Institution: University College London		
Unit of Assessment: 12 - Engineering		
Title of case study: Infrastructure vulnerability assessment tools for the benefit of disaster management		
Period when the underpinning research was undertaken: 2014 – 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:**
Tiziana Rossetto	Professor	2004 – Present
Dina D'Ayala	Professor	2012 – Present
Carmine Galasso	Associate Professor	2014 – Present
Ioanna Ioannou	Senior Research Associate	2010 – Present
Abdelghani Meslem	Research Associate	2010 – 2014
Viviana Novelli	PhD Student/RA	2010 – 2016
Enrica Verrucci	Research Associate	2016 – Present
Arash Nassirpour	PhD Student/RA	2013 – 2018
Rohit Adhikari	PhD Student/RA	2016 – Present
Harriette Stone	PhD student/RA	2014 – 2018
Pierre Gehl	Research Associate	2013 – 2016
Period when the claimed impact occurred: August 2013 – 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

UCL's research to predict the vulnerability of buildings and infrastructure to natural hazards has led to a series of risk models and products that are used worldwide to predict earthquake impacts, inform insurance payouts, and strengthen buildings against damage from natural hazards. (1) The UCL methodological vulnerability guidelines and associated databases are fundamental components of the open access Global Earthquake Model seismic risk modelling tools used by governments, finance industries and NGOs to benefit developing countries in mitigating disaster risks. (2) The UCL seismic analytical vulnerability and risk analysis tools are core to the Global Programme for Safer Schools' GLOSI tool, used to assess the need for retrofitting over 57,000 schools in developing countries and to develop and implement conservation management plans for historical churches in the Philippines.

2. Underpinning research (indicative maximum 500 words)

The risk to buildings and people from a natural hazard is a function of three components: hazard, exposure and vulnerability. The vulnerability links hazard and exposure by providing a relationship for the likelihood of a type of asset sustaining damage or loss for a range of hazard intensities. Vulnerability is a measure of the as-built safety of the built environment, and hence it is a critical prerequisite of risk reduction policies. Nonetheless, vulnerability has only been actively researched for the past 40 years, and methods have evolved to encompass empirical and analytical approaches. Until recently, there was no consensus on how to model the significant aleatory uncertainties (due to natural variations) associated with ground shaking and how different classes of assets respond to it, nor for the epistemic (modelling) uncertainties associated with the observational loss data and numerical modelling underpinning empirical and analytical vulnerability models, respectively.

The UCL's natural hazards vulnerability research led by Professor Tiziana Rossetto (TR) and Professor Dina D'Ayala (DDA) produced two substantial breakthroughs: 1) for the empirical approaches, the use of non-parametric statistical models and the provision of open access R-code for implementing these (**R1**); 2) for the analytical approaches, consistent methods to allow for the variability in the "as-built" in the structural modelling and robust strategies for modelling non engineered structures, forming the majority of the built environment in seismic countries (**R2**). This research, commissioned by the Global Earthquake Model Foundation (GEM), led by DDA and TR and carried out in close collaboration with international partners, entailed an extensive programme of evidence gathering, numerical modelling, statistical testing and sensitivity analyses. The research resulted in two sets of **guidelines for empirical (R1) and analytical (R2) vulnerability modelling**, which present robust frameworks with a hierarchy of complexity, such that analysts with different levels of experience in statistical and structural analysis and computational skills could develop new vulnerability models as well as evaluate the associated uncertainty. These guidelines are state-of-the-art, globally recognised and used equally by academics and the engineering, insurance and finance industries, in disaster management and reduction and in recovery situations.

As part of the Global Earthquake Model (GEM) project, the UCL team also created a compendium of over 600 seismic empirical and analytical fragility, damage-to-loss and vulnerability functions for the global building inventory. This vulnerability function database was accompanied by a scoring system developed by the team for the assessment of the reliability of vulnerability models to guide their selection by risk analysts (**R3**). The database was further expanded and the scoring system was developed into an algorithm for choosing the most appropriate vulnerability function for different exposures by Stone and DDA in collaboration with the World Bank (**R4**). The **vulnerability function database and algorithm** are used by the World Bank in their Global Rapid post-disaster Damage Estimation (GRADE) tool, which determines financial aid needs in the immediate aftermath of a major natural hazard event. The vulnerability database is periodically updated and has been incorporated into several in-house risk databases in insurance and re-insurance companies, and in the GEM Openquake platform (**R5**).

