



THE PRODUCTION AND IMPLEMENTATION OF SOCIOECONOMIC FRAGILITY FUNCTIONS FOR USE IN RAPID WORLDWIDE EARTHQUAKE LOSS ESTIMATION

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ABSTRACT

In this study, an empirical method using 7200 damaging earthquakes from the time period 1900-2012 and the socio-economic loss information in the CATDAT Damaging Earthquakes Database (Daniell et al., 2011) has been established for the translation of earthquake shaking intensity into a reasonable economic loss or cost estimate, and/or a calculation of fatalities. This has been done using a concept called socio-economic fragility functions, which use a direct relationship of intensity to fatalities, but are calibrated by the socioeconomic status of each individual damaging earthquake through time, meaning that much more socio-economic information through time is used to build the functions than in existing methodologies. An extensive amount of historical provincial and sub-provincial data as well as reanalysis of historical events ensure that the functions produced are robust enough to be used in other methodologies and are consistent with existing engineering fragility functions. A significant improvement on existing empirical rapid methodologies for earthquake loss studies tested is shown.

INTRODUCTION

The production of a robust rapid loss estimate for socioeconomic impacts from earthquakes such as fatalities and economic losses has been the goal of many existing software packages and rapid loss algorithms (Globally – PAGER, QLARM; Europe/Asia – ELER). An extensive state-of-the-art was undertaken in the reviewing of over 30 earthquake loss estimation packages (Daniell, 2011; Daniell et al., 2014), as well as over 200 casualty estimation methods, 90+ intensity scales, and 400+ economic loss functions used worldwide over the past 50 years with respect to rapid use. These were reviewed with respect to the data needed, regional applicability and data used in their production. In addition, the speed with which hazard data could be collected was reviewed globally, as well as the ability to which secondary effects such as fire, landslide, liquefaction and tsunami could be split from the shaking losses, costs and fatalities.

Many methodologies use building typology damage-derived fatality functions (Erdik et al., 2007; Wyss, 2004; Jaiswal et al., 2011) and provide a good estimates of socioeconomic losses. Such methods, however, require a large amount of information in a constantly changing and dynamic world of infrastructure.

The analysis of macroseismic intensity bounds vs. the exposed population and economic exposure is not a new concept. The first empirical intensity-population death rate calculations were studied via

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Haihua (1987) for 20 years of Chinese earthquakes and used regression techniques to produce a fatality-intensity relation for China. Tiedemann (1989) and Chen et al. (1997, 2001) using SwissRe and MunichRe data also produced intensity-bound population methodologies for a few events with lognormal and cubic functions used respectively, utilising L2 minimisation. Samardzhieva and Oike (1992) and Samardzhieva and Badal (2002) used population-intensity bounds with historic fatality measurements via magnitude relations for shallow earthquakes to produce intensity vs. death rate. Dunbar (2002) and Badal (2005) also looked at relationships of intensity vs. GDP through population to analyse economic losses. Jaiswal and Wald (2009) were the first to use a combination of a L2 norm and a log norm (G) in order to optimise intensities vs. population and fatalities to create a global set of mathematical functions that optimise upper and lower levels of fatalities. This was extended in Jaiswal and Wald (2013) to economic losses using MunichRe economic cost data and PAGER's own economic exposure. In addition, individual country estimates, such as Sengara et al. (2012) for Indonesia, have been produced using a normal cumulative density function.

METHODOLOGY

In this paper, there is a discussion of a new analysis method of socio-economic fragility functions. The socio-economic fragility functions, which use a direct relationship of intensity to fatalities, are, however, calibrated by the socioeconomic status of each individual damaging earthquake through time either via HDI, occupancy or other socioeconomic indices, some of which are discussed in Daniell, 2010, Daniell et al. (2011, 2012) and Paper No. 1400 and 1505 in this conference, meaning that much more socio-economic information through time is used to build the functions than as is the case in existing methodologies.

Over the past 5 years, in conjunction with earthquake-report.com, different versions of the socio-economic fragility functions have been produced for each major event. The intensity maps of historical events have now been used from historical events in order to create a closer function in terms of macroseismic intensity versus population and economic exposure, as opposed to the initial version of point sources and finite sources which was used for functions such as seen in the initial estimates in the 2010 Haiti, 2010 Chile, 2010 Yushu, 2011 Christchurch and 2011 Tohoku events.

The current methodology functions were created using 1900-2008 data and tested against the 2009-2013 socioeconomic losses to test the quality of the functions. The process of the social fragility function for a single historical event is as follows:-

1. Have a metric of the ground shaking-based damage for an individual earthquake. This can either be point-based (macroseismic data intensity points) or area-based (distribution of intensity over a certain area). If the MDP version does not have enough information to derive a population value, a kriging method should be used.
2. For each of the point or area intensity values (vector/polygon format), recreate the population of the time using census and other forms of data. This will be in raster format. This is then joined as a value to the polygon intensity.
3. These are then split into smaller administrative units or geocells in order to assign socio-economic parameters from the databases (to be created).
4. The death toll for the particular earthquake is attached to the particular earthquake. It is important that this is disaggregated into only ground motion shaking-related fatalities, rather than including secondary effects.
5. The social parameters are joined to the area based on the databases of occupancy, population density, human development index, seismic code index etc. to check for the best regression.

Each of these events is then grouped together in one of three ways:-

- a) As single countries with no additional socioeconomic parameters (traditional method);
- b) As single countries adapted by the joined socioeconomic parameters; and
- c) As socioeconomic parameters joining together countries.

