14TH CANADIAN MASONRY SYMPOSIUM
MONTREAL, CANADA
MAY 16TH – MAY 20TH, 2021

FATALITY LOSS ESTIMATION IN THE 2016 L'AQUILA AND 2006 YOGYAKARTA EARTHQUAKE AND THE IMPACT OF MASONRY ON THE LOSSES

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ABSTRACT

Masonry is a culturally preferred building product in Indonesia and Italy. The use of culturally preferred products, can often lead to interesting challenges in minimizing the loss of life in building collapse in earthquakes. A culturally preferred building product is one that has widespread local acceptance, such as clay roofing tiles in Newcastle, Australia, which often limit the use of other products, from cultural resistance to change. This problem of discussing culturally preferred building product is faced by researchers who look at causes for deaths in earthquakes and who seek to fairly comment on material use, but need to be aware of cultural sensitivities. This paper outlines in a first stage, a statistical analysis of the distribution of deaths in two fatal earthquakes, the 2016 Central Italy and 2006 Jogjakarta events. The two earthquakes are amongst a small category of highly fatal earthquakes for the earthquake magnitude. The highly fatal earthquakes provide an upper bound to likely human losses and human loss rates. The paper compares the results to previous statistical studies of other fatal earthquakes for calibration purposes. The second stage is to consider the impact of a culturally preferred building product on the human losses. As a standard method of analysis, the statistical procedures consider the change in the fatality loss rate with distance and the spatial variations in the rates of loss. The results are entirely consistent with earlier results determined for other fatal events. The findings point to a change in the rate of loss with distance and geographic features, such as river banks or mountains or fault orientation or the use of a preferred building product. The rate of human loss is neither linear or squared, but somewhere in between these extremes. The mathematical results are useful for estimating potential losses in future theoretical earthquakes and for considering the ethical questions as to the use of publicly preferred building products. The events provide a window in the impact of publicly preferred building products and highlight some of the interesting ethical issues in construction.

KEYWORDS: *human, losses, masonry, public preference, loss rate, Indonesia, Italy*

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INTRODUCTION

Unreinforced masonry on soft ground is structural combination that causes two design problems for engineers designing for earthquake loading. The first problem is ethical, related to the use of a publicly preferred building products and the second problem is engineering. Once one accepts the communities' right to the use of a publicly preferred building products, how do you estimate and then minimize the human and economic losses? Two areas with an intense use of a preferred product, masonry, are Central Italy and Java. Both regions have experienced earthquakes over millennia that have killed many humans. Italy has a longer history of construction with fired masonry than Java. Fired masonry represents a significant improvement on unfired masonry and timber buildings in terms of fire losses, which occur frequently. However, fired masonry is a lethal product in earthquakes that occur with a recurrence interval measured in the hundreds of years.

This statistical research looks at two highly fatal earthquakes that occurred recently in Italy and Indonesia. These earthquake locations are close to epicentral spots for previous earthquakes, such as the 1915 Avezzano in Central Italy, investigated by Nichols and Beavers [1] as part of a long running research program. The paper outlines the problem background, presents an overview of the statistical methods, completes a statistical analysis and reaches a conclusion on the hypothesis. The hypothesis developed for this question is the loss rate can be functionally related to the distance from a defined displacement line. The paper begins with a literature review, provides a section on methods, summarizes the key results, and provides a conclusion. The paper then briefly raises the potential ethical issue of construction with publicly preferred building products.

LITERATURE REVIEW

Shiono [2] demonstrates the need for individual study of economic and human losses in major fatal earthquake events. The economic loss is mitigated if adequate insurance is carried for the region. However, there is often insufficient insurance cover, as observed by Kleindorfer and Kunreuther [3]. The first point of interest in human loss estimates in earthquakes is the development of a distance metric. Atkinson and Boore [4] clearly demonstrate the standard attenuation models for spectral amplitudes showing the measured distance dependence of the results. These authors provide the generally accepted relationship between intensity and distance for the USA. Whilst, **MMI** is an important measure, there are limited steps in the **MMI** and the advantage of the numerical distance is clear. The use of **MMI** provides 5 data steps in the typical analysis, but the use of distance metric provides a continuum that can stretch to 250 km for earthquakes.

