EARTHQUAKE LOSS ESTIMATION AND MITIGATION IN EUROPE: A REVIEW AND COMPARISON OF ALTERNATIVE APPROACHES

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ABSTRACT :

The paper contributes to an assessment of the uncertainties involved in the use of current loss modeling methodologies when applied to the estimation of building damage and casualty generation in urban areas. The work derives from studies conducted within the EU-funded LESSLOSS project with the aim of providing a basis for urban planning authorities methods to assess alternative mitigation strategies. Research teams in Istanbul, Thessaloniki and Lisbon developed methods applicable to their own city and building stock. A benchmarking study was then carried out to compare the results of the three approaches when applied to a standardized “urban block”. The paper, presents the results of the benchmarking study, and reviews the differences between the loss estimation approaches used, There are significant differences in surface ground motion, and even greater differences in predicted damage and casualties resulting from the ground motions using the different approaches. The paper discusses possible reasons for these differences and the implications for the estimation of uncertainty in urban loss estimation.

KEYWORDS: Earthquake risk, loss estimation, ground motion, building damage, casualties

1. INTRODUCTION: AIMS AND METHODS

Earthquake loss estimation is of growing importance both for the planning of appropriate and cost effective earthquake mitigation measures and for insurance purposes, and an understanding of the uncertainty in such estimates is vital for informed decision-making on alternative mitigation strategies. In a recently completed collaborative research project (LESSLOSS SP10) new loss estimation studies were carried out for Istanbul, Lisbon and Thessaloniki, based on new approximately 50-year and 500-year earthquake scenarios, and using methods, software and GIS mapping tools which were developed by separate research teams for each of these cities; these scenarios were used to investigate alternative mitigation strategies. The individual city studies have been reported elsewhere (Spence et al., 2007). The approaches used for the three cities had many common elements, but there were also important differences, and in the final phase of the project a benchmarking study was conducted to compare the results obtained by different methods (KoeriLossV2, AUTHloss and LNECloss) used by the separate research.

The study consisted of comparing the results obtained when the three alternative approaches were used for a standardised set of conditions. It involved defining a “standard urban block” in terms of the soil profile, the inventory of building classes, and occupancy; and applying to this urban block several bedrock ground motions of sufficient amplitude to cause significant damage. The ground motions were defined by means of bedrock acceleration time histories. Each team then estimated, using their own chosen methods: (a) the surface ground motion; (b) the level of building damage caused; (c) the number of casualties. These results were then compared.

2. THE STANDARDISED INPUT DATA

Two time histories of bedrock ground motion were adopted to describe different hazard levels:

1. A time history for Gebze (GBZ) in the 1999 Kocaeli, Turkey earthquake (max PGA=0.24g)
2. A synthetic time history (S53) developed by INGV for Istanbul (max PGA=0.63g)

Further details of these time histories, are given in Table 1.

The peak ground motions recorded in the GEBZE (GBZ) record were very low compared with those predicted by empirical relationships; there was significant difference between the NS and WE components due to source effects, and strong low frequency pulses were present on both components. The second record was from a simulated earthquake of M 7.4 occurring in the Central Marmara Basin fault (CMB), located about 20-30 km South-East of central Istanbul, which contributes most to the seismic hazard in Istanbul (Le Pichon et al., 2001). Its peak ground motions are consistent with those predicted by an empirical predictive model valid for the area (Ambraseys et al., 2005).

Table 1 Details of bedrock ground motions used in the simulation.

