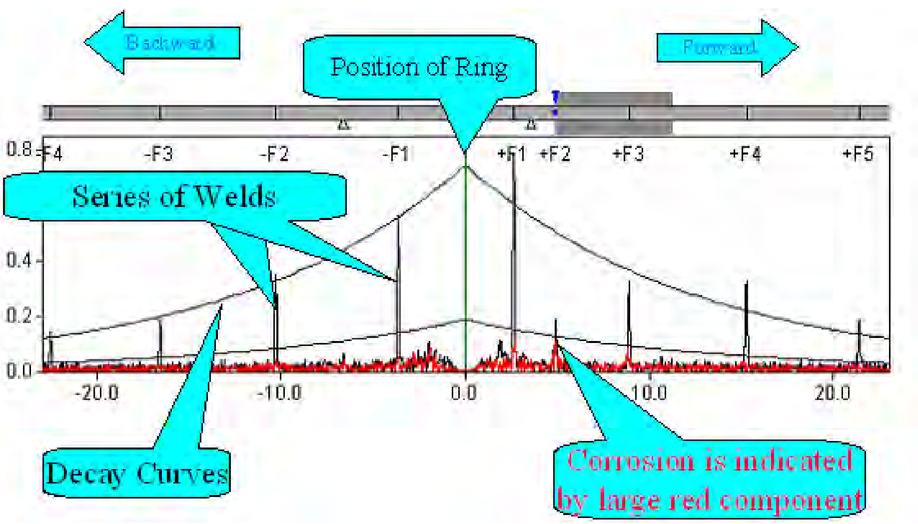


Figure 4: Typical output results from the inspection of a pipeline

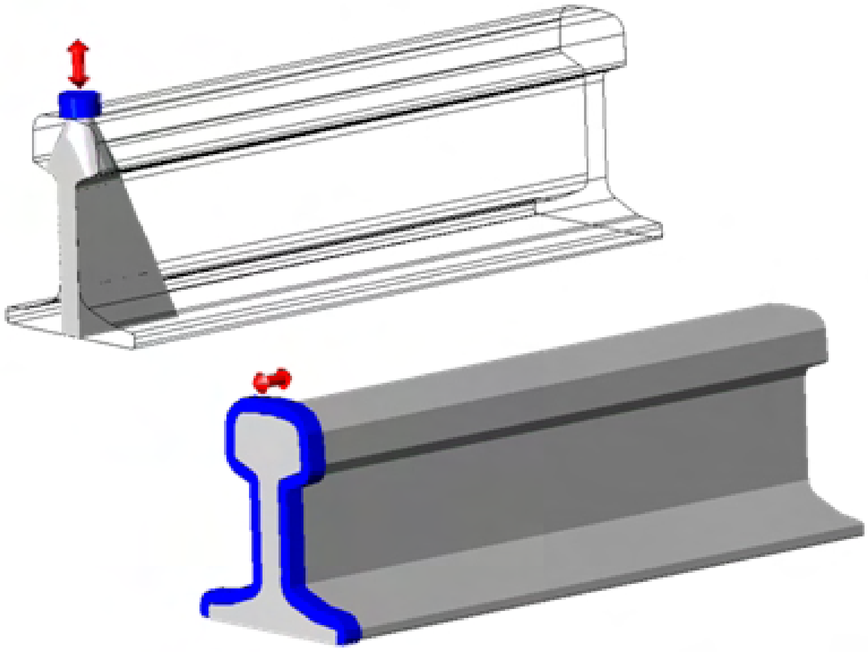


Figure 5: Illustration of conventional testing (a) and long-range guided wave inspection (b) area of rails. The red arrows indicate the direction of the waves. The dark grey area illustrates the area of detection.

A further successful application of the technique is the inspection of rails. Conventional inspection techniques are only able to detect defects in a small area directly below the probe. Through the use of an array of transducers, waves can be sent along the rail and much larger lengths of rails can be inspected (see Figure 5).

A trial application has been carried out on rock bolts used for roof reinforcement in coal mines. Overloading in the bolts can cause undetected tensile failure. Guided waves are reflected by the end of the bolt, allowing the integral length of the bolt to be detected. An example of the detection signal is shown in Figure 6.

This was a fascinating and refreshingly honest presentation of the practical benefits and application limitations of a commercial testing technique and the research behind its development. The questions and lively discussions that ensued, addressed the possibility of future applications of long-range guided wave inspection in civil engineering structures. The success of this talk shows that a lot can be gained from the interaction of mechanical and civil engineers in the area of dynamics.