The interesting legend that the bells of churches rang on the East Coast of the USA in the 1812 New Madrid Great Earthquakes is not likely to be true. The legend points to the likely extent of the damage in a repeat of these great events. One can conclude that although **MMI** represents one measure of damage [5], the death rate is also dependent on local building styles and heights, the specific frequency components of the earthquake and soil types, as clearly demonstrated in Charleston, SC in the late 19th century, [1, 6] and 1989 Newcastle earthquake, [7]. The second point of interest is the definition of the epicenter and the meizoseismal zone defined by Milne [8].

The epicentre is the starting point for an earthquake, but it does not represent the end of the rupture. Earthquake losses in the 1915 Abruzzo earthquake demonstrates this problem in the development of this analysis method. The 1915 Abruzzo earthquake had peak intensities 20 km apart due to the length of the underground fault rupture leading to high human losses in distant villages. The same observation is made in the recent southern 2008 Sichuan Chinese earthquake, as the epicentre is not a point, but a long slide in the geological structure several tens of km in length. Figure 1 shows the loss model distance metric developed for this research problem.

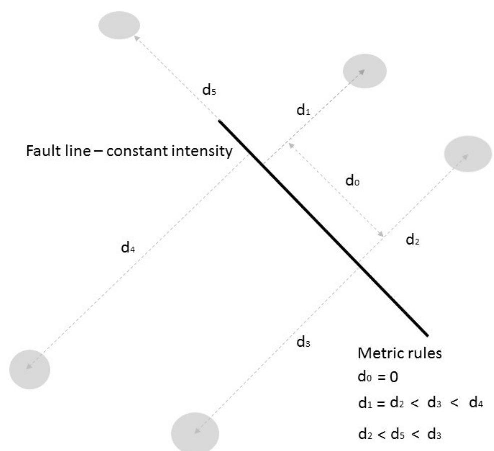

Figure 1: Earthquake Defined Distance Metric

Fatal earthquakes occur on average 16 to 25 times per annum now. The number of fatal earthquakes, has slowly increased, from about 4 per annum, from the middle of the 19th century as the world's population increases. Nichols and Beavers [6] showed that the average annual rate of fatal earthquakes was linearly related to the world's human population count. The annual counts included a harmonic component that set upper and lower limits on the probably number of earthquakes at any time. It is not possible to study all of the fatal earthquakes for a number of reasons, including limited data, low fatality counts and difficulty in data collection

The main use for a study of the fatal earthquake data is to provide a long-term estimate of the likely death tolls in future theoretical earthquakes. But, for statistical methods to work, there needs to be a sufficient density of information for the earthquake. If the population is high and the deaths are low, the statistical analysis fails on the issue of the Central Limit Theorem, [9], which is not a trivial limit on this work. The second matter is a quality of information, which can vary with time and place. Hansen and Condon [10] performed seminal work on the 1906 San Francisco earthquake and clearly highlighted the problem of data quality that persists to this day. The important step is visiting the site of an earthquake to assess the data and building quality, for major earthquakes, such as 2006 Yogyakarta earthquake, [11]. The other issue is the occurrence of Great Earthquakes in intraplate regions that are extremely difficult to predict because of the short database of recorded earthquakes, [12]. The estimated peak fatal count in an earthquake, at the moment, is in the order of 1 million deaths [13].

Milne [8] showed in Japan that the amplitude of the ground movement falls from the peak movement area. Milne termed the region, meizoseismal area, for the peak ground movement. It is considered that an estimated fatality rate can be determined for a continuous urban or rural area, where there are similar characteristics from Milne's note. An old city in Italy or Indonesia may have many different building types, so that the delineation of the different types into common areas is an interesting challenge. But the procedure has merit, as one attempts to estimate future losses in events. Earthquake fatality data is distributed across many centuries and countries. This data presents a number of unique data collection and statistical analysis problems. A simple method using distance as the independent variable and the loss rates as the dependent variable has been accepted from the original work by Shiono. Subsequently, Nichols, Lopes de Oliveira and Totoev [14] outlined the development of a fatality estimation equation for fatal earthquakes. Figure 2 shows a plot of the peak fatal earthquake data collected by NOAA and others [15]

