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EVALUATING EARTHQUAKE LOSSES DUE TO GROUND FAILURE AND IDENTIFYING THEIR RELATIVE CONTRIBUTION

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SUMMARY

Earthquake-induced ground failure, in the form of liquefaction or slope instability, manifests itself as permanent ground deformation (PGD), which can cause significant damage to buildings and infrastructure. Current methodologies for the evaluation of ground failure related earthquake losses are considerably less advanced than those for ground shaking. Most existing damage scales do not incorporate foundation displacements caused by ground failure and there are few published fragility curves dealing with the damage distribution resulting from ground failure.

To incorporate ground failure into a loss model, there are two main options, either to use a simplified approach with a large number of assumptions and hence uncertainties, or a more detailed approach, requiring large amounts of data and analysis, and therefore expense. This paper highlights some important points relating to the choice of methodology. Firstly the relative contribution of the ground failure hazard in past earthquakes is compared to ground shaking-induced damage, both for direct and indirect losses. Secondly, some important uncertainties associated with existing methodologies are highlighted. The objective of this paper is to assist in making an informed and justifiable choice regarding the most appropriate methodology to use as well as the allocation of resources.

INTRODUCTION

The estimation of earthquake losses is becoming increasingly important for governments, businesses, insurers and reinsurers and private stakeholders. The catastrophic losses of the recent earthquakes of Northridge and Kobe (US$20bn and US$150bn respectively) illustrate the true potential for economic losses due to earthquakes. On a site-by-site basis, this problem is being addressed through the development of performance-based design methods, which allow building owners to specify more than just a life-safety level of design, and to define acceptable losses for different levels of earthquake hazard. With respect to the ground failure hazard, methods such as microzonation, improved land use planning and mitigation can be used to control these hazards for future developments. On a regional scale, however, it must be recognised that many existing developments will be vulnerable to earthquake damage, and the main objective of loss estimations is to evaluate the distribution and magnitude of these losses.

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As the many case studies mentioned in this paper will demonstrate, the occurrence of ground failure continues to be an important contributing factor to these earthquake losses.

The definition of the uncertainty relating to loss estimations is of fundamental importance. With respect to earthquake losses related to ground failure, as this paper will demonstrate, failure to incorporate this hazard can lead to inaccurate estimates, and even where it is incorporated there are significant uncertainties related to the methodology and results which must be recognised and, if possible, quantified.

Ground failure hazard needs to be considered within the context of other earthquake hazards facing the built environment, which include shaking, surface fault rupture, tsunami (Figure 1) and induced hazards such as fire or floods. Ground failure hazard refers to both liquefaction and landslide, which manifest themselves in the form of permanent ground deformation. In many earthquakes, the total losses result from a combination of two or more of these hazards.

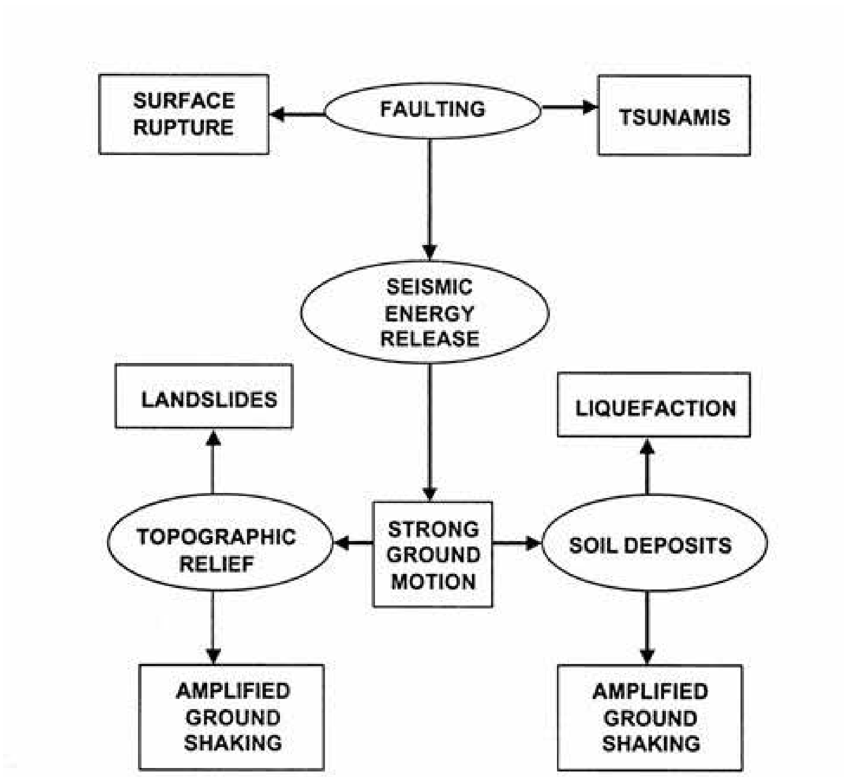

Figure 1: Seismic hazards facing the built environment (Bommer & Boore, [1]). ***Ground failure*** **refers to the hazards of landslides and liquefaction.**

EARTHQUAKE LOSSES DUE TO GROUND FAILURE

Studies of past damaging earthquakes provide a fundamentally important resource in the field of earthquake engineering. Lessons which have been repeatedly highlighted include the occurrence of liquefaction in loose cohesionless soils, and the failure of slopes with marginal safety factors.

