Institution: University of Liverpool		
Unit of Assessment: 7 (Earth Systems and Environmental Sciences)		
Title of case study: Earthquake hazard research shapes UK Government policy on fracking in England and improves engineering and industrial design across Europe		
Period when the underpinning research was undertaken: 2004 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Dr Ben Edwards Prof Andreas Rietbrock	Lecturer - Reader Lecturer - Professor	2015 - present 2002 - 2019
Period when the claimed impact occurred: March 2015 - December 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Research at Liverpool into the use of seismic data to predict the effects of damaging earthquakes has improved accuracy, and led to a reduction in uncertainty, of seismic hazard assessments. This research has **influenced public policy** and **improved engineering and industrial design** across Europe, creating positive impacts for public safety and the environment, including having:

- shaped UK Government policy on the use of hydraulic fracturing (fracking) for hydrocarbons at Preston New Road, Lancashire, leading to a moratorium on fracking across England
- developed safety-linked decision-making for gas production in the Netherlands
- improved engineering seismic-design for the UK's nuclear industry
- assessed seismic risk to buildings in Basel, Switzerland and aided risk mitigation measures to be targeted toward at-risk school buildings

2. Underpinning research

Research at the University of Liverpool into the use of local (micro-)earthquake data to predict the effects of damaging earthquakes delivers an increase in the accuracy and reduction in uncertainty of seismic hazard assessment. The research that underpins this case study has been undertaken between 2004 and 2020 by Dr Edwards [**3.1-3.6**] and Prof Rietbrock [**3.1, 3.2**].

When considering the seismic design of safety critical or economically-sensitive structures, engineers face a safety linked cost-benefit problem. Seismic design processes are heavily regulated and utilise a diverse range of predictive models, which, to ensure robust results, are invariably based on non-local, often global, datasets. The assumption is that earthquake effects in similar geological settings are considered universal, but with high variability. As a result, the assessment of earthquake hazard and risk in data-poor areas, such as central and northern Europe, has, until recently, been subject to high uncertainty and bias.

The scientific and engineering community now realises that understanding the small-scale (km or less) variability and 'regionalisation' of earthquake ground-shaking is critical. This is particularly important if we are to reduce the large uncertainties, and therefore costs, associated with predicting and mitigating low probability (rare), high-consequence earthquake hazards. A physical modelling methodology developed through research at Liverpool moves away from high uncertainty 'one case fits all' approaches using data from around the world, towards physical models based on local data, with reduced uncertainties.

The fundamental underpinning research focusses on the use of monitored seismicity (typically small magnitude, or micro-, earthquakes) in the region of interest to develop physical seismological models [**3.1**] and, subsequently, facilitates the site-specific prediction of earthquake shaking for large hazardous events [**3.2, 3.3**]. Initial research was undertaken at Liverpool (2004 - 2008) [**3.1**] and has been later applied to develop national seismic hazard maps for Switzerland [e.g. **3.4**] and probabilistic seismic hazard analyses for five Swiss nuclear power stations operated by swissnuclear. The work was diversified through application to a geothermal energy project in St Gallen, city-scale local hazard zonation [**3.5**], induced seismicity related to conventional hydrocarbon extraction in the Netherlands [**3.3**] and, most recently, hydraulic fracturing (fracking) in the UK, as part of a consultancy project for the regulator [**3.6**].

The underpinning research has led to the application of the developed methodologies in several large scale (£multi-million) engineering or civil-protection projects for nationally critical infrastructure across Europe, including:

1. Pegasos Refinement Project (seismic hazard assessment of five Swiss nuclear power stations) (2008 - 2015)
2. Swiss national seismic hazard model and building codes (2013 - 2016) [**3.4**]
3. Seismic hazard and risk model for the Groningen gas field, Netherlands (2013 - 2020) [**3.3**]
4. Seismic hazard assessment of three new-build UK nuclear power station sites (2015 - 2016) [**3.1, 3.2**]
5. Seismic hazard assessment of Spanish nuclear power station sites (2017 - 2019)
6. Seismic hazard and risk for 121 school buildings in Basel, Switzerland (2016 - 2018) [**3.5**]
7. Seismic hazard and risk for population centres around the Preston New Road, Lancashire, shale gas (fracking) site (2018 - 2020) [**3.6**]

3. References to the research

3.1. Edwards, B., A. Rietbrock, J. J. Bommer, and B. Baptie (2008). The acquisition of source, path, and site effects from microearthquake recordings using Q tomography: Application to the United Kingdom, B Seismol Soc Am 98, doi: 10.1785/0120070127

3.2. Rietbrock, A., F. Strasser, and B. Edwards (2013). A stochastic earthquake ground-motion prediction model for the United Kingdom. B Seismol Soc Am 103, doi: 10.1785/0120110231.