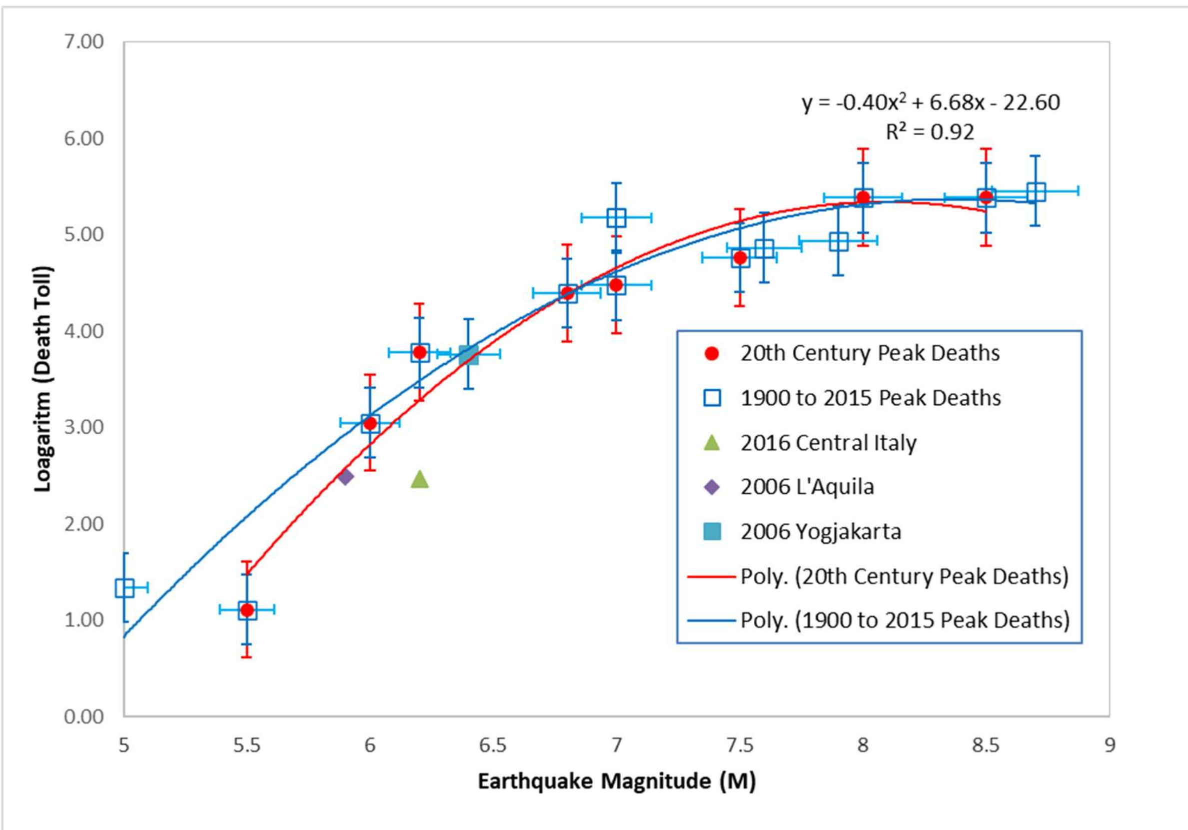

Figure 2: Original and Revised Fatality Function.

Figure 2 includes the plot points for the 2008 L'Aquila and 2016 Central Italian earthquakes. Figure 2 shows a bounding function fitted to the 20th century peak deaths. The fundamental concept for this equation is using the bounding function for the most severe fatal earthquakes to estimate smaller events. A revised function was added for the period to 2016. The fitted function is a second order polynomial equation on a logarithm to linear plot. Five factors will affect a fatality rate estimate, reducing the death tolls below the peak levels shown on Figure 2. The five factors are population density, λ_1 , building and ground factor, λ_2 interplate or intraplate event, λ_3 building collapse rate with seismic intensity, λ_4 and time of day, λ_5 . Nichols and Beavers [1] defined a estimating equation, 1, based on these five factors :

$$\Xi_d(R, M_d) = \sum_{k=1}^{k=m} \prod_{i=1}^{i=n} \lambda_{i,k} \Xi_B(M_d) \tag{1}$$

$\Xi_B(M_d)$ is the loss estimate equation for the earthquake magnitude from Figure 2. $\Xi_d(R, M_d)$ is the estimated loss in a theoretical earthquake, from k distinct urban zones.