In considering the relative contribution of the various hazards in Figure 1 to earthquake losses in past earthquakes, the different exposed elements in a built-up region must be considered, namely building stock, transportation (roads, railways, bridges and ports and harbours) and pipelines (power and water supply). Transportation, pipelines and critical facilities such as hospitals are together classified as lifelines: the components required for a community to function smoothly. Lifeline performance in an earthquake is of fundamental importance for the emergency response and post-earthquake recovery of a region (Lund [2]).

The authors reviewed field reports from numerous recent damaging earthquakes [3] in order to assess the relative contribution of ground failure to direct and indirect losses for each element

Earthquake database

The database comprised 50 earthquakes occurring since 1989, since it was established that since this time, field reconnaissance has focused reasonably consistently on the same features. Limiting the study period also reduces to some extent the variability of the affected building stock and infrastructure, although the global variations in building practice cannot be eliminated. Other than the time constraint, the database aims to be comprehensive and objective, comprising all damaging earthquakes for which published field reconnaissance was available.

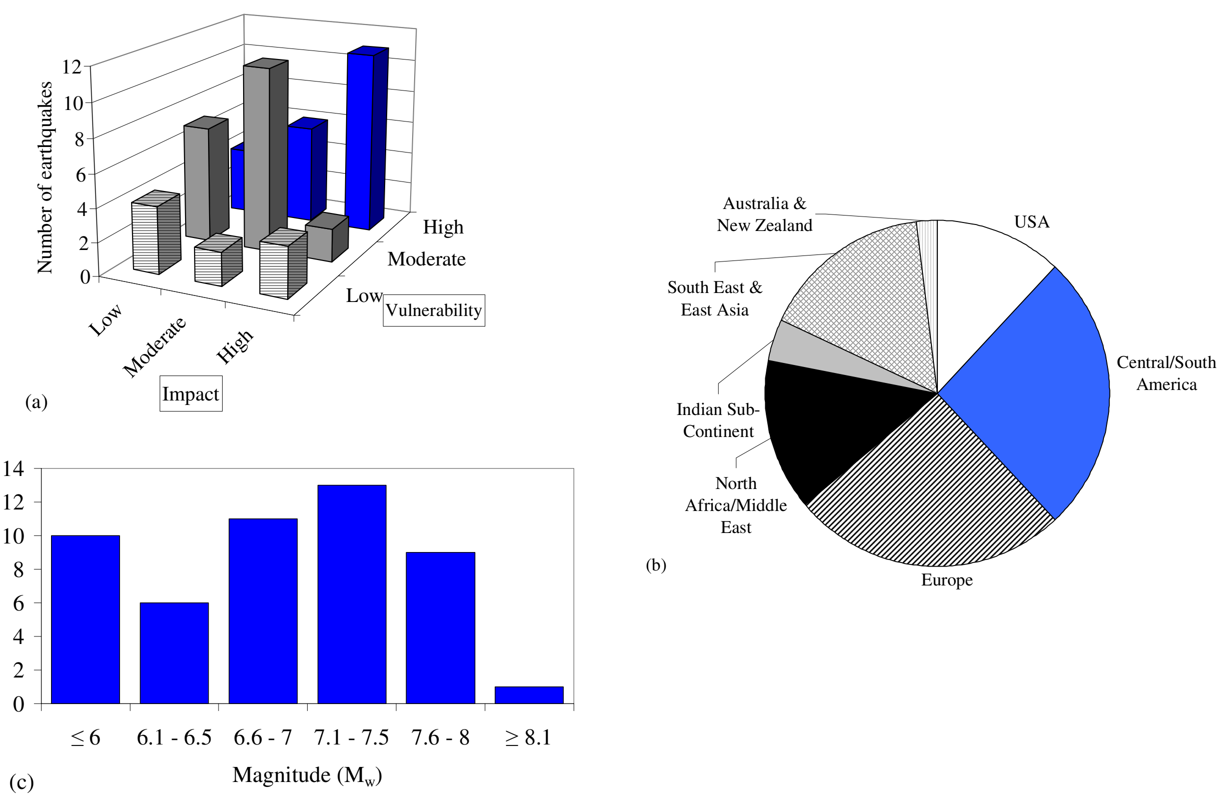

Figure 2: Variability within the earthquake database. (a) *vulnerability* (subjective rating based upon the degree of preparedness and the ability of the affected region to recover from an earthquake) vs. *impact* (the degree of damage and disruption and time taken to recover). (b) distribution of earthquakes by location. (c) distribution of earthquakes by magnitude.