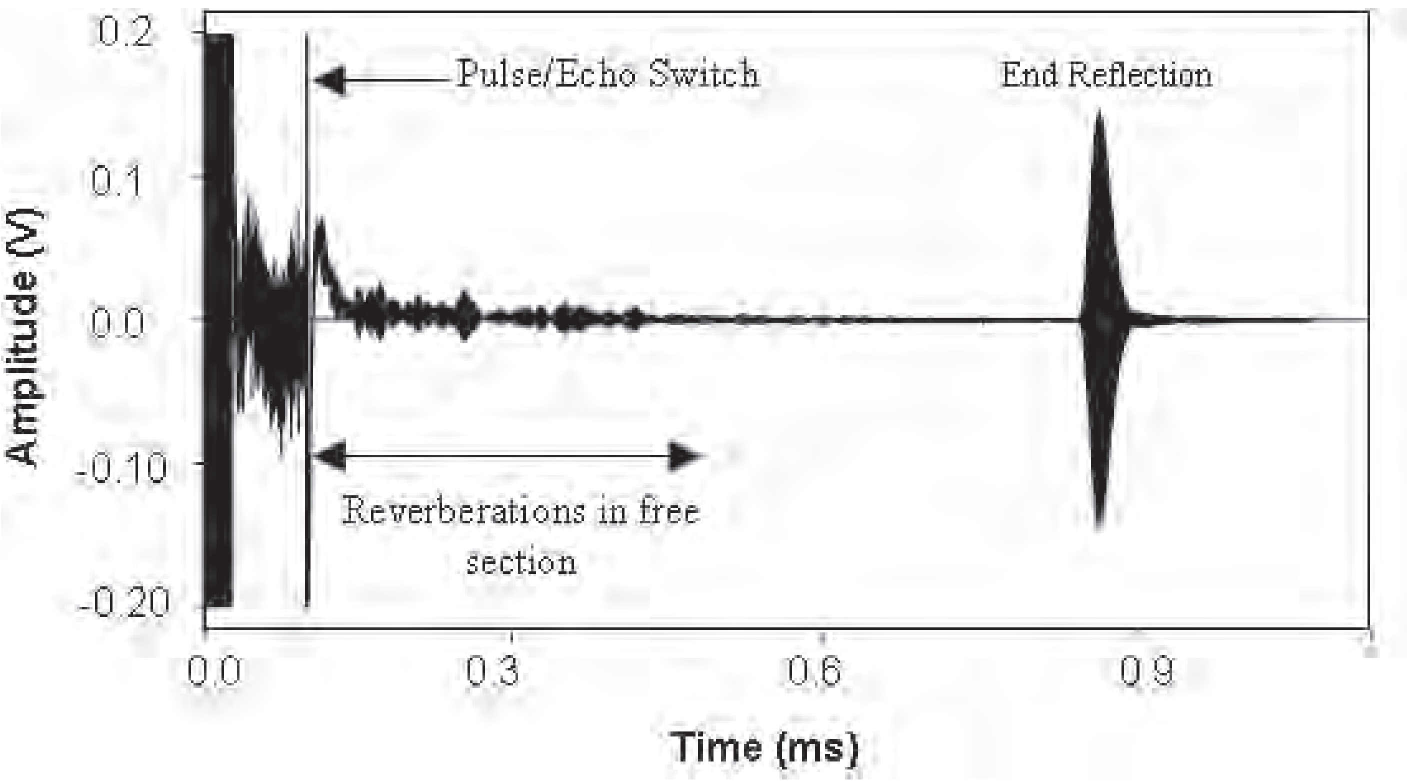


Figure 6: Graph of the response from a 2.4m long rock bolt

The Impact of Engineering Seismology Research on Seismic Hazard Assessments

Julian Bommer SECED Technical Reporter on Engineering Seismology

In an article in the last *SECED Newsletter*, Andrew Coatsworth from HMNII raised several very interesting points related to the specification of response spectra for the seismic design of nuclear facilities in the UK. The article provided a welcome insight to these important issues from the perspective of the regulator. This article explores two of the issues raised in that article, and also makes a proposal for a new paradigm for seismic hazard analysis for critical facilities in the United Kingdom.

In his article, Dr Coatsworth repeats my statement, made at the SECED technical meeting in September of last year, that ground-motion prediction equations tend to become dated after about 10 years. Dr Coatsworth pointed out that nuclear facilities are likely to have design lives closer to 50 years. Therefore there is understandable concern that the evolution of ground-motion prediction (attenuation) equations during the design life of a critical facility might undermine or invalidate the seismic design basis.

There are two issues to address here, the first being why ground-motion prediction equations seem to need updating every decade. Since the most widely-used equations in probabilistic seismic hazard analysis (PSHA) are those derived empirically from regression on strong-motion data, the real driver behind the evolution of predictive models is the ever-growing databank of earthquake accelerograms. Each new earthquake producing a significant number of recordings tends to provide new insight into the nature of ground motion and the causative factors that control the characteristics of ground shaking. These insights allow the development of improved models based on the newly-identified correlations between characteristics of the ground motion and features of the earthquake source, the source-to-site travel path and the recording site itself. An interesting example of how quickly the science of ground-motion prediction advances is the modelling of forward-directivity effects producing high-energy velocity pulses: Somerville *et al*. (1997) produced a model that predicted increases in spectral amplitudes at all periods beyond 0.6 seconds as a result of forward rupture-directivity in earthquakes of M_w 6.5 and greater. The database on which this study was based included 21 earthquakes, 17 of which had magnitudes between M_w 6.0 and 6.9. In 1999, large-magnitude (M_w > 7) earthquakes in Turkey and Taiwan produced many near-source accelerograms, analysis of which did not reveal directivity effects that conformed with the Somerville *et al*. (1997) model but rather as a narrow-band pulse at periods between 3 and 4 seconds. These observations led to re-evaluation of the forward-directivity effects as a narrow-band effect rather than an amplification of the spectral ordinates across the full period range, with the period of the pulse growing with the magnitude of the earthquake (Somerville, 2003). One consequence of this discovery has been that forward-directivity pulses, at periods closer to the natural vibration period of many buildings in urban environments may also be encountered in near-source recordings of smaller magnitude events (Bommer *et al*., 2001).