In some cases where enough fatal earthquakes were not available from 1900-2008, then a regionalisation approach for the grouping may need to be undertaken, such as looking at building typologies, economic situation and practices. This, however, can be hopefully minimised for the final global method by using similar HDI and vulnerability events to populate locations where not many damaging earthquakes have occurred.

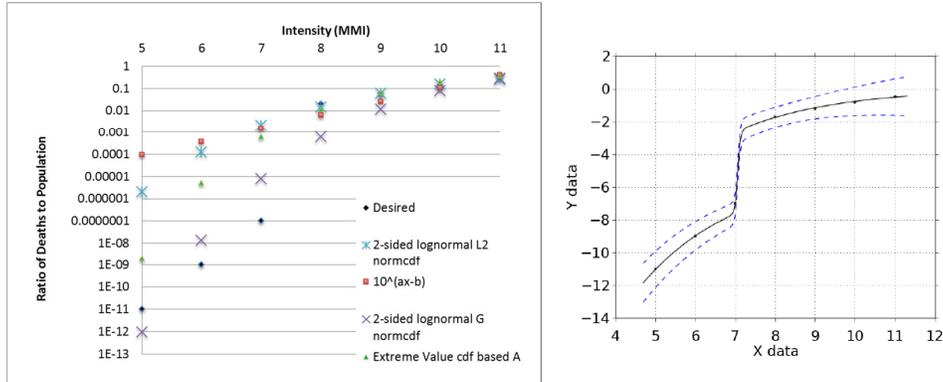


Figure 1: Left: A step in the fatality function due to similar building collapse, is difficult to pick up with less than 2 coefficients; Right: A step in the fatality function due to similar building collapse is modelled with a double exponential function, with 5 coefficients.

An assignment of the distribution translates a single value of deaths over the population intensity bounds, and then this is modified depending on which socio-economic parameters correspond to the earthquake in question. The expected deaths are then optimised against the fatalities observed in events. The regression for each of these groupings a-c is then undertaken using the regression approach of a function distribution optimised for the earthquakes, as has been tested through the Level 2/3 casualty data. The establishment of fatality functions and economic loss functions using the databases and methodologies created was undertaken using intensity maps and the Level 1 (country) and Level 2 (town) fatality and economic loss data.

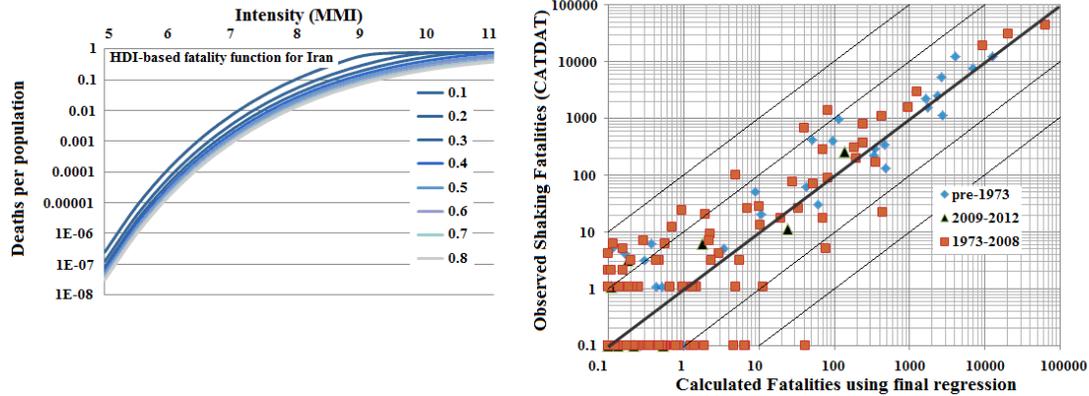


Figure 2: Left: The fatality functions for Iran based on HDI through time; Right: The final fit for Iran based on a time of day and an HDI based fatality function from 1900-2012, calculated on 1900-2008 data. (Daniell, 2014)

One advantage of the current methodology is that the functions have been validated against real data and also trends of data at multiple levels, meaning that the numerical optimisation has not always been the preferred model selected, given that it can often be inaccurate. The shape of the loss function is thus established using sigmoid curves if possible, which is most often best characterised by a tanh function for economic losses and a normal cumulative density function of a lognormal function for fatalities when only using 2 parameters as variables as shown in Figure 1. The variability of the function can be quantified by looking at the residual error. The functions can then be optimised as more data becomes available. The functions are consequently used for the [intensity, population,

socioeconomic parameter] triplets for each new event. The combination of an L2 norm and G norm into a L2+G norm by Jaiswal et al. (2009) is a good solution to the problem of upper and lower residuals; however, for the global method, a dual function was also tested with the L2 (least squares) norm being used for the top, and G (log) norm for the bottom, thus retaining the best possible regression as per Figure 2.

In order to evaluate the economic losses from any earthquake event worldwide, the historical earthquake event data must be aggregated. The process of the economic fragility function for a single historical event is as follows:-

Steps 1-3 are as for the fatality fragility function above.

4. For each of the point or area intensity values (vector/polygon format), recreate the capital stock and GDP of the time using census and other forms of data. This will be in raster format. This is then joined as a value to the polygon intensity.
5. These are then split into smaller administrative units or geocells in order to assign additional socio-economic parameters from the databases (to be created).
6. The direct economic loss for the particular earthquake is attached to the particular earthquake and the gross capital stock. It is important that this is disaggregated into only ground motion shaking-related economic losses, rather than including secondary effects.
7. The economic parameters are joined to the area based on the databases, including human development index, wage, building index etc.