The principle variations within the database were the magnitude, location, degree of damage and the vulnerability of the affected area (Figure 2). A further important variable was the quality and quantity of reporting and damage data, with some earthquakes having hundreds of published reports and papers, and others having only a few. Typically the more recent earthquakes are currently reported in less detail, since it takes some time for the analysis and dissemination of data to be completed and published, and earthquakes in less developed or economically significant regions were also less investigated. Due to the variability of available data, much of the comparison between events had to be done using a simplified scheme. For example, the damage or disruption to different exposed elements was rated using a three point scale of None, Moderate or High. For several earthquakes, such as Northridge (1994), Kobe (1995), Chi-Chi and Kocaeli (1999), the available information, including economic data, is very detailed, and this was considered separately. Table 1 lists the earthquakes in the database, and indicates which hazards were reported and which of these were reported to cause damage to the different exposed elements.

Earthquake damage caused by landslides

Catastrophic landslides are rare but extremely damaging occurrences, which claim massive loss of life and complete destruction of buildings in the affected area. In five of the earthquakes reviewed, massive landslides occurred which caused hundreds of fatalities, often destroying entire villages such as in the mountainous area around Baguio in the Philippines after the 1991 Luzon earthquake. Five further events also caused fatalities, but to a lesser extent. i.e. tens rather than hundreds, and these usually involved the collapse of one building in the path of a destructive landslide, such as the destruction of the Degirmendere Hotel in the 1999 Kocaeli earthquake (Bardet and Seed, [4]). Very few structures are designed to resist the magnitude of permanent ground deformation that a major landslide will generate. The January 2001 earthquake in El Salvador was a significant case study for landslide-induced damage, since landslides were the primary cause of the earthquake losses in the region, over and above the ground-shaking induced damage. A loss estimation considering only ground shaking induced losses in El Salvador would fail to realistically model the field observations.

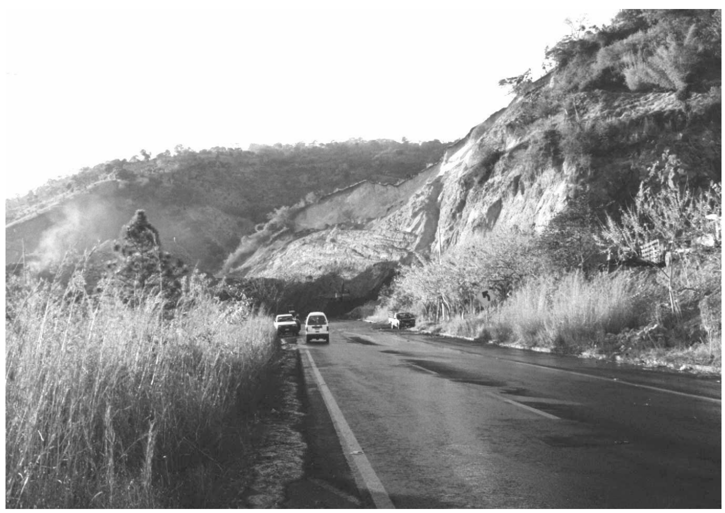

Figure 3: Major landslide at Las Leonas blocking the Pan American Highway, El Salvador, 2001.
Photograph: Julian Bommer, Courtesy EERI

Disruptive landslides, in the form of failures of road, rail or river embankments are more common than catastrophic events, occurring in 46% of the earthquakes in Table 1. There were five cases of major transportation routes being blocked, for example, in the Philippines in 1991, all four roads into the mountain city of Baguio were blocked by landslides causing significant delays to the emergency response operations. Transportation disruption was the most common consequence of these non-fatal landslides, in fact, transportation damage or disruption was the only reported damaging effect of landslides in 40% of the earthquakes in which they occurred.

Table 1: The 50 earthquake reviewed by the authors [3] indicating extent of damage to the main inventory elements as a result of each hazard shown in Figure 1.