Lizzi [16] illustrates the long-term use of masonry in Italy from the perspective of monuments, but the use in Indonesia comes from a cultural importation of the product by the Dutch into the former colony. The use of unreinforced masonry in Holland is not an issue, but the use in a region of high seismicity is a potential problem as observed in the 2006 Yogyakarta earthquake. But culturally, masonry is a preferred building material at these locations. It is extremely difficult to change cultural perceptions in engineered materials, because of human behaviour and prejudices. Richter [5] briefly discusses the use of masonry in Japan after the arrival of the British in the 1860's, but he acknowledges the cessation of this construction method with the high economic and human losses from earthquakes.

METHODS

As for all statistical analysis methods simplifications are made in the assumptions and limitations applied to the problem. The technique outlined here represents a reasonable balance between statistical simplicity and providing useful information for estimating future deaths in earthquakes. There is a small subset of fatal earthquakes that were much more deadly than the average fatal earthquakes. This observation derives from the mathematical statistics for fatal earthquakes being approximated with a Generalized Poissonian distribution [17]. Shiono developed the conceptual mathematics for the analysis of these events using the 1976 Tangshan earthquake as a base model. Since then a number of these deadly events have been studied by the author as part of a long running study into deaths in earthquakes that commenced when the author worked at the Mid America Earthquake Center, [18]. This analysis investigates two recent particularly deadly earthquakes and compares the results to other highly fatal events. The intent is to consider the impact on the cultural choices for building materials.

This first earthquake is the 2016 Central Italy Earthquake. This regional area is heavily rural and woodlands with a scattered set of small villages. The villages mainly occur on ridge top areas and photographic review suggests that location of the house relative to the top of the ridge, angle and size had some impact on the losses, as the failed houses do not appear to be randomly scattered, but cluster in groups or along the steep edge of the town. The earthquake occurred on the 24th August 2016 at 1:36 UTC. The epicentre is near to Accumoli at a depth of 4 ± 1 km. The death toll was 295 with 400 injured, which is a high death to injury ratio. Figure 3 shows earthquake.