Furthermore, in response to the lack of freely available tools for deriving seismic vulnerability functions for masonry structures, between 2014-2016, DDA developed the tool **FaMIVE** (**R6**)**.** This tool focused on the out-of-plane failure of masonry structures, critical, but until then ignored in seismic assessment. FaMIVE is recommended in the analytical vulnerability guidelines (**R2**) and has been endorsed by the Catholic Church in the Philippines as the tool to be adopted for the vulnerability assessment of their historical churches.

Research on vulnerability conducted by DDA (**R7**) highlighted the lack of analytical vulnerability analysis for school infrastructure that allows comparison of facilities worldwide, to support UN policies and specifically the Global Development Target 4: Better Education (GDT 4). In 2016 the Global Programme for School Safety (GPSS) invited DDA to design a framework for the **Global Library of School Infrastructure (GLOSI).** The GLOSI, implemented in collaboration with UNiAndes, Colombia, is a global repository of evidence-based knowledge on the performance of school building types affected by natural hazard events. The underpinning research entailed producing a systematic school building classification system (taxonomy), the derivation of corresponding vulnerability functions and the determination of strengthening solutions, all applicable at global scale (**R7**). The major output of this effort is to mainstream quantitative risk assessment in investment planning. All tools forming the GLOSI were developed under the leadership of DDA, through two GRS-ORS PhD scholarships, a British Council grant and a long-term World Bank contract, as reported in (**R7**). Through third party applications, the GLOSI is currently used by Ministries of Education in more than 20 countries worldwide. The activity and output carried out with this work has been recognized by UNESCO UK, which has endorsed a UNESCO Chair in Infrastructure Engineering resilience at UCL, led by DDA.

3. References to the research (indicative maximum of six references)

R1. **Rossetto, T, Ioannou**, **I**, Grant, DN, Maqsood T. (2014), *Guidelines for empirical vulnerability assessment*. GEM Technical Report 2014-08 V1.0.0, 140 pp., GEM Foundation, Pavia, Italy. DOI: 10.13117/GEM.VULN-MOD.TR2014.11

R2. **D'Ayala D, Meslem A.**, Vamvatsikos D, Porter, K., **Rossetto T**, Crowley H, Silva V. (2015). *Guidelines for analytical vulnerability assessment of low- to mid-rise buildings – Methodology*. GEM Technical Report 2015-08 V1.0.0. GEM Foundation. DOI: 10.13117/GEM.VULN-MOD.TR2014.12

R3. **Rossetto T, D'Ayala D, Ioannou I, Meslem A.** (2014). Evaluation of existing fragility curves. In K. Pitilakis, H. Crowley, & A. M. Kaynia (Eds.), *SYNER-G: Typology definition and fragility functions for physical elements at seismic risk* (Vol. 27, pp. 47-93). Springer. Available upon reqeust.

R4. **Stone, H, D'Ayala D,** Gunasekera R, Ishizawa O. (2017). On the use of existing fragility and vulnerability functions. Santiago: 16th World Conference of Earthquake Engineering

R5. Yepes-Estrada C, Silva V, **Rossetto T, D'Ayala D, Ioannou I, Meslem A**, Crowley H. (2016). The Global Earthquake Model Physical Vulnerability Database. *Earthquake Spectra*, 32 (4), 2567-2585. Doi: 10.1193/011816EQS015DP.

R6. **Novelli VI, D'Ayala D**, Makhloufi N, Benouar D, Zekagh A. (2015). A procedure for the identification of the seismic vulnerability at territorial scale. Application to the Casbah of Algiers. *Bulletin of Earthquake Engineering*, 13(1), pp.177-202. DOI: 10.1007/s10518-014-9666-1.

R7. **D'Ayala D, Galasso C, Nassirpour A, Adhikari RK**, Yamin L, Fernandez R, Lo D, Garciano L, Oreta A. (2020). Resilient communities through safer schools. *International journal of disaster risk reduction*, 45, p.101446. DOI: 10.1016/j.ijdrr.2019.101446.

References (R3), (R6) and (R7) best indicate the quality of the underpinning research

4. Details of the impact (indicative maximum 750 words)

UCL research has led to the development and application of analytical tools that enhance vulnerability modelling and are being used by NGOs, finance industries and governments worldwide to inform disaster risk assessments and mitigation plans to protect people and buildings at risk of natural hazards.