Event	Distance to fault rupture	Record/Component	Site	High-Pass filter (Hz)	Low-Pass filter (Hz)	PGA (g)	PGV (cm/s)	PGD (cm)
Kocaeli, 1999, M=7.4	17 km	KOCAELI/GBZ-UP	Rock	0.1	40.0	0.203	11.4	4.78
		KOCAELI/GBZ000		0.03	25.0	0.244	50.3	42.74
		KOCAELI/GBZ270		0.08	30.0	0.137	29.7	27.54
Synthetic, M=7.4	14 km	S53/B13_53NS	Rock	--	50.0	0.630	76.9	75.7
		S53/B13_53WE		--	50.0	0.587	97.5	63.15

Three separate soil profiles were adopted as follows:

- A 150m soil to bedrock profile from Istanbul
- A 90m soil to bedrock profile from Thessaloniki
- A 30m soil to bedrock profile from Lisbon

Each research team provided geotechnical data (including borehole log/ soil classification vs depth data, water level and shear wave velocities). The interpretation of the soil data, including the use of degradation curves was decided by the individual partners. Summary data for 3 soil profiles used is shown in Table 2:

Table 2 The three common soil profiles adopted

Layer	**Istanbul**			**Thessaloniki**			**Lisbon**		
	Thickn's	Description	Vs (m/s)	Thickn's	Description	Vs (m/s)	Thickn's	Description	Vs (m/s)
1	1.5	Topsoil	157	5.5	Fill	220-225	4.1	Fill	292
2	13.8	gravelly sandy clay	150-290	6.3	Clay	220-380	12.2	Soft organic clay	183
3	18.9	Limestone	280-390	14.5	Stiff clay	350-450	2.8	Soft organic clay	144
4	32	sandy clay	360-830	63	Very stiff clay	400-750	3	Soft to medium silty sand	142
5	1.5	clayey sand	490				2	Basal clayey gravel bed	260
7	4.5	sandy clay	490-520					Stiff clayey silt	>1000
8	28	clayey sand	520-850						
9	50	Sandstone	>1300						

Table 3 The common building inventory adopted

Class	Age	Height	Number of buildings
RC	Pre 1960	Equal numbers at 1-3, 4-7, 10 storeys	300
RC	1960-1980	Equal numbers at 1-3, 4-7, 10 storeys	300
RC	Post 1980	Equal numbers at 1-3, 4-7, 10 storeys	300
Masonry	RC diaphragms	Up to 3	100
Masonry	Unit masonry, no RC diaphragms	Up to 3	100
Total			1100

The building inventory adopted was as shown in Table 3. Occupancy rates used were: 1-3 storey buildings: 5 occupants; 4-7 storey: 70 occupants; 10 storey:100 occupants. It was also assumed that earthquake occurred at midnight. For damage estimation the damage states D1-D5 used were as defined in the EMS scale document (Grünthal, 1998). Where the HAZUS damage states are used, it was assumed that slight= D1, moderate= D2, extensive= D3, and complete includes both D4 and D5, with some estimate of the proportion of those in this damage state between D4 and D5.

Finally, the standard output from each run was agreed to be:

1. Site-specific surface ground motion
2. Numbers of buildings of each class in each damage state (D1-D5)
3. Proportions of occupants of each building class killed and severely injured.

3. METHODS USED FOR DETERMINATION OF SURFACE GROUND MOTION

In KoeriLossV2 the earthquake characteristics on the ground surface were determined based on one dimensional site response analysis conducted using Shake91 (Idriss and Sun, 1992) where the given acceleration time histories were used as rock outcrop input motion and the acceleration response spectra were calculated for 5% damping on the ground surface. An algorithm was developed to calculate NEHRP Uniform Hazard Response Spectra that fits as the best envelope to the acceleration response spectra calculated by Shake91. These best fit NEHRP spectra were used to define the spectral accelerations at T=0.2s and T=1.0s on the ground surface to be used for the damage assessment.

In AUTHloss peak ground accelerations were calculated based on 1D EQ analysis (EERA, Bardet et al, 2000). A potential problem arises in soil layers with very low shear wave velocity (Lisbon site). The site response analysis calculation using the conventional equivalent linear procedure predicts large (1% or more) cyclic strains and hence great loss of stiffness and relatively small computed acceleration at ground surface (large deamplification). Reliable results with these soil models can only be achieved within an allowable strain level depending on the soil type.

LNECloss algorithms take into account site effects due to soil dynamic amplification by means of an equivalent stochastic nonlinear one-dimensional ground response analysis of stratified soil profile units designed for the soil profile used.