For the next event, the couplets of intensity, population, economic exposure and socio-economic parameters are used in conjunction with the function from 1900-2008 to create the loss estimate.

REGIONALISATION

The grouping of countries which do not have a significant number of historical events is required, especially for countries like Australia where not many events have occurred with larger historical intensities. For economic losses, a different regionalisation is used than for fatalities, as there are significantly less events with reasonable economic loss estimates and loss functions are very different due to different building typologies and socioeconomic status between the two. The fatality regionalisations are shown in the following diagram using the parameters discussed in previous papers in the AEES, WCEE conferences, as well as Daniell (2014). A combination of the six elements shown in Figure 3 (infrastructure age, building stock, earthquake HDI, climate, fatality vulnerability and income) is used to choose the country combinations.

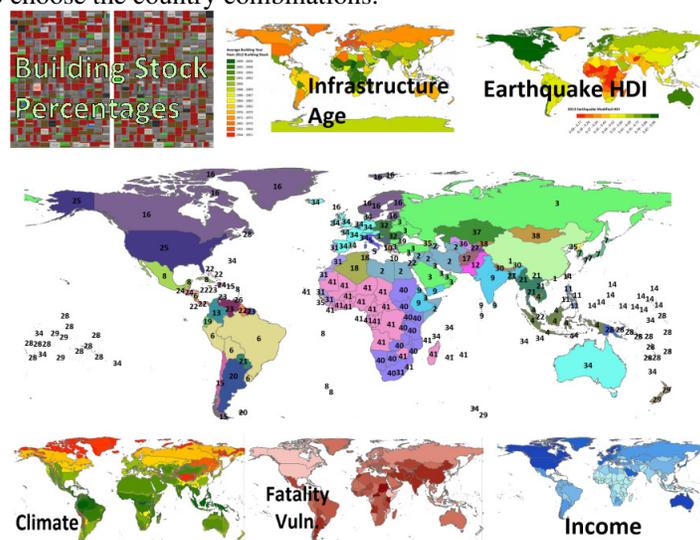


Figure 3: Some of the various components which were looked at in the country classification system in addition to the number of fatal events and fatalities. In the future, as larger fatal events occur in countries which have not been seen from 1900-2012 globally, this regionalisation should be adapted.

HISTORICAL ANALYSIS FROM 1900-2008

Historical Earthquake Losses:

The CATDAT Damaging Earthquakes Database of historical earthquake socio-economic losses from 1900-2012 has been extended and improved for 7208 earthquakes, including a rigorous process of validation, calibration, quantification and data searching. From 2003-2014, over 22,000 sources have been collected and the database has been used in a wide range of research projects, studies, analyses and for major events, as per Daniell et al. (2011, 2012).

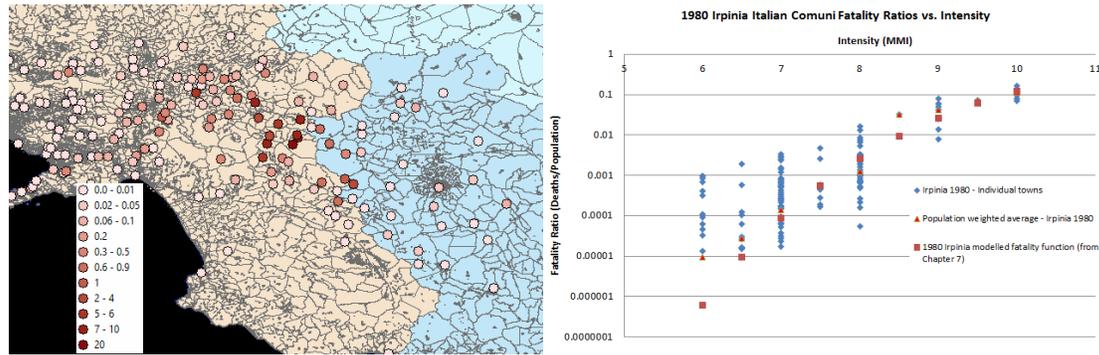


Figure 4: Left: Fatality statistics for the 1980 Irpinia earthquake in terms of fatality % compared to population of the village; Right: Validation of the 1980 Irpinia fatality function compared to Level 2 data.

A large number of historical loss estimates have been re-evaluated, and a range of fatalities and economic losses is presented for each earthquake, given uncertainties in historical events. The database represents the state-of-the-art in the field, given the number of sources and parameters researched for each earthquake. Over 100 Level 2 and 3 events, with examples as shown in Figure 4 and Figure 5, provide fatality and economic loss values disaggregated over the various towns and locations where data has been collected.

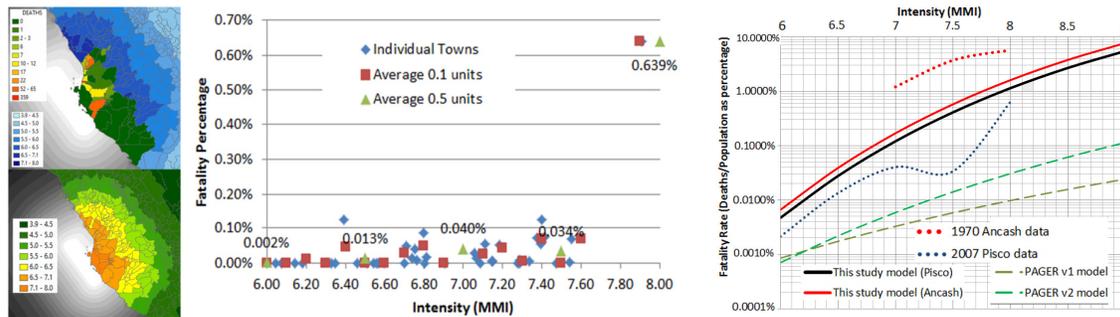


Figure 5: Left: USGS 2007 Pisco earthquake shakemap intensities averaged in each of the census units and the number of deaths in each of the districts in Ica Province (586 deaths); Right: Fatalities as a percentage of population in each census unit shown for individual town districts, also averaged on 0.1 intensity unit values and on 0.5 intensity unit values.