The acquisition of new data, plus advances in strong-motion processing, improvements in regression techniques and the re-assessment of magnitudes, distances and site classifications, all drive the need to periodically update and revise ground-motion prediction equations. For example, most of the western US equations presented in a special issue of *Seismological Research Letters* in 1997 (e.g., Boore *et al*., 1997; Campbell, 1997; Abrahamson and Silva, 1997) have recently been superseded by the equations produced in the Next Generation of Attenuation (NGA) project run by the Pacific Earthquake Engineering Research (PEER) Center (Power *et al*., 2006). Similarly the European spectral prediction equations of Ambraseys *et al.* (1996) have been superseded by Ambraseys *et al.* (2005) and by Akkar and Bommer (2007).

The revisions of models may lead to higher or lower hazard estimates, depending on changes in the median estimates and in the size and nature of the associated scatter (standard deviation). This is impossible to predict at the time of carrying out a PSHA, but one should be prepared for changes to the hazard estimates to arise 10 or 20 years later as a result of modifications to the ground-motion models and other aspects of the analyses. The changes in ground-motion models reflect epistemic uncertainty, which means that our knowledge at any time is incomplete and as more knowledge is acquired our estimates of the ground motions due to future earthquakes will change. The important thing is that this epistemic uncertainty needs to be captured in the PSHA, which cannot be done by using a single ground-motion prediction equation. The main reason for this is that all strong-motion datasets, even in California, are rather sparse in terms of coverage of all the possible combinations of explanatory variables (magnitude, style-of-faulting, distance, site conditions, etc.) and also likely to be biased since, for example, the few large-magnitude events recorded may be untypical in terms of stress drop or other characteristics of the fault rupture. The inadequacy of a single ground-motion prediction equation for a low-seismicity region such as the UK is even more pronounced, because there is very little indigenous strong-motion data with which to test the applicability of equations and certainly not enough to derive robust local equations despite valiant attempts to do so (e.g., Allen, 2006). One of the key problems with only possessing recordings of small-magnitude events is that PSHA invariably models the effects of larger earthquakes (in the UK, hazard integrations will generally extend to at least magnitude 6.5) and as a result of non-linear magnitude dependence and magnitude-dependent geometrical spreading, equations derived from small earthquakes are likely to underestimate motions from the larger events that drive seismic hazard (Figure 1).

The correct approach is to select a suite of equations that capture the range of possible ground motions from future earthquakes in the region under study (e.g., Cotton *et al*., 2006) and to combine these in a logic-tree (e.g., Bommer *et al*., 2005). If the logic-tree is assembled appropriately, one can expect that future estimates of ground motions, which one would hope to have a lower associated epistemic uncertainty, should fall within the bounds defined by the ground-motion branches. For the design return period, one can then increase the confidence in having really captured the ground motions corresponding to this hazard level by selecting a higher fractile hazard curve (Abrahamson and Bommer, 2005), although this option is not open if one follows the standard industry practice of using the mean