No.	Name	Collateral Hazards	Buildings					Transportation					Utilities				
			FR	T	GS	SF	L	FR	T	GS	SF	L	FR	T	GS	SF	L
1	Loma Prieta, 1989	SF, L			●	●	○			●	●	○			○	○	○
2	Newcastle, Aus., 1989				●										○		
3	Manjil, Iran, 1990	FR, SF, L			●	●	●									○	○
4	Luzon, Phil., 1990	FR, SF, L	○		●	●	●				●	●	○		○	○	●
5	Augusta, Sicily, 1990				●												
6	Limon, CR, 1991	T, SF, L			●						○	●				○	●
7	Georgia, 1991	SF			●	○											
8	Erzincan, Turkey, 1992	SF, L			●		○			○	○	○			○		
9	Landers, USA, 1992	FR, SF	○		●						○		○		○		
10	Big Bear, USA, 1992	SF			●					○	○	○					
11	Cairo, 1992	L			●					○		○					
12	Flores Island, 1992	T, SF, L		●	○	○			●		○	○		●			
13	Hokkaido, 1993	T, SF, L		●	○	○	○		●		○	○		●			●
14	Guam, 1989	SF, L			●		○										●
15	Khalari, India, 1993	FR			●												
16	Northridge, US, 1994	SF, L			●	○				●	●				●	●	○
17	Paez, Colombia, 1994	SF			○	●											
18	Kobe, 1995	SF, L			●	○	○			●		●			●		○
19	Kozani-Grevena, 1995	L			●							○					
20	Sakhalin, 1995	L			●							○			○		
21	Aegion, Greece, 1995	SF, L			●		○					○					
22	Guerrero, Mex., 1995				●												
23	Dinar, Turkey, 1995				●										○		
24	Ecuador, 1995				●					○							
25	Manzanillo, Mex., 1995	T, SF, L		○	○		●		○		○	●		○			○
26	Gulf of Aqaba, 1995	SF, L			●						○	○					
27	Pujili, Ecuador, 1996	SF			●												
28	Nazca, Peru, 1996	SF, L			●						○	○					
29	Bojnool, Iran, 1997				●										●		
30	Ardebil, Iran, 1997	SF			●	●					○				○		
31	Ardekul, Iran, 1997	SF, L			○						○				○		
32	Cariaco, Ven., 1997	FR, SF, L			○							○			○	○	●
33	Umbria-Marche, 1997	SF			●						○						
34	Adana-Ceyhan, 1998	L			●		○			○		○					○
35	PNG, 1998	T		●					●					●			
36	Armenia, Col., 1999	SF			●						○				●		
37	Kocaeli, Turkey, 1999	FR, SF, L	○		●	○	●	●			○	○	●		●		●
38	Athens, 1999	L			●										○		
39	Chi Chi, Taiwan, 1999	FR, SF	○		●	●	●	●			●	○	●		●	●	●
40	Düzce, Turkey, 1999	FR, SF, L?	○		●			●		●	○					○	
41	El Salvador, 2001	SF, L			●	●	○				●	●			●		
42	Bhuj, India, 2001	SF, L			●					●		●			●		
43	El Salvador, 2001	SF			●										●		
44	Nisqually, USA, 2001	SF, L			●	○	○			○	○	○					○
45	Atico, Peru, 2001	T, SF, L		●	●				○		○	●		○			
46	Molise, Italy, 2002	SF			●						○						
47	Denali, Alaska, 2002	FR, SF, L			○		○					●	●		○		
48	Colima, Mexico, 2003	SF, L			●		○				○	○			○		○
49	Bingöl, Turkey, 2003	SF, L			●						○						
50	Boumerdes, Alg., 2003	T, SF, L			●					○		○					

FR = Fault Rupture; T = Tsunami; GS = Ground shaking; SF = Slope Failure; L = Liquefaction. Empty cell = hazard not reported, or reported but no mention of damage; ○ = minor or moderate damage reported, relative to overall damage; ● = major damage reported relative to overall damage.

The direct cost of transportation disruption compared to the total cost of earthquake damage tends to be relatively small. For example, the direct cost of repairing damage to roads following the El Salvador 2001 earthquakes was estimated at US$2.7 million, less than 1% of the total losses. Nonetheless, the impact of the long term closure of the Pan-American Highway (Figure 3) would have had significant consequences other than the direct cost of repair, both for immediate emergency response and the post-earthquake recovery of the affected communities and businesses.

Surprisingly few cases of landslide damage or disruption to utility lifelines (gas, power and water) have been reported over recent years. One notable exception was the landslide-induced damage to an electricity substation in Taiwan following the 1999 Chi-Chi earthquake, which contributed to the major power outages after the earthquake. In this particular case, the impact of the power disruptions was very far-reaching, causing a significant drop in technology stock prices on international stock exchanges as a result of the disruption to the semi-conductor manufacturing facilities (Schiff & Tang [5]). An important example of landslide induced lifeline damage and loss is the 1987 Ecuador earthquake, where over 40km of crude-oil pipeline was destroyed due to massive debris flows following the earthquake. The loss of revenue during the 5 months required to repair the pipeline was $800million; 80% of the total earthquake losses (Schuster [6]).

Non-damaging landslides were reported in many earthquakes in mountainous regions. Such events are important in advancing understanding of earthquake-induced landslide hazard. However, there is little to be learnt with respect to earthquake-induced losses since these landslides did not interact with the built environment in any way.

Earthquake damage caused by liquefaction

Liquefaction is a frequent occurrence in earthquakes, being reported in 31 of the 50 events in Table 1. It is important to note that there were no real surprises related to liquefaction occurrence in that back analyses, where undertaken, showed that liquefaction could have been predicted using state-of-the-practice methodologies. Direct evidence of the occurrence of liquefaction comprises sand boils and lateral spreading; indirect evidence can be obtained from observations of building response. The 1995 Kobe earthquake and the 1999 Kocaeli earthquake in particular provide unprecedented levels of data about the impact of liquefaction on urban environments.

Liquefaction-induced damage to buildings most commonly comprises foundation settlement or tilting (Figure 4), or lateral displacement. In such cases, there is often no significant structural damage to the building. Other building damage caused by liquefaction includes basement damage by sand ejecta, flooding of settled buildings or impact of tilted buildings on to their neighbours.

For loss estimations, losses are generally estimated in terms of the damage ratio, D_r, where:

$$D_r = \frac{\text{cost of repair}}{\text{replacement value}} \qquad (1)$$

A building which has suffered complete collapse will therefore have $D_r=1$. Damage ratios can usually be related to structural damage indices or damage state descriptions such as the EMS-98 scale (Grünthal, [7]) which defines damage in terms of cracking to structural members or collapse. The building in Figure 4 is suitable only for demolition even though it has not suffered complete collapse in the usual sense. However, there is currently no scale that relates the damage ratio or damage state to effects of ground failure such as settlement, tilt or lateral movement. There is a clear need for a damage scale that includes descriptions of tilted and settled buildings and allows these effects to be directly related to structural damage through consideration of the repair costs (Bird [8]).