Historical Earthquake Intensities:

The database also contains key data on multiple levels, allowing for the analysis of earthquakes not only on a country level, but also often on province and town level for many earthquakes. During this study, the database has been supplemented with the linking of the GIS system, enabling visualisation and multi-level analysis of the collected earthquake data spatially as well as temporally. Over 3000 damaging earthquakes have been linked to 3900 isoseismals and intensity maps to allow analysis, including over 1000 pre-1960 earthquakes (as shown in Figure 6).

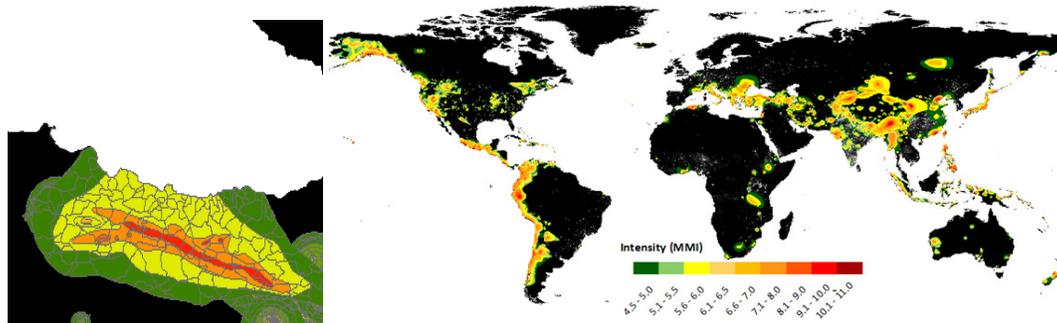


Figure 6: Left: An example of the splits of administrative units over an intensity map to form intensity, administrative unit couplets for 1939 Erzincan, Turkey; Right: Isoseismal maps created and collected worldwide correlated to damaging earthquakes in the database with an intensity greater than 5. In some cases, damaging earthquakes only had bounds to a minimum of intensity 6, and thus were not extrapolated.

Globally, many papers and studies have been undertaken to quantify the effects of historical events. These were integrated into a global database, combining the spatial, temporal, socio-economic and seismological aspects of the particular earthquakes. Each individual earthquake was examined, and the key earthquakes were searched for in multiple languages in order to attempt to improve the dataset. Isoseismals from many different atlases, papers and sources were collected over the time period and these have been integrated into the database to create a larger sample space through time with which to create functions and trends.

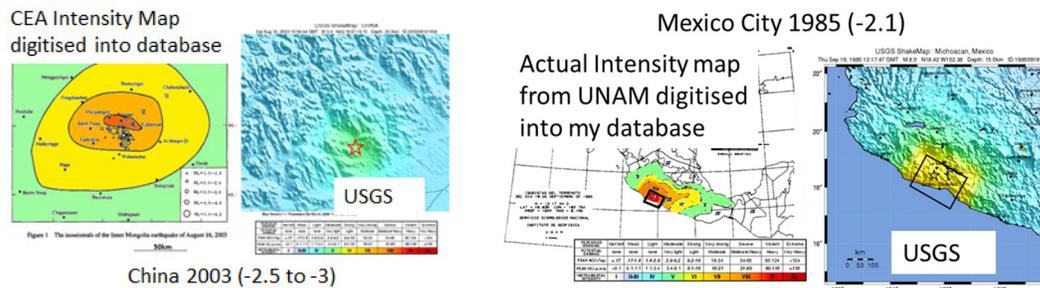


Figure 7: Left: A comparison between two intensity maps of the same earthquake in China from the 16th August 2003 (Gao et al., 2005), which caused 102 million USD damage (around 70 million USD capital stock cost); Right: Differences of shakemap isoseismals for the 1985 Mexico City event – a: Modified UNAM; b: USGS Shakemap. The fault block and the same colouring have been included on the UNAM shakemap.

The earthquakes were all disaggregated with respect to shaking and secondary losses; it has also been an extensive effort during this study creating disaggregation of social and economic losses from earthquakes through time from 1900-2012. Isoseismals and intensities from local databases and studies were preferred where multiple versions occurred over global databases as there were many differences between existing estimates and global databases as shown in Figure 7, especially for Chinese, Mexican, Italian, Turkish and South American events.

Exposure:

The evaluation and creation of a virtual earth for use in this analysis included an accurate calculation of economic exposure worldwide. For example, for the 1909 Provence earthquake in France, the distribution for the Level 3 units from 1900-2012 is shown in Figure 8. It can be seen that between the highest decrease and increase in population from 1900 to 2012 is around 15 times (Creuse (loss), Essonne (increase)). A key output of this study was the establishment of the exposure and vulnerability component globally. The production of a virtual earth of infrastructure typologies, population estimation on multiple levels (country, province, sub-province and city) using census information as well as proxies enables the next earthquake to be quantified accurately, allowing for picking up of regional differences such as the difference between an Istanbul (western Turkey) and Van (eastern Turkey) earthquake in terms of economic exposure as well as population and vulnerability.