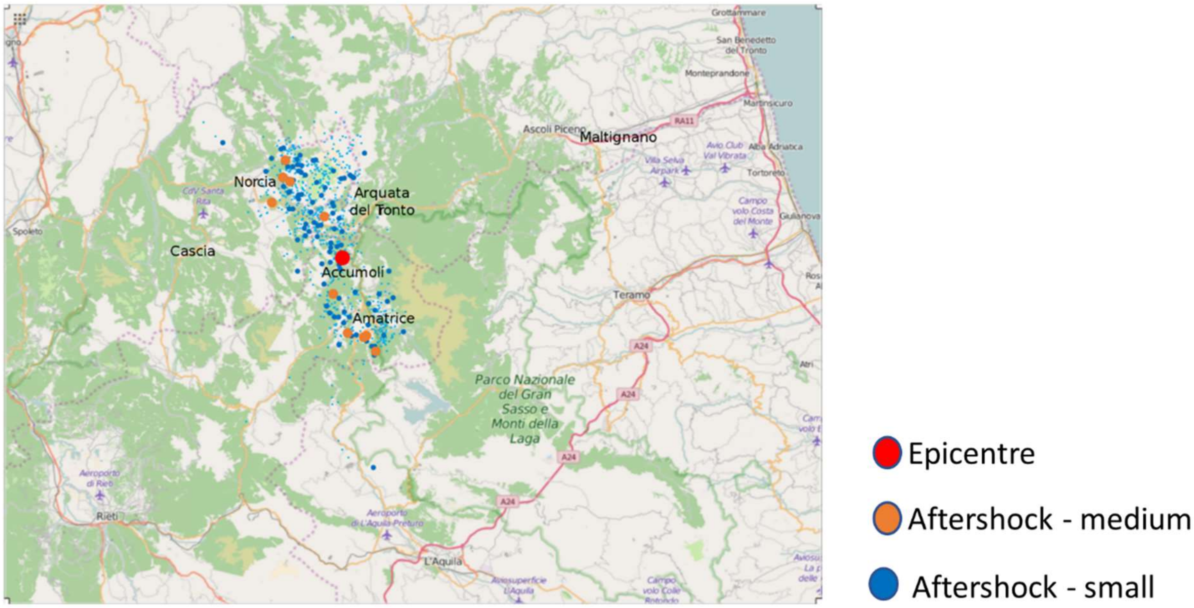

Figure 3: 2016 Central Italy earthquake shock locations from (Istituto Nazionale di Geofisica e Vulcanologia)

Figure 3 shows the other characteristic feature of interplate earthquakes, the disturbed region has an elliptical rather then circular shape that is characteristic for intraplate regions. This shape difference is one of the reasons for higher death tolls in intraplate events. Figure 1 illustrates the distance metric that overcomes the problem of determining a distance metric for the elliptical shape of the meizoseismal area for interplate events.

An Mw 6.3 earthquake occurred near the city of Yogyakarta (20 km SSW) on the island of Java on May 27, 2006 resulting in 5782 deaths, and 36,299 injuries. The likely peak intensity was **MMI IX** based on the observed damage to masonry buildings near the coastal epicentre by the author. This death toll places the 2006 Yogyakarta earthquake into the group of rare earthquakes in the last two millennia that define the bounds of deaths in such events. These rare events, only seven in the 20th century, are critical to understanding the site factors that affect losses in earthquakes, [19]. One of the significant engineering issues in Yogyakarta is the use of masonry in dwellings. There are historical reasons for the movement from wooden to masonry buildings in the last centuries in Java, but the use of un-reinforced masonry leads to catastrophic failure in earthquakes. There is now an increased use of reinforced concrete with masonry infill for domestic dwellings in Yogyakarta. Yogyakarta is no different than many other cities in the world. The higher or elevated regions of cities are often developed later, with larger dwellings, and at a lower density, leading to higher death tolls in the lower river valleys. Figure 4 shows the population density and distribution from UNISAT [20]. This map demonstrates, see insert, the well observed fact about many cities growing along the river plains, because of ease of transport and simplicity in building. The basic analysis method is, data on the location of deaths in a particular earthquake is mapped onto a topographic map. The approximate density of residents in the earthquake meizoseismal relative to the death locations are determined from local and state government data. The clusters of deaths and the appropriate urban region and population set from which the deaths are drawn are averaged to determine loss rates. The location of the fault line, determined from the earthquake data, is plotted on the topographic map. The distance from fault slip line to each of the death locations is determined and recorded in a spreadsheet. The aggregated data is plotted in EXCEL using a standard scatter plot chart. The regression function in EXCEL is then used to plot a functional relationship on the chart. A linear regression analysis of the transformed data provides a method for recovering an exponential equation. The results provide insight into loss with distance.