3.3. Bommer, J. J., B. Dost, B. Edwards, P. J. Stafford, J. van Elk, D. Doornhof, and M. Ntinalexis (2016). Developing an application-specific ground-motion model for induced seismicity, B Seismol Soc Am 106, doi: 10.1785/0120150184

3.4. Edwards, B., C. Cauzzi, L. Danciu, and D. Fäh (2016). Region-specific Assessment, Adjustment and Weighting of Ground Motion Prediction Models: application to the 2015 Swiss Seismic Hazard Maps, B Seismol Soc Am 106, doi: 10.1785/0120150367

3.5. Michel, C., D. Fäh, B. Edwards, and C. Cauzzi (2017). Site amplification at the city scale in Basel (Switzerland) from geophysical site characterization and spectral modelling of recorded earthquakes, Physics and Chemistry of the Earth, Parts A/B/C 98 27-40, doi: 10.1016/j.pce.2016.07.005

3.6. Edwards, B., H. Crowley and R. Pinho (2019). Final Report on: “WP2 – Impacts of Seismicity: Transmission to People, Property and Well Integrity”. A Technical Report commissioned by the Oil and Gas Authority (OGA). 115 pp. Online: https://web.archive.org/web/20191102070745/https://www.ogauthority.co.uk/media/6127/final-reports-wp2-2.pdf

4. Details of the impact

The University of Liverpool’s earthquake hazard research has influenced public policy in the UK and improved engineering and industrial design across Europe. Impacts include:

1. shaping of UK Government policy on the use of hydraulic fracturing for hydrocarbons at Preston New Road, Lancashire, leading to a moratorium on fracking across England
2. developing improved safety-linked decision-making for gas production in the Netherlands
3. improving engineering seismic-design for the UK’s nuclear industry for increased safety
4. assessing seismic risk to school buildings in Basel, Switzerland, which aided mitigation measures to be targeted for increased public safety

4.1 Shaped UK Government policy on fracking at Preston New Road and across England

Between 2019 and 2020, Liverpool’s research [**3.6**] has been used by the Oil and Gas Authority (OGA), the UK regulator, and the UK’s Department of Business, Energy and Industrial Strategy

(BEIS) to change public policy and guidance related to induced earthquakes due to hydraulic fracturing (fracking) at Preston New Road, Lancashire. As part of an OGA-led review led by Dr Edwards and reported to BEIS, Liverpool undertook a study into the risk due to seismic activity at Preston New Road, as summarised by the OGA [**5.1**].

Liverpool's work concluded that an unlikely future scenario of a magnitude 4.5 event (2.9 was largest to date) would lead to widespread building damage that could also be a serious risk to public safety; from cracked plasterwork affecting 10% of buildings, to more serious structural damage of varying degrees affecting 5.4% of buildings, with 5.4% also likely to suffer chimney failure. Minister for Energy and Clean Growth, Claire Perry MP, cited Liverpool's research within a BEIS topical questions debate with fellow MPs in the House of Commons in January 2019, stating [**5.2**]: "*we have had some great evidence from the University of Liverpool*" in response to a question from the MP for Sheffield South East about the impact of fracking in Lancashire.

As a direct result of Liverpool research, fracking was ultimately suspended across England in late 2019 by the UK Government, with the Secretary of State for Business, Energy and Industrial Strategy (BEIS), Andrea Leadsom MP, stating [**5.3**]: "…*I've also always been clear that shale gas exploration must be carried out safely. In the UK, we have been led by the best available scientific evidence, and closely regulated by the Oil and Gas Authority, one of the best regulators in the world. After reviewing the OGA's report* [**5.1**] [summarising Dr Edwards team's research] *into recent seismic activity at Preston New Road, it is clear that we cannot rule out future unacceptable impacts on the local community. For this reason, I have concluded that we should put a moratorium on fracking in England with immediate effect.*"

4.2 Developed improved safety-linked decision-making for gas production in the Netherlands

An ongoing review (2015 and 2020) of induced seismicity in the Groningen Gas Field, the Netherlands, has led to the development of seven sequential hazard and risk models, all utilising Liverpool's research into local seismic hazard [**3.3**]. These models have been submitted by the operator to the Dutch regulator and used as the basis for decisions on production levels, maximising economic benefits (profit and tax revenue), while ensuring safe continued operation.