Figure 4: Tilted building, Sedat Sokak, central Adapazari, 1999. ***Courtesy Earthquake Engineering Field Investigation Team (EEFIT), UK***

Figure 5: Liquefaction-induced damage of a technical school building damaged beyond repair after the 1999 Chi Chi earthquake. ***Photograph: Marshall Lew, Los Angeles Tall Buildings Structural Design Council***

Amongst liquefaction related hazards, lateral spreading has the greatest potential to destroy buildings. Buildings at greatest potential risk have poor, shallow foundations and are located on or near to a slope or free face in an area of liquefiable soils. Figure 5 shows a school building located next to a river bank, which was damaged beyond repair due to non-uniform settlement and lateral spreading during the Chi-Chi earthquake (Lew *et al*. [9]).

Of the 31 earthquakes where liquefaction was reported, damage to structures as a result of settlement, tilt or lateral spread, was reported in 14. Within these 14, nine reports were of isolated cases or very small zones of building damage, such as the damage to one airport in Alaska in 2002, or the damage to a small number of buildings in coastal and lakeside areas in the 2001 El Salvador earthquakes. Even in Kobe, in 1995, despite the widespread occurrence of liquefaction, few buildings were seriously affected, mainly due to their piled foundations. In the context of regional damage or losses, liquefaction related damage to buildings has only been significant in 10% of the recent earthquakes.

There is a clear relationship between poor foundations and building damage due to liquefaction. Piled buildings such as those in Kobe generally suffer the least damage. Stiff, well-reinforced, tied or mat foundations will tend to lead to rigid body rotation (Figure 4), whereas isolated pad footings are at risk of settling differentially, or settling away from non-load bearing walls (Figure 5).

Liquefaction-related transportation disruption can result from two causes: damage to road pavements or railway tracks due to settlement or lateral spreading, or damage to bridges. The first is very common, but generally comprises minor damage, easily repaired at relatively low cost. In some cases the damage is not minor; for example in Costa Rica in 1991, approximately 30% of the highway network in the affected area was disrupted due to liquefaction (Youd [10]). Bridge embankments are vulnerable to lateral spreading damage due to the presence of susceptible river channel deposits plus a sloping or free face. Minor damage to bridges due to ground deformation was reported in almost half of the earthquakes where liquefaction occurred, the most common form being settlement of approach embankments, which is easily repairable. In four earthquakes, collapse or partial collapse of bridges occurred due to liquefaction-induced movement (Figure 6).

Figure 6: Collapse of the Magsaysay Bridge in Dagupan, after the 1990 Luzon earthquake. ***Courtesy Earthquake Engineering Field Investigation Team (EEFIT), UK***

Another significant consequence of liquefaction is the damage to ports and harbours, which tend to be very vulnerable due to the combination of man-made fill and high water tables. The most significant liquefaction related losses reported in any earthquake were in Kobe in 1995, when direct losses of US$1 billion dollars were incurred due to the almost complete destruction of the Port of Kobe as a result of liquefaction of reclaimed soil.

Buried utilities are also vulnerable to liquefaction-induced permanent ground deformation and numerous cases were identified by the authors of breakage of buried gas or water pipes in liquefied zones. Although not reported in any recent earthquakes, a potentially catastrophic consequence of this is the outbreak of fire, which can be triggered by ruptured gas pipes, and can spread rapidly if water supplies are interrupted. A less catastrophic but nonetheless financially significant effect of pipeline damage is the business interruption due to utilities disruption.

Comparison of ground failure- and ground shaking-induced damage

The above discussion has concentrated on the damaging effects of earthquake-induced ground failure, of which there are many significant examples. Nonetheless, the relative contribution of ground failure compared to ground shaking is extremely important when defining a methodology for a risk or loss assessment. Some key points regarding the relative damage caused by different hazards from this review of recent damaging earthquakes include:

- In 72% of the earthquakes, all fatalities were related to ground-shaking induced building damage and collapse.

- In 44% of the earthquakes, ground shaking was the *only* hazard which caused any damage to buildings, i.e. in 56% building damage was a result of two or more hazards.
- Landslides caused massive damage and casualties in 10% of the earthquakes.
- Tsunamis caused widespread damage and casualties in 6% of the earthquakes.
- Liquefaction and fault rupture caused significant building damage in 28% and 8% of the earthquakes respectively. In all of these cases, ground shaking damaged a greater number of buildings.
- Significant transportation disruption occurred in 12 earthquakes, related to major landslides or bridge collapse. Bridge collapse was caused by ground shaking, fault rupture and liquefaction i.e. no single hazard was dominant.
- Significant utilities disruption occurred in 15 earthquakes, of which nine cases were related to ground shaking induced damage to plants and facilities. The other six cases were related to fault rupture or liquefaction.