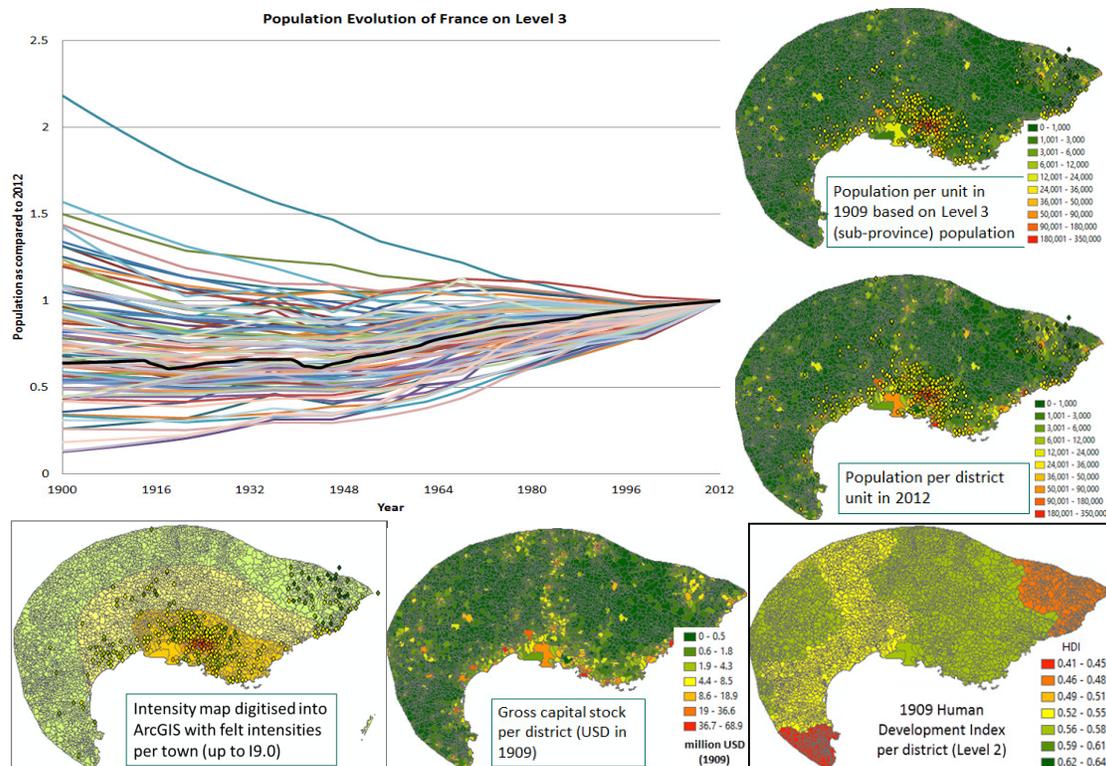


Figure 8: The intensity, population, gross capital stock and human development for the 1909 Provence earthquake, showing the variability also of population in France on Level 3 as a percentage of 2012 population.

For the current Earth (circa 2013), extensive work into establishing the economic exposure through net capital stock and gross capital stock in addition to GDP was undertaken using historical depreciation rate methods and existing studies to establish a value of assets that could be impacted by an earthquake currently. Economic exposure has been shown through the CATDAT database to be a combination of gross capital stock and GDP for economic costs, and net capital stock and GDP for economic loss. These were validated against national databases and many existing studies, thus proving a major improvement on global analyses checking out with the SOPAC PCRAFI estimates, as well as many individual country estimates.

These differed by a factor of 3 to 4 from PAGER (Jaiswal and Wald, 2013) which uses wealth rather than economic exposure. This comes about because of the use of the incorrect wealth estimates from the Wealth of Nations report (including values such as forests, future mining etc. into the exposure estimate where these should not ever be used) as opposed to physical capital stock shown in Figure 9.

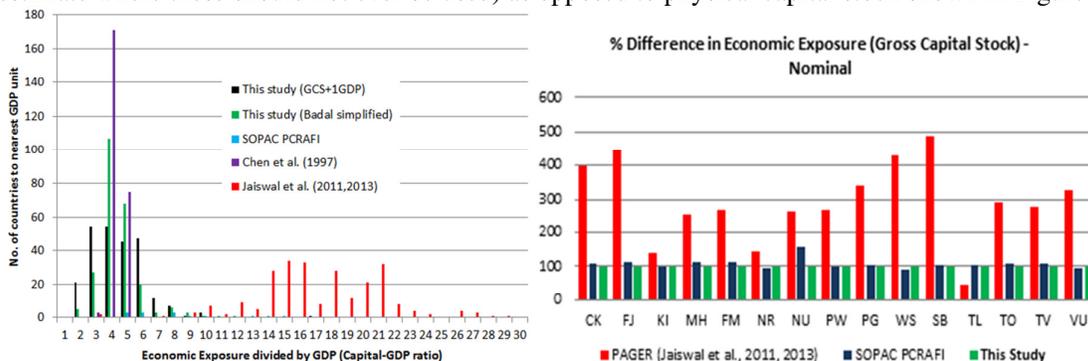


Figure 9: Left: A comparison between economic exposure models presented in literature for natural disasters. This study is shown in black and demonstrates the difference in global economic exposure from country to country when looking at exposure to output; Right: The difference of various models for economic exposure, that have been undertaken for natural disasters in the Pacific countries.