To understand and mitigate the effects of earthquakes induced due to gas-field compaction, a probabilistic seismic and risk analysis in the Groningen Gas Field was commissioned by the gas field operator Nederlandse Aardolie Maatschappij BV (NAM) in 2013. The Groningen gas field is the largest natural gas field in Europe and makes a significant contribution toward the Dutch economy. The "*total value of gas sales from 1963 to 2019 is some 417 bln Euro"* [**5.4**]. This generates substantial tax revenues: *"Since production started in 1963 to 2019 the tax income from the Groningen field for the Dutch state was some 360 bln Euro*" [**5.4**]. However, due to increasing induced seismicity, since 2014 the Dutch government decided to impose annual cuts in production output, leading to a planned closure of the gas field in 2022, with projected losses in tax revenue amounting to billions of Euros.

Liverpool's research into site-specific earthquake ground motion [e.g. **3.1, 3.3, 3.4**] has provided the basis for (gas) output dependent risk calculations in Groningen, as detailed by the Earthquake Advisor to NAM: "*Regional, never-mind global models, as typically used in large-scale engineering projects were not fit for purpose*" [**5.4**]. It was therefore imperative "*to avoid the use 'typical' industry-standard approaches such as the use of global empirical models and instead to develop a site-specific physics- based ground motion model*" [**5.4**]. "*Work undertaken by the NAM Ground motion characterisation team, comprising internationally leading experts, including Dr Edwards (University of Liverpool), has led to the development of a state-of-the art model for earthquake ground motion*" [**5.4**]. The work has enabled the operator to define production levels that reduce the incidence of earthquakes and maintain risk exposure at a level acceptable to the regulator.

Liverpool's work has been extensively used for operational planning (by the operator), assessment of safe production levels (by the regulator, SodM, and Ministry of Economic Affairs [**5.5**]), assessment of the safety of buildings for chemical production [**5.6**], engineering design of the commercial 'Groninger Forum', risk assessment of levees/dams and an update of building design criteria. The wider impact of this work is highlighted by the Earthquake lead of NAM, who noted that "*due to the importance for the Dutch economy the studies are followed closely by the media in The Netherlands and are discussed regularly in the Dutch Parliament*" [**5.4**].

4.3 Improved engineering seismic-design for UK's nuclear industry for increased safety

Liverpool's research has provided regulatory compliance for existing and new-build nuclear sites across Europe and has been successfully used in the development of nuclear power station design [**3.1, 3.2**]. The Horizon Nuclear Power project (2008 - 2019), which developed the design earthquake criteria for the £15 bn new-build nuclear power station at the Wylfa Newydd site in Wales, used a novel approach that has not been used previously in the UK [**5.7a**]. As part of this, Liverpool's research was used to develop a site-specific ground motion model which allowed the reduction in uncertainties and subsequently a reduction in conservatism.

As a result of Liverpool's research, the contractor ARUP could utilise an approach that defines the earthquake criteria to ensure a consistent risk for all elements of the nuclear facility, and for which they were shortlisted for the Ground Engineering Awards 2020 [**5.7a**]. Taking advantage of Liverpool's research, the criteria ensures a design "*with lower … uncertainty, ultimately reducing design costs, but ensuring safety and operational performance during earthquakes*" according to the Associate Director of ARUP [**5.7a**]. A journal article [**5.7b**] written by the ARUP project team noted that "*the site-specific stochastic model* [**3.2**, and updates thereof] *was the preferred model from those included on the logic tree as it has been developed specifically for the Wylfa Newydd site, utilizing ground motion data recorded throughout the UK as well as at the WPS station adjacent to Wylfa Newydd*." More realistic seismic criteria that ensured an appropriate level of resilience and safety was therefore achieved, whilst ensuring unnecessary conservatism was removed and financial costs were minimised.

4.4 Assessed seismic risk to school buildings in Basel, Switzerland and aided mitigation measures to be targeted for increased public safety

Liverpool's research [**3.4, 3.5**] has also provided improved seismic hazard assessment in Switzerland, highlighting the potential threat to school buildings in Basel [**5.8**]. To apply research into local seismic hazard assessments, a methodology was developed by Liverpool, alongside partners at ETH Zurich, for determining local-scale earthquake effects across a city-region [**3.5**].

The Head of Earthquake Hazard and Risk at the Swiss Seismological Service [**5.9**], notes that the "*research has allowed us to reduce uncertainty in probabilistic seismic hazard on a national scale – and consequently more accurate and reliable national seismic building codes, which ensure occupants safety during earthquakes. It has further facilitated the development of products aimed at improving disaster response that allow to direct help and resources immediately following an earthquake. At the smallest scale, school building stock in Basel has directly benefitted from this research, allowing the prioritisation of seismic retrofitting to vulnerable buildings and ensuring the safety of school children*."