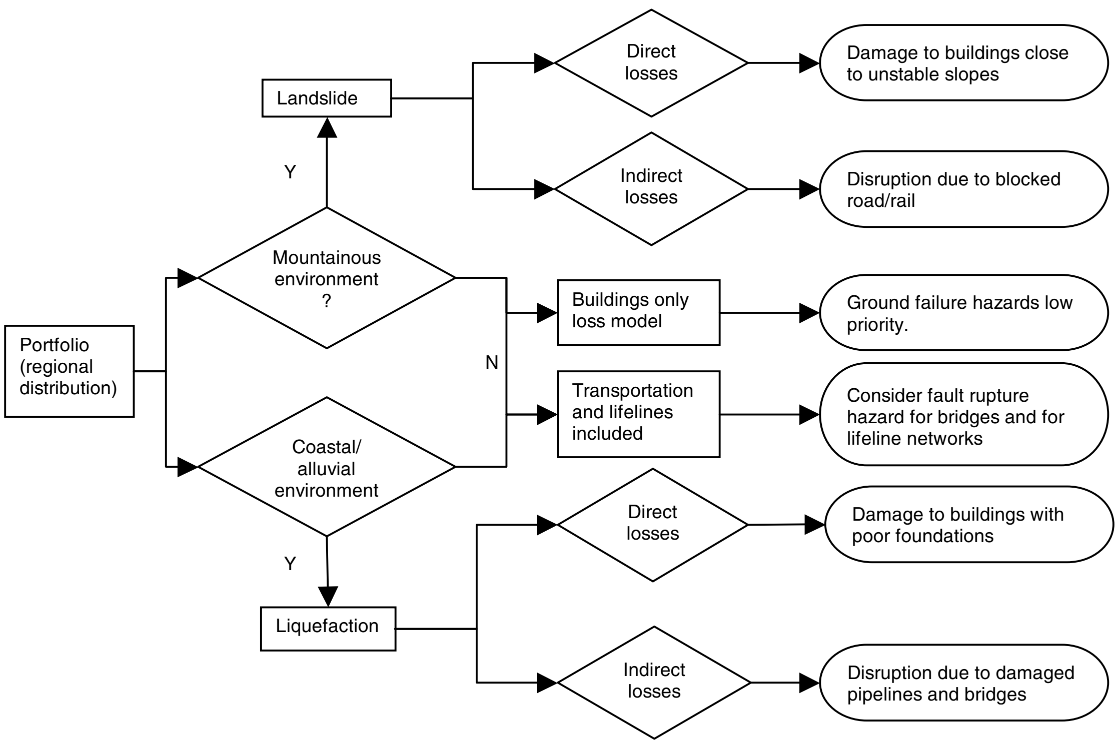

Figure 7: Simplified decision tree shows some of the key factors that will influence the selection of hazards to be included in a preliminary risk or loss assessment. For a single site loss model, it is expected that ground failure would always be included. Other factors not included in this figure include: quality of available data, time and resources available, knowledge of foundation types and end user of loss results

The following preliminary conclusions are made for guidance in determining the most appropriate loss modelling procedure, summarised in Figure 7:

- Considering an entire affected region, there are very few cases where ground shaking does not dominate the damage distribution after an earthquake, particularly for building damage. A notable exception to this rule is tsunami damage, which has the potential to overshadow all other hazards and merits separate consideration in areas of tsunami hazard.

- For smaller survey areas, there is a greater potential for a secondary hazard (liquefaction, landslide or fault rupture) to dominate the damage pattern, and to fail to consider these hazards will lead to an incorrect result.
- For consideration of transportation and lifeline systems and the indirect losses to businesses, individuals and governments that will result from their damage, it is essential to consider landslide- and liquefaction-induced damage.

ESTIMATING EARTHQUAKE LOSSES DUE TO GROUND FAILURE

The first part of this paper made some preliminary recommendations as to when the incorporation of ground failure into a risk or loss assessment is of particular importance. Further to this, it is necessary to consider the various options for such studies, and their associated shortcomings and uncertainties.

Existing methodologies

The main options available to loss modellers with respect to incorporating liquefaction ground failure are summarised in Table 2, below. This discussion focuses on liquefaction, although many of the issues also relate to slope failures.

Table 2: Options for including liquefaction in a loss estimation study

Method	Advantages	Disadvantages
Ignore liquefaction	No additional data or analysis required.	Incorrect damage distribution, particularly for small areas or lifeline/transportation losses
Assign soil class with highest amplification to any liquefiable soils	Very small amount of extra work needed.	Damage estimation still looks at shaking-induced damage only
Use published methodology such as HAZUS [11]	Small amount of additional input data compared to final option, below.	Many assumptions and uncertainties necessary for simplification.
Detailed analysis using in situ geotechnical data.	Reduces uncertainties. Specific to study region. Up to date.	Very demanding of time and expense.

The HAZUS methodology, developed by FEMA [11], has made a significant step forward in terms of incorporating ground failure into loss models, without requiring the large volumes of data and analysis of the final method in Table 2. HAZUS is a GIS-based program, intended for both local government and private users throughout the US. It provides comprehensive databases and methodology for regional loss estimation and emergency planning. HAZUS, or particular aspects of it, has also been widely adopted for loss estimations outside the US, due primarily to the lack of any openly available alternatives developed to such a high level (e.g. Bommer *et al*. [12]; Loh *et al*. [13]).