4. METHODS USED FOR BUILDING DAMAGE ESTIMATION

In both KOERIloss and LNECloss an analytical computation of the vulnerability relationship is based on the well-established capacity spectrum method (ATC, 1996, Kircher et al, 1997, Erdik et al 2002). For a given spectral displacement (defined at the performance point for the given earthquake scenario demand and building capacity curve, fragility curves (eg Figure 1) give the probabilities of exceedance of 4 damage states, slight, moderate, extensive and complete.

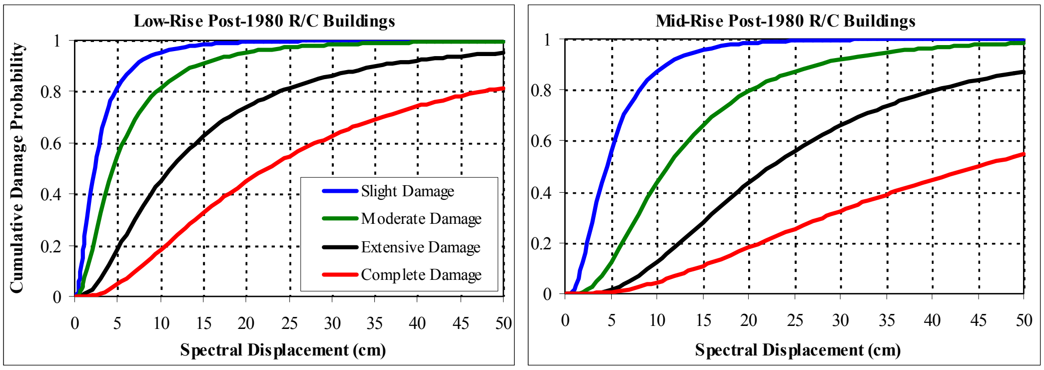


Figure 1 Spectral displacement based vulnerability curves for low-rise and midrise, post-1980, R/C frame type buildings used in KoeriLossV2

To estimate numbers of casualties, a further assumption is needed to evaluate the proportion of buildings suffering "complete" damage which totally collapse. In KoeriLossV2, based on Turkish experience, 10% of buildings with "complete" damage were assumed to collapse. In LNECloss the probability of total collapse among buildings with complete damage ranges from 10% to 25% depending on the class of building, and following HAZUS (FEMA, 1999).

In AUTHloss, the vulnerability analysis of RC buildings is performed based on fragility curves (in terms of PGA) that have been developed using a combination of analysis and statistical data, the so-called 'hybrid' approach (Kappos et al 2006), deriving from Greek practice, and largely making use of the statistical data from the 1978 Thessaloniki earthquake. The method uses 6 damage states (DS0-DS5). DS5 is here taken to imply total loss, not complete collapse, and only a proportion of buildings in damage states DS4/DS5 are assumed to collapse. To estimate this proportion, a complex algorithm has been developed in which the proportion of collapsed buildings depends on the PGA of the ground motion as well as the fragility curve used (Spence et. al, 2008).

5. METHODS USED FOR CASUALTY ESTIMATION

In KoeriLossV2, following Petal (2003) and Erdik et al (2002), casualty rates among occupants at the time of the earthquake were proposed for 4 levels of injury severity and for each of 5 damage states, as shown in Table 3. LNECloss follows a similar approach, deriving casualty rates from HAZUS, adopted to the specific classes of buildings in the Lisbon building stock as needed. Table 3 shows those proposed for RC buildings, for comparison with the casualty rates proposed for KOERI loss.

In AUTHloss, the computation of casualties is estimated (following Coburn et al, 1992), as a function of the number of collapsed buildings, using assumed estimates of

- Occupancy at the time of the earthquake (depending on time of day)
- Percentage of occupants trapped by collapse (depending on level of shaking)
- Injury distribution at collapse (depending on class of building)
- Mortality post collapse (depending on class of building).