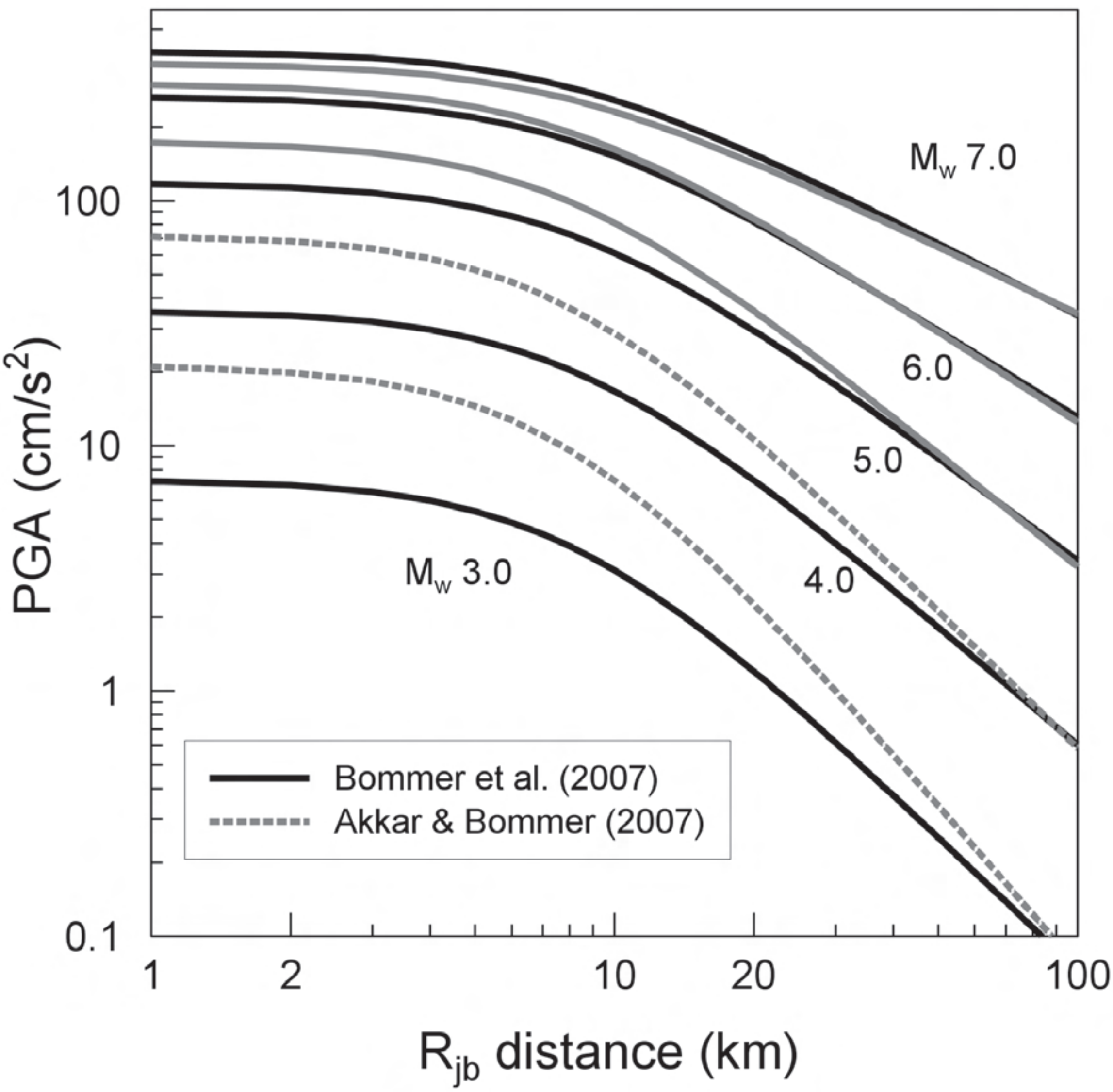


Figure 1. Predicted values of PGA on rock sites derived from a dataset consisting of only events of M_w 5 and greater (grey lines) and another extending the lower limit to M_w 3 (adapted from Bommer *et al*., 2007). The equation derived from only larger-magnitude events overestimates the motions from smaller events; the converse – underestimation of large-magnitude motions using an equation derived from smaller events – can therefore be expected.

hazard curve (McGuire *et al*., 2005; Musson, 2005). Ensuring that epistemic uncertainties are adequately identified and captured in the logic-tree generally requires multiple expert opinions to be combined, an issue discussed later.

The second issue for discussion is the statement by Dr Coatsworth that "*the emphasis of the nuclear industry in seismic research for 20 years has been to reduce the design basis hazard, which in the end remains uncertain*". It is perfectly understandable that nuclear power companies will be motivated to fund research in this area at least partly in the hope of obtaining reduced hazard estimates, given that provided these are robust they can lead to very significant cost reductions. There has been a case recently, in Switzerland, in which power plant owners have very clearly been looking to reduce the new hazard estimates for their sites, for the simple reason that the large increase with respect to the original hazard estimates (which contained a fundamental error), present them with a real problem (Bommer and Abrahamson, 2006). In this respect, Dr Coatsworth makes the very relevant observation that "*the industry has seen engineering seismology, rather than more realistic methods of assessment* [of seismic capacity], *as the solution*." The correct response to increased hazard estimates does indeed lie in engineering solutions (which may include analyses that account for soil-structure interaction and allow some inelastic response in non-critical elements) rather than trying to artificially reduce the hazard by manipulation of the input data and models to obtain a more acceptable answer.

One would hope that researchers in engineering seismology are never motivated by a desired outcome to produce lower hazard estimates except in our attempts to reduce the aleatory variability (scatter) associated with the equations, as represented by the standard deviation of the logarithmic residuals, often referred to as sigma (σ). Despite the growth of strong-motion databanks and the inclusion of additional explanatory variables in predictive equations, the reductions in the standard deviations achieved to date have been rather small (e.g., Douglas, 2003). However, even small reductions in sigma can lead to appreciable reductions in hazard estimates (Figure 2).