An evaluation of the approach based on Liverpool research [**5.8**] was performed by ETH Zurich and the Swiss Seismological Service as part of a risk assessment into all school buildings in the city of Basel, funded by the Cantonal Emergency Organisation (KKO) of the Canton Basel-Stadt (the city Region of Basel). The study was published in technical reports and a journal article [**5.8**] in 2017. It was found that if there were a similar earthquake to the historical event that occurred in 1356, of 121 school buildings in Basel, 102 would be unusable, with 35 partially collapsing and 12 fully collapsing. Of 16,960 pupils in Basel, their estimates expected 305 fatalities and 1,814 injured. Total potential economic losses were assessed at 566 million Swiss Francs [**5.8**].

The study was subsequently used to identify school buildings that needed to be prioritised for seismic retrofitting measures [**5.7**]. This city-wide assessment of risk was supported through the Swiss Federal Nuclear Safety Inspectorate and by the Swiss Federal Offices for the Environment, Roads, and Railways, the Swiss Earthquake Insurance Pool, and ETH Zurich. The method based on Liverpool's research has further been implemented in the real-time monitoring of the Swiss Seismological observatory, facilitating the rapid identification of at-risk areas such that mitigating measures can be implemented [**5.9, 5.10**].

5. Sources to corroborate the impact

5.1. Interim report of the scientific analysis of data gathered from Cuadrilla's operations at Preston New Road by the Oil and Gas Authority, as provided to the Department of Business, Energy and Industrial Strategy, supporting the impact of Liverpool research on the UK Government's decision to place a moratorium on fracking in England.

5.2. Response of Ms Perry, Minister of State at the Department for Business, Energy and Industrial Strategy to Mr Clive Betts (MP Sheffield South East), supporting the impact of Liverpool research on the impacts of hydraulic fracturing: https://hansard.parliament.uk/Commons/2019-01-08/debates/1F579CC8-CD80-49E2-B0EF-A3B3B8FB9868/OralAnswersToQuestions#contribution-1F9ED73C-51B4-42F1-9366-36AA3CA02DA1 [Accessed 7 December 2020].

5.3. UK Government press release entitled 'government ends support for fracking' published 2 November 2019, supporting the impact of Liverpool research on the moratorium on fracking: https://web.archive.org/web/20201112002407/https://www.gov.uk/government/news/government-ends-support-for-fracking [Accessed 7 December 2020].

5.4. Testimonial from the Groningen Earthquake Advisor for Nederlandse Aardolie Maatschappij (NAM, who supply 75% of the natural gas required by Dutch households and businesses), supporting the impact of Liverpool research on improved safety-linked decision-making for gas production in the Groningen Gas Field, Netherlands.

5.5. Report on Seismic Hazard Assessment of Production Scenarios in Groningen, prepared for the Dutch Ministry of Economic Affairs and Climate Policy by the Royal Netherlands Meteorological Institute, supporting the impact of Liverpool research on region-specific seismic hazard due to induced seismicity in the Groningen Gas Field. Here, models developed using Liverpool research are used for production scenario hazard estimates to inform the Ministry of Economic Affairs and Climate Policy.

5.6. Parliamentary report [**in Dutch and English**] of the workgroup on earthquake load for industry entitled, 'Towards a quick, simple, transparent and robust test on the earthquake resistance of the chemical industry in Groningen', citing various works supported by research at Liverpool, and thereby supporting the impact of Liverpool research on site-specific seismic hazard due to induced seismicity in the Groningen Gas Field.

5.7 Evidence relating to the impact on improved engineering seismic-design for nuclear industry:

- **5.7a.** Testimonial from the Associate Director of ARUP and Associate of ARUP, supporting the impact of Liverpool research on improving engineering seismic-design for the UK's nuclear industry for increased safety.
- **5.7b**. Journal paper entitled 'A probabilistic seismic hazard assessment for Wylfa Newydd, a new nuclear site in the United Kingdom' by the ARUP project team. DOI: 10.1007/s10518-020-00862-8

5.8. Journal paper on 'loss scenarios for school buildings in Basel (Switzerland)' by Clotaire Michel and Donat Fäh (Swiss Seismological Service), Pia Hannewald and Pierino Lestuzzi (Résonance Ingénieurs-Conseils), and Stephan Husen (State Laboratory, Basel City), supporting the impact of Liverpool research on local amplification effects and their relation to seismic risk. DOI: 10.1007/s10518-016-0025-2

5.9. Testimonial from Head of the Earthquake Hazard & Risk Assessment Section at the Swiss Seismological Service, supporting the impact of Liverpool research on region-specific seismic hazard and risk assessment in various applications across Switzerland.

5.10. Publication [**in German**] on 'Earthquakes: Maps of subsoil classes, creation and use'. Published by the Swiss Federal Office for the Environment (used to inform 'best-practice' for earthquake engineering design), supporting the impact of Liverpool research on regionalised seismic hazard. Input hazard in the report (Fig 3.) is defined on models developed [**3.4, 5.9**].