- The UCL methodological vulnerability guidelines and associated databases are **(i)** fundamental components of the Global Earthquake Model (GEM) seismic risk modelling tools, (**ii**) used by the financial sector to produce and calibrate the pricing of insurance products for value exceeding EUR 229,000,000,000 in Iceland and Morocco, and (**iii**) form the established reference for the World Bank GRADE, which is used to conduct rapid post-disaster situational assessments that inform deployment of USD 1,000,000,000 emergency aid.
- UCL seismic and multi-hazard vulnerability and risk analysis tools are core to the Global Programme for Safer Schools' GLOSI tool, used to assess and finance the retrofitting of over 57,000 schools in developing countries; and are being used in the Philippines to develop and implement conservation management plans for churches that provide vital shelter during emergencies.

<u>Informing Global Earthquake Model Foundation (GEM) products and training</u>

The UCL Vulnerability Guidelines (**R1, R2**) are an integral part of the risk training provided by GEM to increase capacity of local experts in developing countries to assess disaster risk. Since 2014, the training has been delivered to more than 500 participants from 68 countries and the guidelines have been accessed more than 4,000 times via the GEM website portal (**S1**). The guidelines were used by GEM to develop the first detailed Seismic Risk Map of the world in December 2018. GEM stated that "*the research from UCL has been particularly relevant on this front…This map has been accessed more than 10,000 times to date, and it is being used by the insurance industry and global organisations such as the United Nations Disaster Risk and Recovery and the World Bank (in particular for Europe)"* (**S1**). Moreover, UCL's Vulnerability Database forms the basis of the physical vulnerability database implemented by GEM in their OpenQuake platform (**R5**). The latter "*has been accessed more than 5,500 times between 2018-19. For engineers in less developed countries, this database is the primary source of vulnerability information for their activities. For example, the database was used (by GEM) to provide vulnerability functions to experts in Guatemala for a project regarding the seismic safety of schools. The database has been also used by experts in Nepal for the assessment of damage in the residential building stock.*" As stated by the Seismic Risk Coordinator at GEM (**S1**).

Enabling insurance and re-insurance sectors to create new vulnerability and catastrophe models

UCL facilitated the use of its empirical guidelines (**R1**) by University of Iceland and the Natural Catastrophe Insurance of Iceland (NTI) to construct new vulnerability models (**S2**) that have been used by NTI to update the national risk model for Iceland in 2018 (**S3**). The Damage and Risk Analyst at NTI stated "*the new functions have improved our understanding of uncertainty and sensitivity of different parameters. Our seismic risk model is a fundamental part of our risk assessment and we use it in our financial risk management (reinsurance cover, reinsurance pricing) as well as in the general risk management of NTI…for about two years now*". NTI is a government owned agency that reports under the Iceland Ministry of Finance and Economic Affairs and directly uses the risk model to price its catastrophe insurance for earthquakes. The insurance is compulsory for all real estate in Iceland. NTI insures a total of 278,000 buildings with a total value of ISK10,200,000,000 (EUR63,000,000,000) (**S3**).

Between 2016 and 2018, the UCL team collaborated with Willis Re, a global reinsurance company, to apply practical hazards risk modelling in the insurance sector. As a result, Willis Re have implemented the UCL vulnerability guidelines (**R1**) and database (**R5**) to define a new vulnerability model and new catastrophe model for the Middle East and North Africa (**S4,S5**). The catastrophe model is used by more than 10 insurers in the region to (a) define their reinsurance capacity and avoid insolvency and (b) price the reinsurance cover in the reinsurance transaction. The Divisional Director at Willis Re states: *"The vulnerability database has direct impact on the reinsurance spend of the whole region, where there is no valid alternative to Willis Re catastrophe model in the market to assess earthquake risk. The (…) catastrophe model is a clear differentiator to Willis Re competitors in the region, thus allowing Willis Re [to retain a] large presence in the Middle East and North Africa market* **….** '*The empirical methodology and database [produced by UCL] have been used to assess the risk profile of Morocco and calibrate the parametric cover for the Fonds de Solidarité Contre les événements Catastrophique (FSEC)* [the Moroccan National Insurance Monetary Fund Against Natural Hazards]*. The cover will allow protecting all uninsured residential buildings, worth approximately USD200,000,000,000, against earthquake events in Morocco, playing a key role in reducing the protection gap in the country"* (**S5**).