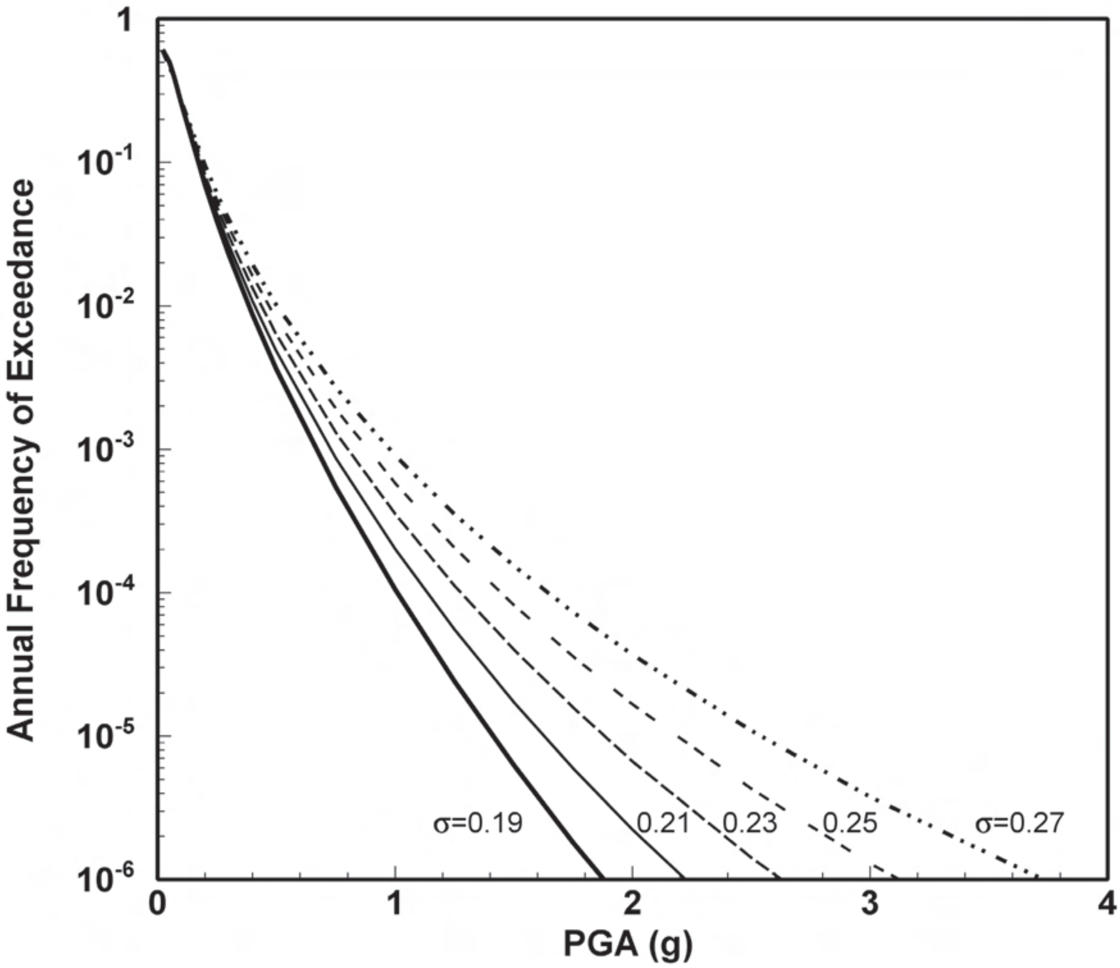


Figure 2. Hazard curves for PGA showing the sensitivity of the hazard to the value of the logarithmic standard deviation associated with the attenuation equation (Bommer and Abrahamson, 2006).