The full set of assumptions is shown in Spence et al (2008). For collapsed RC buildings, the given estimates lead to the expected casualty rates shown in the final column of Table 4, depending on the severity of the earthquake ground motion.

It is clear from Table 4 that substantial variation exists between the 3 models about the assumptions on casualty rates resulting from different damage levels. These are discussed in Section 6.3

Table 4 Casualty rate for Reinforced concrete structures used in the three models

	Injury Severity	Casualty Rates for RC structures (%)				
		Slight Damage	Moderate Damage	Extensive Damage	Collapsed	
					Partial	Total
KOERI	Moderate	0.005	0.02	0.5	8	15
	Severe	0	0	0.01	4	10
	Fatal	0	0	0.01	4	10
LNEC	Moderate	0.005	0.02	0.1	1	10
	Severe	0	0	0.001	0.01	2
	Fatal	0	0	0.001	0.01	2
AUTH	Moderate					5 to 16
	Severe					2 to 9
	Fatal					4 to 12

6. RESULTS AND COMPARISON OF THE THREE MODELS

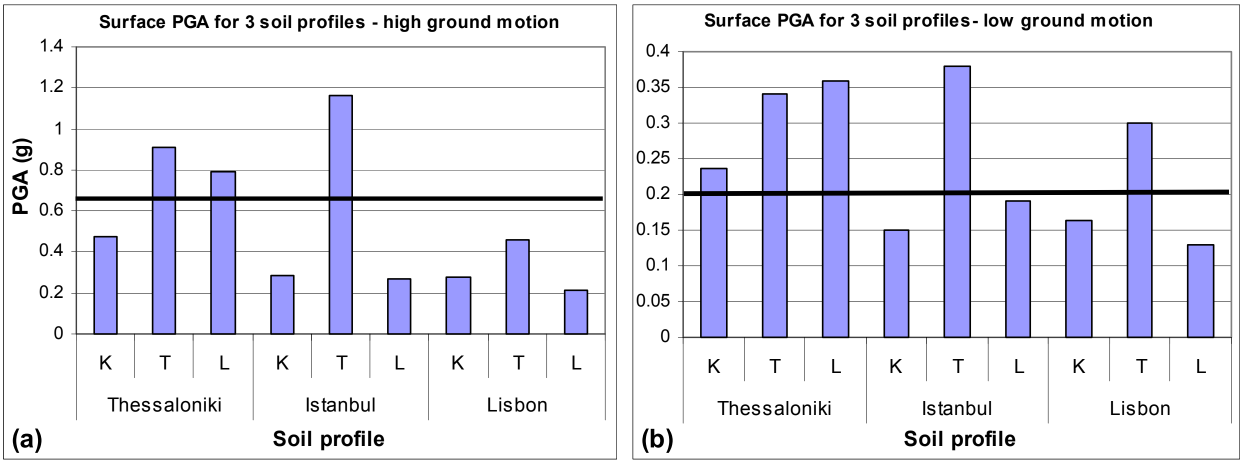
6.1 Comparison on the basis of surface PGA

Table 5 summarises the results compared on the basis of damage rates and casualty rates. Figures 2a and 2b show the comparisons on the basis of the estimated value of peak PGA for the high and low ground motion scenario associated with each of the three soil profiles Thessaloniki, Istanbul and Lisbon by each of the three modelling approaches KOERI (K), AUTH (T) and LNEC (L).

The variation in surface peak PGA values can be measured by the coefficient of variation (CoV) of values, averaged across the three soil profiles. For the S53 scenario, the average CoV ranges from 0.25 to 0.73 (average value 0.44) , while for the GBZ scenario it ranges from 0.17 to 0.42 (average value 0.32) For both ground motions, the largest range is associated with the Istanbul soil profile. This indicates a surprising level of uncertainty in the surface ground motion, even where common soil profiles are adopted; however a significant variation of values is to be expected given that the modelling approaches adopted were very different in the three cases (Section 3).