Development of socio-economic indices from 1900 to 2013:

Globally, population estimates, life expectancy, literacy rate, average years of schooling, economic indices of CPI, GDP (PPP and nominal), net capital stock, gross capital stock and unskilled wage indices (on multiple levels) and approximate infrastructure vulnerability, infrastructure typologies, age of infrastructure, the seismic code index, and building practice factor (on a country level) have been filled in using existing census data, worldwide datasets, and a plethora of studies.

The first worldwide production of the Human Development Index (HDI) through time from 1900-2013 has been established, which allows for the quick comparison of the socioeconomic status of the location at the time of an earthquake, giving a key normalization tool. As well as this, an earthquake HDI integrating components of earthquake vulnerability with this HDI allowed for an additional normalization tool.

VALIDATION AND TESTING AGAINST EXISTING METHODS

The worldwide models were established using 1900-2008 data, and the events from 2009-2012 have been tested, with reasonable results showing the use of such a methodology. It is expected that the functions can be optimised in the future by inclusion of the 2009-2012 data.

The worldwide empirical method has been established for fatalities with an overall standard error of $e^{1.73}$ which means that the fatalities can be calculated to within a reasonable level of quality globally, with some of the error coming from difficulties with historical earthquakes and certain types of volcanic earthquakes or earthquakes which need additional checking of the intensities observed. The functions were optimised when corrected by the time of the day (affecting the occupancy) when the historical earthquakes had occurred, and the HDI and building typologies at the time of the event versus the whole function HDI. The need for the function to follow historical event typologies on a town basis meant that the overall standard error was around 0.6 points higher than otherwise (1.1). The sample space of 2614 earthquakes with fatal and non-fatal events from 1900-2008, with 900+ events before 1973, gave a good basis for calculation (Figure 10). For fatalities, the methodology predicted 45% of fatal events to within 50% of the death toll reported and 59% for all events. 69% of fatal events were calculated to within 100% of the fatalities reported. 90% of the fatal events tested and 89% of all events were within one order of magnitude below or above the mean.

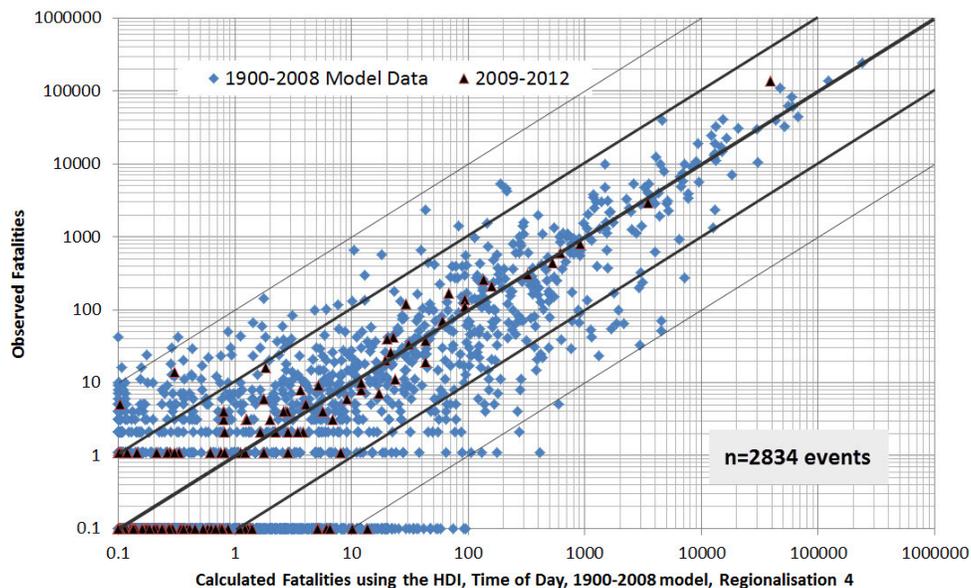


Figure 10: The tested 2009-2012 shaking fatality data using the regionalisation 4 country grouping built from 1900-2008. It can be seen that there are 2 fatal quakes underestimated by the model of 5 and 13 deaths respectively. In addition, 5 misses with overestimates over 2 fatalities result from the model.

In terms of economic loss functions, a check was made against the functions in every case being produced, such as for China and that of existing methodologies such as PAGER (Jaiswal and Wald, 2011; 2013; Chen et al. (2001)). It can be seen in Figure 11 that this paper study is in line with the average losses for China via their standard and also for average houses, which seems reasonable. Also, it can be seen that the function of the Jaiswal and Wald (2011; 2013) is a large underestimation and has a strange shape as compared to the existing fragility functions.