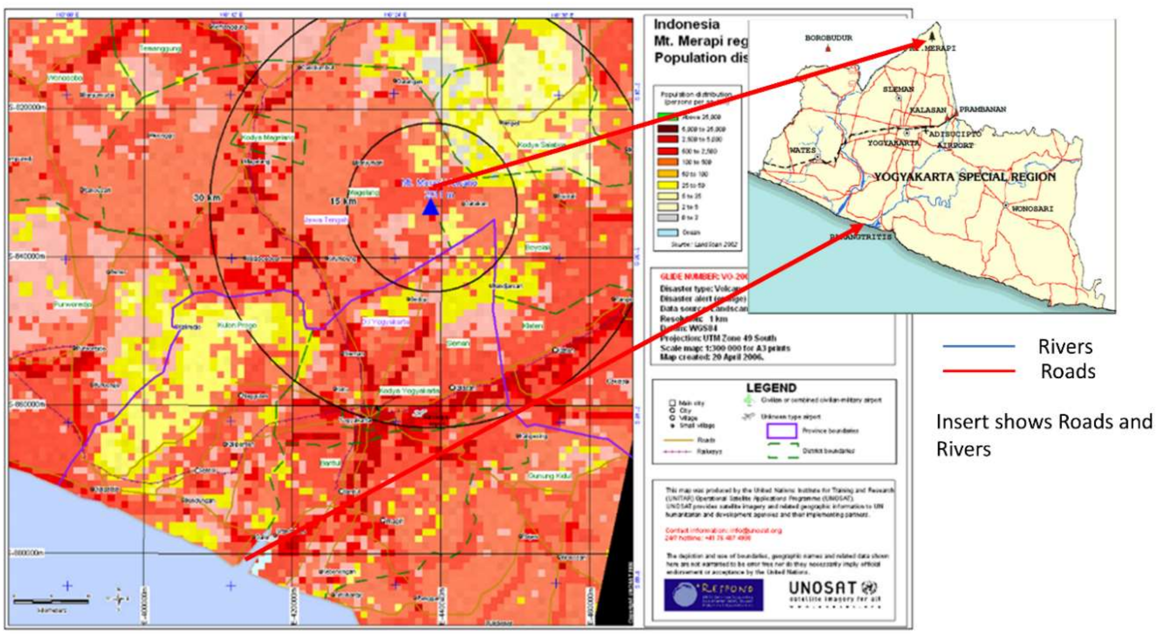

Figure 4: Yogjakarta Population Density and Distribution from UNISAT,(2006)

RESULTS

The hypothesis postulates that the loss rate has a distance dependence. The first analysis will provide an analysis of the complete data set to compare the loss rate with distance. The second stage of the analysis will develop the functional form of the loss equation using standard regression analysis on a natural logarithm transformed data set. The third stage of the analysis is to summarize the results for the regression analysis. The first statistical test is to determine loss rate for a set of fatal earthquakes with distance from the epicentre distance as determined using the metric shown on Figure 1.

Figure 5 shows the plot of loss rates with distance for a number of major fatal earthquakes including, 1931 Napier, NZ (M7.9, deaths 256), 1976 Tangshan, China (7.2, 242,000), 1999 Chi-Chi, Taiwan (7.3, 2416), 2001 Gujarat (7.7, 20005), 2005 Pakistan, (7.6, 72248), 2008 Sichuan (8, 69,180), 2011 Christchurch, NZ (6.3, 181) and the events in Italy and Indonesia.