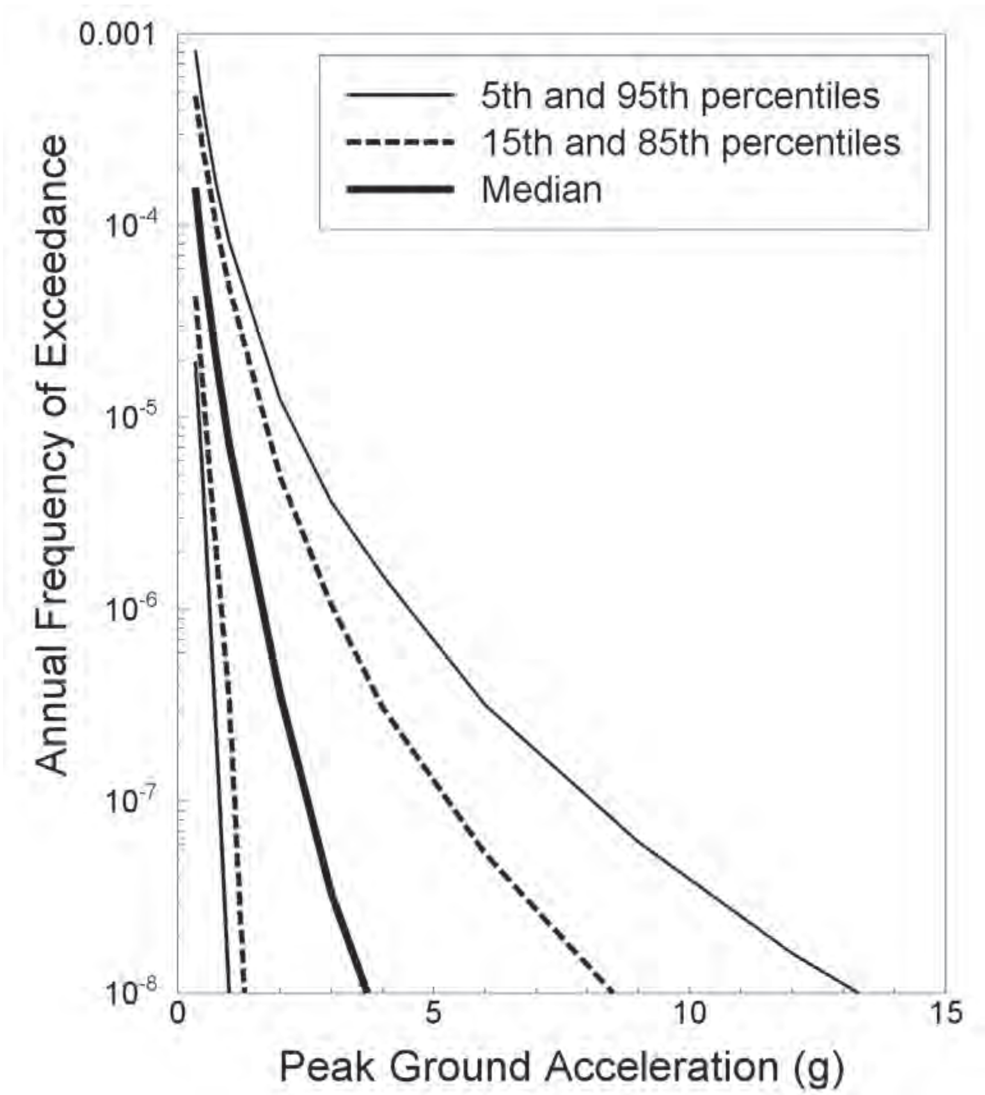


Figure 3. Hazard curves for Yucca Mountian showing the spreading of hazard estimates corresponding to different fractiles, which reflects the influence of the epistemic uncertainty (adapted from Abrahamson and Bommer, 2005). Research and increased data would be expected to reduce the spread of the hazard curves but the curves could be compressed in either direction, with the median hazard increasing or decreasing.

The most promising avenues for substantial reductions in sigma would appear to lie not in developing more complex models, but rather in moving away from sigma values that result from combining strong-motion data from several different regions so that temporal variation of ground motion at a site is modelled by spatial variability from many sites, what has been called the ergodic assumption (Anderson and Brune, 1999). Recent work has shown that if recordings from a single station are used, appreciable reductions (on the order of 10%) in sigma can be achieved, and even greater reductions can be achieved if only single source-site combinations are considered (Atkinson, 2006). In all other respects, research in engineering seismology aims at achieving more robust and reliable estimates of future ground motions, regardless of whether these lead to higher or lower hazard estimates. The objective could be stated as reducing the spread of the hazard curves (Figure 3), but the reduced hazard space may result in any given fractile being at a higher or lower level than before.

The engineering seismology community in the UK is small, but active and also growing. In the distant past, work on seismic hazard was dominated by a few groups, most notably Principia Mechanica Ltd (PML) and the Seismic Hazard Working Party (SHWP), with academic research being conducted at a few universities. In recent years the tendency has been for work in this field to be awarded through direct engagement of individual groups or competitive bidding, with other parties then undertaking peer review, generally after the analyses have been completed. In organising things in this way, we may be losing the opportunity to bring the collective knowledge and experience of the UK engineering seismology community to bear on these important projects. UK companies, individuals, institutions and university departments are engaged in seismic hazard work both at home and internationally, and in some cases bringing together the views and insights of several experts could be very valuable. There are already many several examples of collaboration in this field, such as a current project to develop a stochastic ground-motion model for the UK being carried out at the University of Liverpool in association with the British Geological Survey (BGS) and Imperial College (Edwards *et al*., 2007). Many advantages could be gained by using multiple expert judgements in seismic hazard analyses in the UK; this does not necessarily preclude contracts being awarded to individual groups or analysts, but we could start to think about creating the facility in such projects to obtain multiple views on the key input parameters and models. One example of this is the new hazard map being produced for the National Annex to Eurocode 8 by Dr Roger Musson of BGS, for which a workshop was held at the Institution of Civil Engineers in April 2007, where several engineering seismologists discussed appropriate input parameters and successfully contributed to forming a consensus view of inputs to the hazard analysis that will be the basis of the map. Such an approach could be extended to use expert elicitation frameworks (see Bommer, 2004) to populate and weight the branches of logic-trees in hazard assessments for critical facilities in the UK. Such structured interactions amongst our small but active community, at early stages of projects, may prove much more useful in helping us to achieve robust hazard assessments than critical peer reviews of final project reports.

References

Abrahamson, N.A. & W.J. Silva (1997). Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismological Research Letters* **68**(1), 94-127

Abrahamson, N.A. & J.J. Bommer (2005). Probability and uncertainty in seismic hazard analysis. *Earthquake Spectra* **21**(2), 603-607.

Akkar, S. & J.J. Bommer (2007). Prediction of elastic displacement response spectra at multiple damping levels in Europe and the Middle East. *Earthquake Engineering & Structural Dynamics, in press.*

Allen, C. (2006). The estimation of peak ground acceleration in the UK after an earthquake. *SECED Newsletter* **19**(2), March, pp.6-8, Society for Earthquake and Civil Engineering Dynamics, ICE, London.