There is a danger that the more often the methodology is uncritically applied, the more the uncertainties are camouflaged, even though it is acknowledged in the foreword to the HAZUS manuals that there are still significant uncertainties associated with the results and that it '*should be regarded as a work in progress*' [11]. Nonetheless, the fact that it is so widely used demonstrates a strong need for such a methodology, which is both standardised and simple to use.

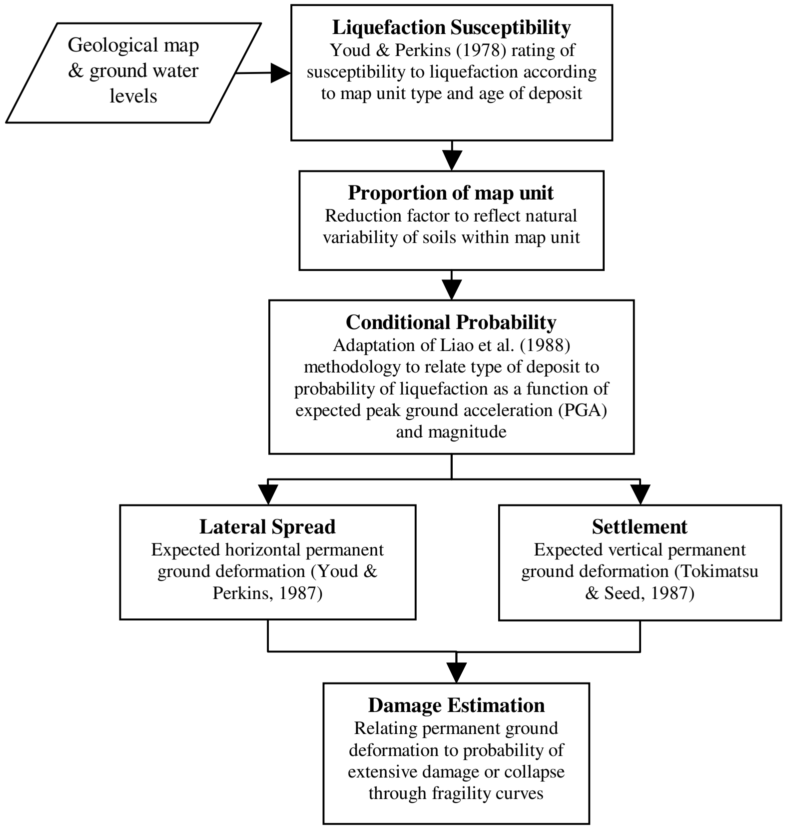

Figure 8: The HAZUS methodology for estimating building damage due to liquefaction

The ground failure component of HAZUS is summarised in Figure 8. The user input required is a map, defining the susceptibility of surface soil deposits to liquefaction according to the methodology of Youd & Perkins [14] from None to Very High. The first four stages in Figure 7 produce a probability of liquefaction for a scenario earthquake event, and an estimated 'permanent ground deformation' (PGD) at the ground surface. Simplified fragility curves, relating PGD to damage distribution, have been presented in HAZUS (e.g. Figure 9). The only distinction made with respect to building classifications is between shallow and deep foundations.

The final estimation of damage state in HAZUS considers the combination of ground shaking and ground failure, where for example, the probability of building collapse is assumed to be:

$$P(DS \geq C) = P(DS \geq C)_{GS} + P(DS \geq C)_{GF} - P(PS \geq C)_{GS} \cdot P(DS \geq C)_{GF} \qquad (2)$$

where P(DS≥C) is the probability that the damage state is greater than or equal to *complete* (equal to 100% loss); *GS* signifies damage due to ground shaking and *GF* signifies damage due to ground failure. Equation 2 is based upon two assumptions; the first being that the probability of collapse due to shaking is not affected by the probability of collapse due to ground failure and the second that any damage state will be attained due to one or other hazard, but not due to a combination of both.

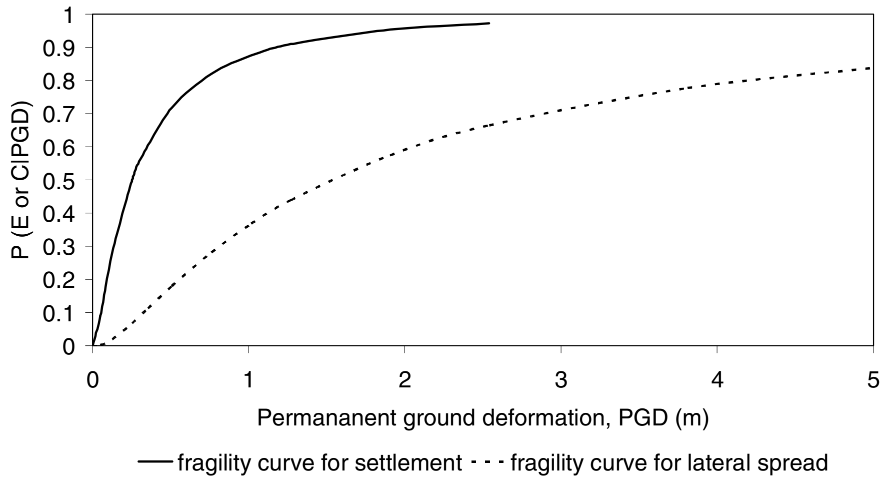

Figure 9: HAZUS fragility curve for all buildings with shallow foundations on failed ground (liquefaction or landslide). Probability of extensive or complete damage states due to permanent ground deformation (PGD). P[E or C|PGD] is the probability of extensive or complete collapse for a given permanent ground deformation (PGD).