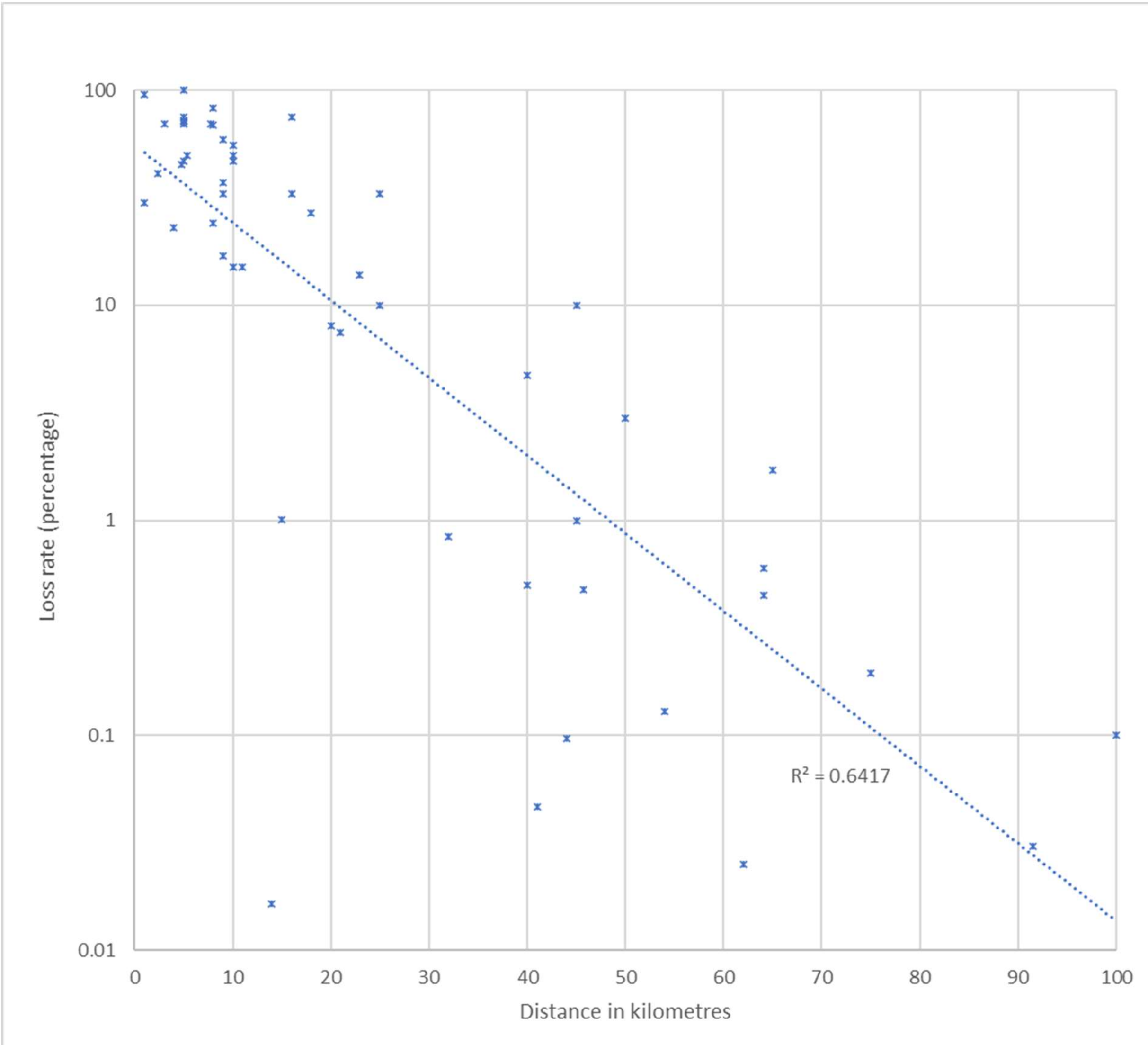

Figure 5: Fatality loss rates for a set of major earthquakes with metric distance from Figure 1

The equation defined on Figure 5 is:

$$L(D) = Ce^{-BD} \tag{2}$$

Where L is the loss as a percentage with distance, C and B are constants and D is the distance measured in accordance with Figure 1. A summary of the statistics is presented in Table 1.

Table 1: Linear Regression Analysis results

Description	Coefficients	Stand. Error	t Stat.	P-value	Lower 95%	Upper 95%
Intercept	4.0193	0.0304	13.25	4.39525E-18	3.4083	4.6304
Slope	-0.08313	0.008698	9.557	5.90638E-13	-0.1005	0.06567

The regression results show that an exponential regression equation can be applied to the data and the R^2 has a value of 0.64. Clearly, this regression function provides a reasonable statistical upper limit to the loss rate function. There will be very many earthquakes that have the potential for deaths, but have zero losses. A zero-population density in a region is the usual reason for no deaths.

The average annual deaths in earthquakes are a result of the nature of the Poissonian statistics that control earthquake deaths with time for the entire world. Earthquake deaths represent the intersection of two sets. The first set is the list of earthquakes for a given time, termed E. The second set is the location of all humans in the world, termed H. This set has a particular time function, which has an impact on actual human losses in an earthquake. The fatality losses are the intersection of the two sets $E \cap \mathrm{H}$, but the timing of the event is critical for the actual losses. Three examples are used to illustrate the point about timing. An earthquake occurred in 1886 in Charleston, SC. The earthquake struck at about 9:50 p.m. on August 31. The estimated moment magnitude was 6.9–7.3 and the estimated **MMI** was **X**. The event on a Sunday night occurred just as people were arriving home from church. A significant number are noted as dying from collapsing building facades as they ran from the buildings [14]. The 2006 Yogjakarta earthquakes occurred at 5:54am on a weekday. The first author in discussions with local residents was told that a significant number of people were outside the collapsed masonry houses on their way to work and school at that time. The 1989 Newcastle earthquake occurred at about 9:58 a.m. The main doors of the collapsed Workers Club normally opened at 10 am, so the people waiting to enter the club avoided death by a few minutes in the collapsed club and only employees died in the tragic collapse, [7]. Poissonian statistics is a relentless march following well defined parameters that yield an estimable long term world fatal loss count, with really only one unknown, location. There are a number of observed strict statistical limits on the intersection set of deaths in earthquakes that have remained steady over the long term of measurements. These limits are constrained by:

- a probable two million deaths in the next century at current world population levels
- an estimated 15 to 25 fatal earthquakes per annum now, rising in line with world population
- the Generalized Poissonian Distribution (GPD) providing a reasonable estimate of the human losses over the century in terms of distribution of deaths on a world basis
- GPD leading to:
    - the peak estimated deaths in single event with century return period - currently 1,000,000, where a million-death event will strike in a major intraplate city, which is a necessary mathematical constraint to provide the sufficient population and density to overcome the limit imposed by λ_2 on interplate events, examples include, Sydney, New York and Lisbon
    - the estimated deaths in a single event with a 30-year return period - 250,000
- the observation that a M5.4 is the lowest magnitude earthquake with known fatalities
- the observation that multiple deaths occur in similar buildings failing as a group

The result is that a probability field exists across the world for estimating fatality counts in earthquakes. Early estimates of this field by Bird coupled with a Monte Carlo analysis provides a method to estimate synthetic earthquake catalogues and from these catalogues develop estimates of the losses. This is an area of future research. We are always going to be able to improve estimates of the probability field, but this work provides a solid starting point for quantifying the potential probability of earthquake losses for each urban area. This estimated loss set must meet the requirements of the stated limits to be statistically valid.

CONCLUSIONS

The primary objective of this research is to investigate the rate of decay of the loss function for earthquake fatality rates with distance from the epicenter. The hypothesis developed for this paper is the loss rate can be functionally related to the distance from a defined displacement line. Two recent fatal earthquakes were investigated for this study, the first event was 2016 Central Italian earthquake and the second event was 2006 Yogjakarta earthquake. The analysis was based on metric distance that allowed for the finite length of the fault rupture. A plot of the deaths in a number of highly fatal earthquakes against distance shows that a relationship exists between the loss rate and the distance. The R^2 for the equation at 0.64 indicates that a reasonable statistical relationship exists. The equation when coupled with Bird's method for estimating a theoretical earthquake catalogue provides a method to establish a Monte Carlo analysis to estimate likely loss ranges for all urban locations. The scatter on the plot shows that other factors impact on the loss rate, or in simpler terms at a given distance, there is a measured range of losses. The variations in the losses for distance can be attributed to the difference in earthquake magnitude, the timing of the event as discussed, the ground motion and the building materials. Most earthquakes have zero deaths, but a few earthquakes each year are fatal. The method outlined in this paper provides one equation used for estimating annual losses on a world basis. One cannot estimate fatality loss rates as a probability function for an area less than the world, the statistic is simply not available as the analysis must meet the outlined constraints, as the GPD model cannot be divided into subsets

Building materials are an interesting issue. In ordinary engineering terms, the use of unreinforced masonry in high seismic regions such as Java and Italy represent an extremely poor engineering decision. Interestingly, a similar statement can be made about a low seismic area, such as Newcastle, Australia, which has a continuous series of small earthquakes since the European invasion in 1788. These three urban areas all share a common use of unreinforced masonry. This building material is a preferred building material for the community, essentially for historical reasons related to societal influences. The use of unreinforced masonry usually results in higher rates of death in earthquake when compared to other materials, such as timber. The 1886 Charleston, SC earthquake provided direct evidence of this problem. But a society is free to chose building materials and engineering practices are generally bound to accept such decisions. This is an interesting ethical issue of some significance in the future development of codes and standards. However, the author will continue to study the impact masonry and other factors on the C variable in equation (1). This research will slowly shed light on the further problems of culturally preferred building materials in seismic and other high load zones. However, the cultural resistance to change is significant and change is often wrought by insurance company demands and not locals.

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