Ambraseys, N.N., K.A. Simpson & J.J. Bommer (1996). Prediction of horizontal response spectra in Europe. *Earthquake Engineering & Structural Dynamics* **25**, 371-400.

Ambraseys N.N., J. Douglas, S.K. Sarma & P.M. Smit (2005). Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Horizontal peak ground acceleration and spectral acceleration. *Bulletin of Earthquake Engineering* **3**(1), 1-53.

Anderson, J.G. & J.N. Brune (1999). Probabilistic seismic hazard analysis without the ergodic assumption. *Seismological Research Letters* **70**, 19-28.

Atkinson, G.M. (2006). Single-station sigma. *Bulletin of the Seismological Society of America* **96**(2), 446-455.

Bommer, J. (2004). Expert judgement in seismic hazard assessment. *SECED Newsletter* **17**(4), February, pp.7-11, Society for Earthquake and Civil Engineering Dynamics, ICE, London.

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

Bommer, J.J., G. Georgallides & I.J. Tromans (2001). Is there a near-field for small-to-moderate magnitude earthquakes? *Journal of Earthquake Engineering* **5**(3), 395-423.

Bommer, J.J., F. Scherbaum, H. Bungum, F. Cotton, F. Sabetta & N.A. Abrahamson (2005). On the use of logic trees for ground-motion prediction equations in seismic hazard assessment. *Bulletin of the Seismological Society of America* **95**(2), 377-389.

Bommer, J.J., P.J. Stafford, J.E. Alarcón & S. Akkar (2007). Empirical ground-motion prediction over an extended magnitude range. *Submitted to Bulletin of the Seismological Society of America.*

Boore, D.M, W.B. Joyner & T.E. Fumal (1997). Estimation of response spectra and peak accelerations from western North American earthquakes: a summary of recent work. *Seismological Research Letters* **68**(1), 129-153.

Campbell, K.W. (1997). Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response. *Seismological Research Letters* **68** (1), 154-179.

Cotton, F., F. Scherbaum, J.J. Bommer & H. Bungum (2006). Criteria for selecting and adjusting ground-motion models for specific target applications: applications to Central Europe and rock sites. *Journal of Seismology* **10**(2), 137-156.

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**, 43-104.

Edwards, B., A. Rietbrock, J.J. Bommer & B. Baptie (2007). The acquisition of source, path and site effects from micro-earthquake recordings using Q tomography: applications to the UK. *Submitted to the Bulletin of the Seismological Society of America.*

McGuire, R.K., C.A. Cornell & G.R. Toro (2005). The case for using mean seismic hazard. *Earthquake Spectra* **21**(3), 879-886.

Musson, R. (2005). Against fractiles. *Earthquake Spectra* **21**(3), 887-891.

Power, M., B. Chiou, N. Abrahamson & C. Roble (2006). The "Next Generation of Ground Motion Attenuation Models" (NGA) Project: An overview. *Proceedings of the 8th US National Conference on Earthquake Engineering*, San Francisco, Paper no. 2022.

Somerville, P.G., N.F. Smith, R.W Graves & N.A. Abrahamson (1997). Modification of empirical ground motion attenuation relations to include the amplitude and duration effects of rupture directivity. *Seismological Research Letters* **68**(1), 199-222.

Somerville, P.G. (2003). Magnitude scaling of the near fault rupture directivity pulse. *Physics of the Earth and Planetary Interiors* **137**, 201-212.

NOTABLE EARTHQUAKES OCTOBER - DECEMBER 2006

Reported by British Geological Survey

YEAR	DAY	MON	TIME UTC	LAT	LON	DEP KM	MAGNITUDES ML	MB	MW	LOCATION
2006	**1**	**OCT**	**09:06**	**46.47N**	**153.24E**	**19**			**6.6**	**KURIL ISLANDS**
2006	**9**	**OCT**	**05:12**	**30.94N**	**66.54E**	**10**		**4.4**		**PAKISTAN**

Three people injured in Chaman.

2006	**13**	**OCT**	**04:21**	**56.70N**	**5.25W**	**7**	**1.4**			**BALLACHULISH**

Felt in Ballachulish, Highland region (3 EMS).

2006	**15**	**OCT**	**17:07**	**19.88N**	**155.94W**	**39**			**6.7**	**HAWAII**

Many people suffered minor injuries. At least 1,173 buildings were damaged, several roads were destroyed, mainly from landslides, and power outages occurred throughout the island. Damage has been estimated at US$73 million.

2006	**17**	**OCT**	**01:25**	**5.88S**	**150.98E**	**32**			**6.7**	**PAPUA NEW GUINEA**
2006	**17**	**OCT**	**06:47**	**60.32N**	**0.41E**	**14**	**2.3**			**OFFSHORE SHETLAND**
2006	**20**	**OCT**	**10:48**	**13.46S**	**76.68W**	**23**			**6.7**	**CENTRAL PERU**

Minor damage to some houses in Pisco.