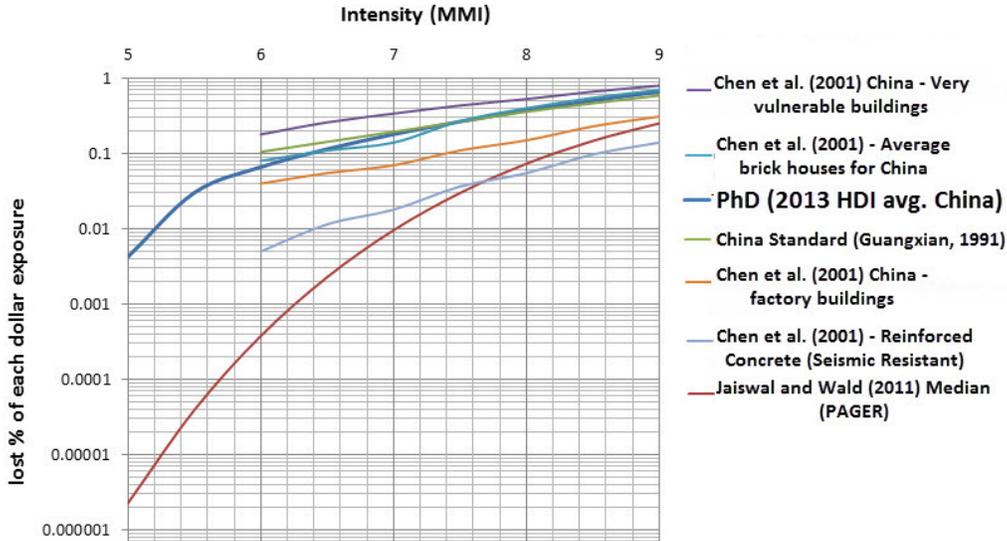


Figure 11: Various damage functions for the exposure of China. It can be seen that there is a wide range of damage functions used, which can result in a wide range of loss estimates depending on exposure.

For economic loss functions as shown in Figure 12, the methodology predicted 42% of events to within 50% of the economic costs reported and 65% of events to within 100% of the economic costs reported. 98% of the events tested were within one order of magnitude in either direction. Less events have accurate economic cost estimates historically from 1900-2012, thus the sample space is smaller when compared to the fatality model.

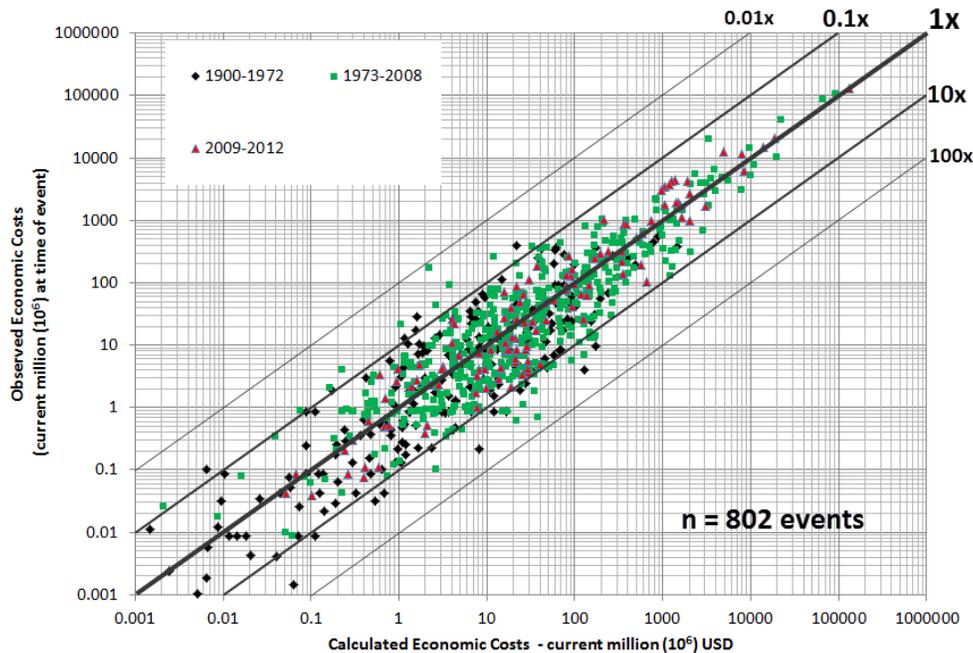


Figure 12: The finalised economic cost model (regionalisation 6, HDI) in current dollars, testing the period from 2009-2012 against the 1900-1972 and 1973-2008 data. (log residual error, $\xi_{v1}=1.28$)

Larger events have a much higher chance of being accurate under each function, as more events of lower intensity exist within the database (Figure 13). In terms of the uncertainties, these are calculated using the spread as a difference from the median.

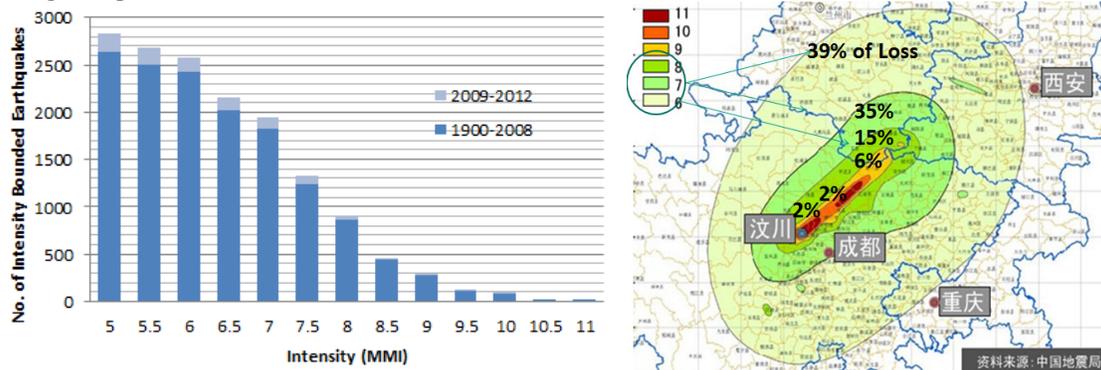


Figure 13: Left: The intensities within the events in the constructed database from 1900-2008 vs. 2009-2012; Right: The economic loss in each intensity bound for the 2008 Sichuan earthquake on CEA map.

The loss functions were calibrated based on capital stock and GDP which will be explained in the accompanying paper in this conference. It can be seen in Figure 14 that the economic loss functions (green) are much more consistent than the existing tested functions of Badal (2005), Chen et al. (1997, 2001) and PAGER (Jaiswal and Wald, 2013).