Assisting the insurance and re-insurance sector to use third-party vulnerability functions to evaluate existing catastrophe models

UCL's vulnerability database and scoring system are extensively used to evaluate catastrophe models from model vendor companies such as Risk Management Solutions and AIR Worldwide (**S5**) which can predict significantly different earthquake risk for the same location and assets. Willis Re adopt the UCL database to validate vendor risk models and advise their clients on which models to use to evaluate their reinsurance spending and the cost of reinsurance cover (a market worth approximately USD600,000,000,000 globally). They state: "*the quantity of reinsurance that each insurer buys is directly related to the catastrophe model that proves to be most reliable in Willis Re analysis*" (**S5**).

At Guy Carpenter, a leading reinsurance intermediary, whose Model Suitability Analysis tool also adopts vulnerability functions that UCL specifically tailored for their system, state that UCL expertise has "*allowed us (Guy Carpenter) to advise our clients on damage functions for a much wider range of building types, (and) enabled us to rapidly up-scale our database of benchmark functions*"(**S6**).

Facilitating damage assessment in post-disaster contexts

GRADE (Global RApid post-disaster Damage Estimate), is a remote, desk-based, rapid damage assessment method deployed on request soon after a disaster. Through collaboration with the World Bank (2014-2018), UCL's analytical vulnerability guidelines, database and algorithm (**R2, R5**) have helped define and calibrate the GRADE methodology (**S7**) which allows national governments to rapidly assess damage and develop strategies to support post-disaster recovery and reconstruction. The Senior Disaster Risk Management Specialist at the World Bank stated:"...*a GRADE assessment following the 2018 Sulawesi Earthquake and Tsunami resulted in the World Bank providing USD1,000,000,000 assistance for Indonesia Natural Disaster Recovery and Preparedness. The value of GRADE's remote assessments are further apparent during the current COVID crisis, where on-the-ground damage assessments are not possible. This has been demonstrated by the GRADE assessment following the March 2020 earthquake in Zagreb, Croatia*." (**S7**).

Enhancing building resilience, globally

From 2017-2020, GLOSI tools, developed by UCL, including dedicated taxonomy, fragility and vulnerability function databases and strengthening measures, have been used in World Bank engagements to assess the seismic performance of national portfolios of school buildings in El Salvador (15,000 school buildings), Dominican Republic (18,000 school buildings), and Kyrgyz Republic (18,000 school buildings) (**S8**). In Mexico, the GLOSI taxonomy was used to classify the 6,000 school buildings affected by the September 2017 earthquakes. In 2019, the methodology was successfully used, for the first time, at municipality level in Cali (Colombia) for a portfolio of 300 school facilities. "*The results of these assessments were integrated into an investment planning process …and informed the prioritisation of retrofitting interventions in schools, by maximizing the number of children protected from earthquakes. Over 500,000 school children are benefiting from the ongoing USD 800,000,000 investment programs to intervene vulnerable school buildings*" (**S8**). In addition, through third party applications, the GLOSI is currently used by Ministries of Education in more than 20 countries worldwide.

Catholic churches in the Philippines act as cultural and social centres and are used as emergency shelters during natural damaging events. Following the destructive earthquake and typhoon of 2013, the Philippines' Department of Tourism (DoT) commissioned, through the World Bank, an "Assessment Of The Multi-Hazard Vulnerability of Priority Cultural Heritage Structures In The Philippines", where UCL's FaMIVE paradigm (**R6**) is being applied to at least 28 heritage sites including Spanish colonial period Catholic churches (**S9**) and being incorporated into the Guimbal Church Conservation Management Plans. It is also included in training for conservation architects and heritage practitioners in the Philipinnes (**S10**).

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Testimonial provided by GEM Foundation

S2. **Ioannou I**, Bessason B, Kosmidis I, Bjarnason JÖ, **Rossetto T**. (2018). Empirical seismic vulnerability assessment of Icelandic buildings affected by the 2000 sequence of earthquakes. *Bulletin of Earthquake Engineering*, 16(12), pp.5875-5903

S3. Correspondence with NTI, Iceland

S4. **Rossetto T, Ioannou I**, Petrone C. (2020). Deciphering the black box of earthquake vulnerability to disasters: From academic research to applications in the (re)insurance industry. IVASS Conference, Rome 2020.

S5. Correspondence; Willis Re.

S6. Testimonial of Guy Carpenter

S7. Testimonial World Bank

S8. Testimonial World Bank – GPSS

S9. Correspondence Philippines

S10. Testimonial Philippines Catholic Church