2006	**24**	**OCT**	**23:00**	**58.11N**	**0.84E**	**12**	**2.5**			**CENTRAL NORTH SEA**
2006	**5**	**NOV**	**22:35**	**52.41N**	**2.62W**	**4**	**2.2**			**LUDLOW, SHROPSHIRE**
2006	**7**	**NOV**	**17:38**	**6.48S**	**151.20E**	**10**			**6.5**	**PAPUA NEW GUINEA**
2006	**13**	**NOV**	**01:26**	**26.04S**	**63.22W**	**552**			**6.8**	**ARGENTINA**
2006	**15**	**NOV**	**11:14**	**46.59N**	**153.27E**	**10**			**8.3**	**KURIL ISLANDS**

One person injured at Waikiki, Hawaii as a result of a tsunami with wave heights of up to 34cm and two docks destroyed and another damaged at Crescent City, California by a tsunami with wave heights of around 176cm. Damage has been estimated at approximately US$750,000.

2006	**15**	**NOV**	**11:34**	**46.64N**	**155.31E**	**10**		**6.5**		**KURIL ISLANDS**
2006	**30**	**NOV**	**21:51**	**51.41N**	**4.58W**	**6**	**1.6**			**BRISTOL CHANNEL**
2006	**1**	**DEC**	**14:01**	**8.24S**	**118.80E**	**40**			**6.3**	**SUMBAWA, INDONESIA**

One person killed, as a result of a heart attack, 14 others injured, 20 houses destroyed and many others damaged at Bima.

2006	**16**	**DEC**	**16:08**	**53.63N**	**2.36W**	**10**	**2.1**			**BOLTON**
2006	**17**	**DEC**	**21:39**	**0.64N**	**100.04E**	**30**			**5.8**	**SUMATRA, INDONESIA**

Seven people killed, 100 others injured and over 680 homes destroyed or damaged in the Muarasipongi area.

2006	**19**	**DEC**	**02:20**	**50.35N**	**4.51W**	**8**	**1.8**			**LOOE, CORNWALL**

Felt Herodsfoot, Polruan, Trewidland, St Austell, Carluddon, Penwithick, Bodwen and Rillaton in the Cornwall and Devon regions (3 EMS).

2006	**26**	**DEC**	**10:40**	**55.09N**	**3.64W**	**8**	**3.6**			**DUMFRIES, D & G**

Felt throughout Dumfries and Galloway over an area of some 3,600 km^2 at 3 EMS. The highest intensity, experienced over a significant area, was 5 EMS, which was observed over an area of over 230 km^2 around the epicentre.

2006	**26**	**DEC**	**12:26**	**21.83N**	**120.54E**	**10**			**7.1**	**TAIWAN**

One person killed and three others injured at P'ing-tung. Many building destroyed or damaged in the epicentral area. Felt throughout Taiwan and along the coast of SE China.

2006	**26**	**DEC**	**12:34**	**22.02N**	**120.49E**	**10**			**6.9**	**TAIWAN**
2006	**30**	**DEC**	**08:30**	**13.35N**	**51.41E**	**15**			**6.6**	**GULF OF ADEN**
2006	**30**	**DEC**	**09:15**	**53.67N**	**1.00E**	**11**	**3.1**			**SOUTHERN NORTH SEA**
2006	**30**	**DEC**	**16:22**	**55.08**	**3.62W**	**6**	**1.7**			**DUMFRIES, D & G**

Issued by: Davie Galloway, British Geological Survey, February 2007.
Non British Earthquake Data supplied by: The United States Geological Survey.

Forthcoming Events

31 October 2007
Predicting Earthquake Ground Motions: Myths and Mysteries. 2007 William Joyner Memorial Lecture.
ICE 6.00pm

SECED Newsletter

The SECED Newsletter is published quarterly. Contributions are welcome and manuscripts should be sent on a PC compatible disk or directly by Email. Diagrams, pictures and text should be in separate electronic files.

Copy typed on paper is also acceptable. Diagrams should be sharply defined and prepared in a form suitable for direct reproduction. Photographs should be high quality (black and white prints are preferred). Diagrams and photographs are only returned to the authors on request.

Articles should be sent to:

John Sawyer,
Editor SECED Newsletter,
c/o The Secretary,
SECED,
Institution of Civil Engineers,
Great George Street,
London
SW1P 3AA, UK.

E: john.sawyer@projectservices.com

SECED

SECED, The Society for Earthquake and Civil Engineering Dynamics, is the UK national section of the International and European Associations for Earthquake Engineering and is an affiliated society of the Institution of Civil Engineers.

It is also sponsored by the Institution of Mechanical Engineers, the Institution of Structural Engineers, and the Geological Society. The Society is also closely associated with the UK Earthquake Engineering Field Investigation Team. The objective of the Society is to promote co-operation in the advancement of knowledge in the fields of earthquake engineering and civil engineering dynamics including blast, impact and other vibration problems.

For further information about SECED contact:
The Secretary,
SECED,
Institution of Civil Engineers,
Great George Street,
London SW1P 3AA, UK.

SECED Website

Visit the SECED website which can be found at http://www.seced.org.uk for additional information and links to items that will be of interest to SECED members.
Email: webmaster@seced.org.uk