Table 5 Comparison of results; (K= KoeriLoss V2, T=AUTHloss. L=LNECloss, %Ns= %seriously injured, %Nd= % of deaths)

Ground motion	Soil profile		PGA	%>D1	%>D3	%D5	%Ns	%Nd
High S53_NS 0.65g	Thessaloniki	K	0.474	94.6%	57.6%	2.5%	1.75%	1.75%
		T	0.91	67.1%	36.8%	2.5%	0.40%	0.44%
		L	0.79	98.0%	61.9%	3.0%	0.03%	0.03%
	Istanbul	K	0.283	90.5%	37.0%	1.2%	0.96%	0.96%
		T	1.16	63.2%	41.0%	5.9%	1.12%	1.22%
		L	0.27	93.7%	82.6%	5.7%	0.10%	0.10%
	Lisbon	K	0.28	88.9%	32.3%	1.0%	0.84%	0.84%
		T	0.46	78.8%	25.2%	0.4%	0.03%	0.04%
		L	0.21	83.8%	47.1%	2.2%	0.05%	0.05%
Low GZ_NS 0.24g	Thessaloniki	K	0.237	76.7%	15.1%	0.2%	0.25%	0.25%
		T	0.34	77.5%	19.0%	0.2%	0.01%	0.01%
		L	0.36	81.0%	24.9%	0.8%	0.00%	0.00%
	Istanbul	K	0.149	54.9%	5.7%	0.0%	0.11%	0.11%
		T	0.38	78.7%	21.4%	0.3%	0.02%	0.02%
		L	0.19	84.1%	41.8%	1.6%	0.02%	0.02%
	Lisbon	K	0.163	64.3%	8.7%	0.0%	0.22%	0.22%
		T	0.3	75.6%	16.5%	0.2%	0.01%	0.01%
		L	0.13	52.1%	11.0%	0.2%	0.01%	0.01%



Figures 2 PGA values of surface ground motion for (a) S53 and (b) GBZ ground motion scenarios

Specific reasons for the variation may include the following:

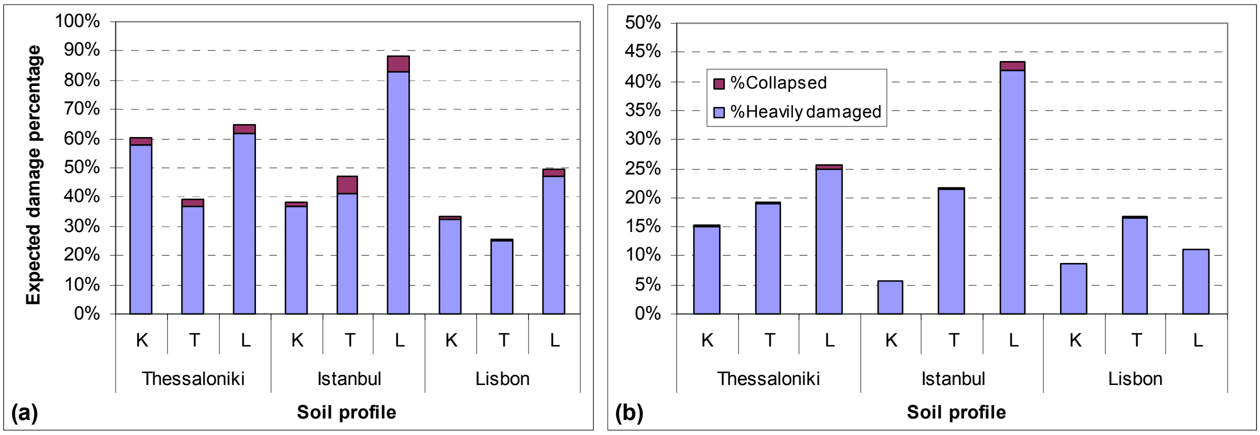
1. PGA does not give a complete or appropriate measure of the ground motion needed for spectral response analysis of buildings, and spectral response is important, particularly in the range of periods from 0.2 to 2

secs. As observed in the LNEC modelling method, the soil profiles of Lisbon and Istanbul change the frequency content, amplifying displacements and velocities and reducing acceleration, while the Thessaloniki soil profile amplifies all three.