The Jaiswal and Wald (2013) function can be shown to have a problem at lower intensities. The use of a non-sigmoid curve in combination with the overestimation of economic exposure, and mathematical optimisation of underestimated and non-engineering shaped loss functions explains this problem. Badal (2005) and Chen et al. (1997) use assumed capital stock values based on simplified GFCF and also use only a few functions over the globe, thus showing a higher spread.

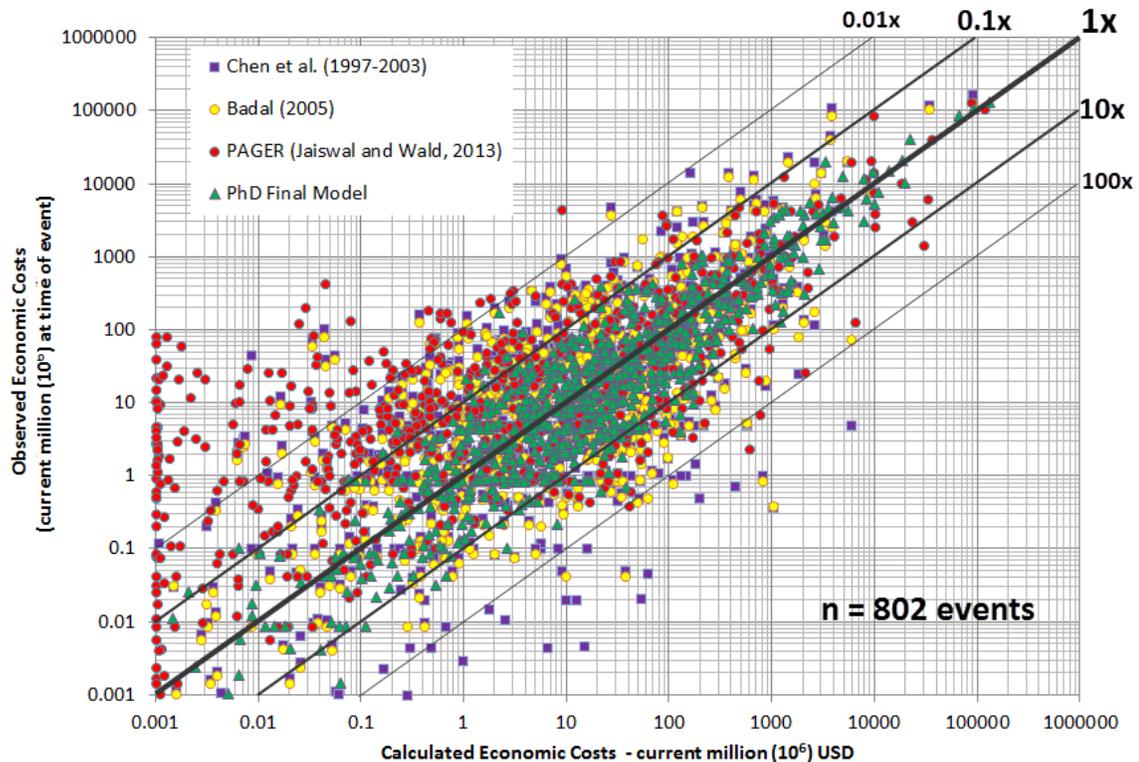


Figure 14: Observed vs. calculated costs for 4 different studies, including this paper in green (Doctorate Final Model, this study) versus Chen et al. (1997-2003), Badal (2005) and PAGER (Jaiswal and Wald, 2013).

CONCLUSION

Three key types of functions have been established: economic cost; economic loss; and fatality for rapid loss estimation. The ability of the model to output globally with confidence that the socioeconomic parameters are reasonable in any country is a big advantage of such a methodology. It has been shown to give reasonable results when tested against earthquakes during the last 4 years (Figure 15), and has been integrated with www.earthquake-report.com into worldwide reporting of earthquakes such as the 2013 Bushehr (Iran) and 2013 Bohol (Philippines) earthquakes, which allows for social input of data into the functions in the future. Having such trending mechanisms enabled the creation of normalisation methodologies to model all historical earthquakes with today's exposure. This provides an accurate, parsimonious view of the possible socioeconomic losses worldwide for each earthquake. It has also shown the deficiencies of existing rapid loss methods using mathematical regression of historical events without accurate estimates of economic loss, population, vulnerability and hazard. It has also been designed to be compatible with other earthquake loss estimation methodologies using macroseismic intensity in a “plug and play” type approach for the various components of fatality, economic loss functions, capital stock, population, building typologies and the other tools described in this methodology.

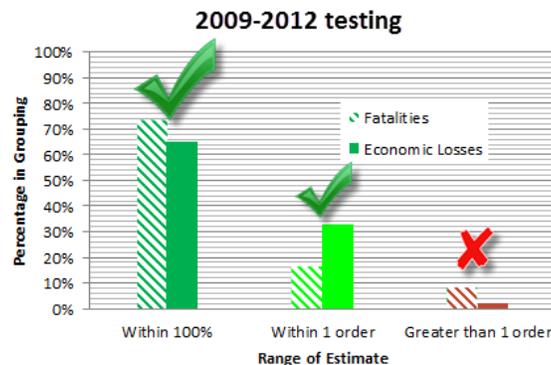


Figure 15: The testing of 2009-2012 with the 1900-2008 model for rapid earthquake loss and fatalities.

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