2. The soil profiles were defined in a realistic rather than standardised way, and this has allowed differences in interpretation of the dynamic properties by the three groups.
3. The larger of the two input ground motions, with a PGA of 0.65g, turns out to be beyond the range which non-linear analyses can give reliable results, because of their dependence on the non-linear constitutive relationships adopted. This is particularly problematic when soils have a low shear-wave velocity as in the Lisbon case.
4. The LNEC works in the frequency domain, defining seismic motion as a power spectra density function of the input time history.

6.2 Comparison on the basis of building damage rates

Figures 4a and 4b show the comparison on the basis of percentage of heavily damaged and collapsed buildings for the two ground motion inputs.



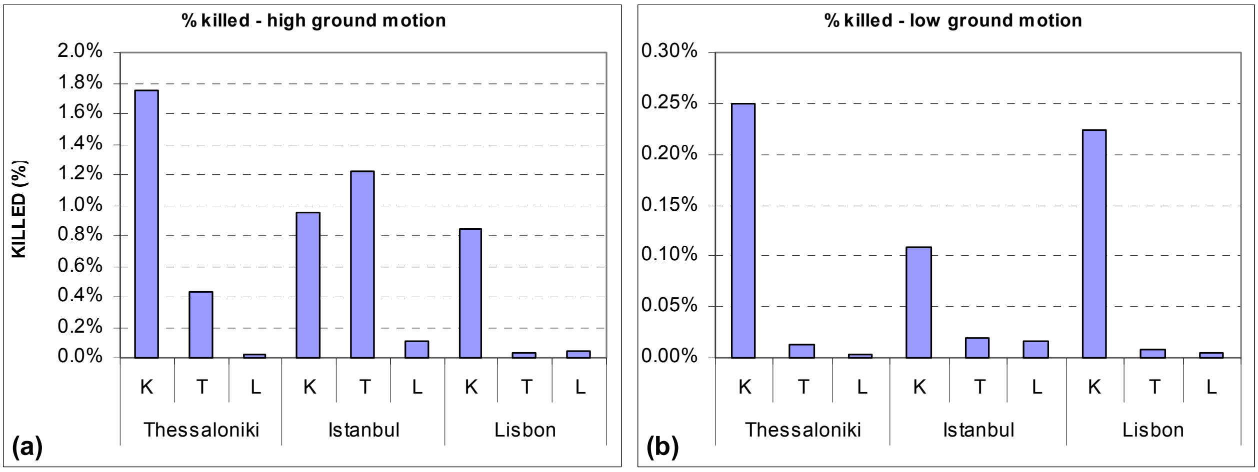
Figures 4 Expected percentages of heavily damaged and collapsed buildings in (a) S53 and (b) GBZ ground motion scenarios

For heavily damaged buildings, the average coefficient of variation is lower than for ground motion, 0.29 on the S53 scenario, and 0.37 on the GBZ scenario; in each case KoeriLoss V2 gives relatively lower values for losses for the Istanbul soil profile. For collapsed buildings, given the more marked differences of approach described in Sections 4, the average CoVs for the two scenarios are 0.41 (S53) and 0.86 (GBZ), with KoeriLoss V2 again giving the lower values. Variations in the rate of heavily damaged buildings are most marked with the Istanbul soil profile where they vary from 6% to 42% for GBZ and from 37% to 83% for the S53 ground motion. Variations in the rate of collapsed buildings are also most marked for the Istanbul soil profile, where they vary from 0 to 1.6% for GBZ and from 1.2% to 6% for the S53 ground motion.

Inevitably some differences of heavy damage and collapse rates will be observed, even given an equal surface ground motion input, because assumptions differ about the quality of the building stock made by the different groups. Also the comparison is not made on the basis of the same surface ground motion inputs, so bigger differences are expected. The relatively lower damage rates from the KOERI model are consistent with relatively lower PGA values.

6.3 Comparison on the basis of casualty rates

Figures 5a and 5b show the comparison of casualty rates between the 3 models for (a) S53 and (b) GBZ ground motion scenarios. As would be expected, given the differences in modelling assumptions, there are substantial variations for all ground motions and soil profiles. The average coefficient of variation is 0.95 for the S53 profile and 1.16 for the GBZ profile. In each case it is the Thessaloniki soil profile which produces the greatest range; the highest estimates are those produced by the KoeriLoss V2 model, and the lowest are produced by the LNEC loss model. Each of the three models uses the rate of collapsed and partially collapsed buildings as the basis for the casualty estimate, so the differences partly reflect the differences in the modelled proportion of collapsed buildings, already discussed.



Figures 5. Expected percentage of occupants killed in (a) S53 (above) and (b) GBZ (below) ground motion scenarios

However there are in addition very significant differences in the casualty rates per collapsed building. For example, KoeriLoss V2 assumes 10% for a totally collapsed building and 4% killed for a partially collapsed building (see Table 4). By contrast, LNECloss bases its estimates on HAZUS, and assumes only 2% killed for a collapsed RC building, and 0.01% killed for a partially collapsed building. AUTHloss ascribes losses only to the totally collapsed buildings, and estimates the proportion of occupants who eventually die (either after entrapment, or later) at 4 to 12% of the occupants of totally collapsed buildings, depending on the level of the ground motion. These very different assumptions reflect the evidence available locally of deaths and injuries in earthquakes, and an attempt to make the model fit the data available. In the KoeriLoss V2 model this relates to recent experience of casualties in the Kocaeli earthquake; but in Thessaloniki it relates to much more limited experience of events causing casualties in Greece, including the one fatal collapse in the 1978 Thessaloniki earthquake, while in the LNEC model there is no recent experience of earthquake fatalities, with the result that the HAZUS model, derived from California experience, has been adopted.

An attempt has been made to allocate the variation in the eventual casualty estimates to the different stages of the process. Assuming that the variances $(CoV)^2$ at each stage of the loss estimation are additive, it emerges that, of the variance on the estimated casualty rates, about 13% can be ascribed to the variance on the surface ground motion estimate, a further 24% to the variance on estimating the proportion of collapsed buildings, and the remaining 63% is the result of the variance on the method of estimating casualties.

There is no doubt that if the standard urban block described was in fact located in one of the three cities, local factors like building standards (and possibly earthquake awareness) would result in very significant differences in casualty rates, so this calculation is not one in which we are comparing like with like. However, the range of estimates is still very striking, and suggests the need for more research on each component of the calculation is needed, especially on the causes and rates of death and injury in building collapse.

7. CONCLUSIONS

Based on a standardised urban block containing a mixture of building classes and occupancy levels, using two different damaging ground motion time-histories and three standard soil profiles, a comparison has been made of the results obtained by three alternative modelling approaches described. The comparison has been presented in terms of the estimated surface ground motion, the estimated building damage and the estimated numbers of deaths caused.

For comparing surface ground motion, only PGA was available as a comparator, even though this is not the ground motion input used in two of the three models. Across the six scenarios the coefficient of variation across the three models averaged 0.38. For numbers of damaged buildings the coefficient of variation was 0.30, while for collapsed buildings it averaged 0.64. For casualty rates the variation is even more significant, with an average coefficient of variation between the models of 1.05. Of the variance on the estimated casualty rates, it has been roughly estimated that about 13% derives from the surface ground motion estimate, a further 24% from the building damage, and the remaining 63%from the method of estimating casualties.

The reasons for the differences have been discussed. They include both differences in interpretation of data, factors of local difference between the context in which the three models were developed, as well as the modelling methods themselves. The results give an indication of the importance of precise definition of the elements at risk being modeled (whether soil, buildings or people), and of the inherent epistemic (or knowledge) uncertainties which need to be considered in interpreting the results of such loss modelling.

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