Uncertainties related to the HAZUS approach

The main advantage of the HAZUS liquefaction methodology is that it does not require any site specific input data. Many loss models have to be based upon very crude data, even for fundamentally important variables such as the building type and location. Since the only additional input required in HAZUS to estimate the damage due to liquefaction is a geological map defining the relative susceptibility of surface soils, it is possible to add in this component without generating significant extra work, which can be very important. Nonetheless, there is still some work required to define the susceptibility of the soils, and these definitions are unrelated to the NEHRP soil classifications used to determine soil amplification. Therefore the balance between the additional input data and the resulting improvement in the model needs some consideration. Each step in the HAZUS methodology shown in Figure 8 is based upon some assumptions and simplifications. The calculation of the probability of liquefaction and of the permanent ground deformation are both based upon empirical relationships which relate the strength of ground shaking to the in situ density of the soil, usually defined by a standard penetration test (SPT) blow count. Therefore, although this data is not required as input, an assumed value is implicit in the calculations, as is a depth and thickness of the liquefiable layer, with no allowance for the uncertainty related to these parameters.

However, of much more importance is the uncertainty related to the estimation of the damage state, shown in Figure 9. These relationships are based on a number of assumptions, namely that:

- The only variable that influences the damage due to permanent ground deformation is whether foundations are *shallow* or *deep*.
- Buildings damaged by ground failure will be either undamaged or at least extensively damaged. In between damage states are assumed to be caused largely by ground shaking damage.
- Lateral movement has to be many times greater than vertical movement to cause the same degree of damage.
- The worst case of lateral or vertical movement should be used to estimate the damage, and lateral movement has the same damaging potential whether it is due to liquefaction or slope failure.

It seems that a large amount of judgement has been used to develop these relationships, which although understandable in the absence of much empirical data in this field, certainly requires further consideration. In the light of the earthquake review presented in the first part of this paper, the following points are noted with respect to the relationship between building damage and ground failure:

- The damage scale used in HAZUS describes damage to buildings in terms of the extent of structural damage, cracking or collapse. There is no correlation between this scale and the type of damage most commonly observed in areas of liquefaction, which is uniform settlement or tilt of buildings.
- The methodology estimates permanent ground deformation in terms of vertical or lateral movement, but makes no attempt to relate this to the building response, a tilted building requires much greater repair than a uniformly settled building.
- From field observations, buildings which have undergone settlement or tilt would frequently be classified as *slightly* or *moderately* damaged, in that some degree of repair is required, but overall the buildings are repairable so the use of only two damage states in HAZUS is probably an over-simplification.
- The foundation type has been observed in many cases to be fundamentally important with respect to the building response to ground failure, and ideally an adequate number of classifications should be used to reflect this.
- Depending on the foundation type, lateral movement can potentially be equally as damaging as vertical movement, as in the example in Figure 5.
- There are many differences between the response to liquefaction-induced ground failure and landslides and it may be more appropriate to separate the two, particularly since liquefaction impact will always be local whereas landslides may impact at some distance.
- Variables other than the foundation type, including the building height, aspect ratio (height/foundation width) and proximity to other buildings, have been observed to influence the response to liquefaction.

Despite the above points, it is fully appreciated that the simplified HAZUS methodology is a response to a clear need for a simple methodology that requires reasonable quantities of input data and is relatively easy to put into practice. Loss estimations are not, after all, intended to reproduce with engineering detail the expected consequences of an earthquake. The objective of the issues raised herein is intended to highlight the uncertainties associated with such a simplified methodology so that they can be quantified and reduced in future studies.

Methodology using in situ geotechnical data
Many of the uncertainties related to the HAZUS default approach can be reduced through specialist analysis using liquefaction evaluation techniques based upon site specific SPT, CPT or V_s measurements and empirical relationships; this is referred to as the 'expert-generated' approach in HAZUS. This will require large volumes of data, which are not always available, and often prohibitive time and effort in their collation and computation. Although the increased costs are significant, there will be many cases where this approach is the only justifiable option for studies outside the US, due to the reliance of the HAZUS methodology on empirical relationships developed for the western USA [15], [16], [17].

Uncertainties relating to the probability of liquefaction and the expected permanent ground deformation can be reduced or at least quantified where there is more detailed information available. The susceptibility of the surface soils can be defined according to the recommendations of Youd & Perkins [11], as in the first step of the HAZUS methodology. The volume of data can thus be reduced to some extent by only carrying out detailed analyses for the High and Very High susceptibility categories (e.g. Pappin *et al*. [18]). It is important to note that with the use of in situ geotechnical data there would remain unresolved issues for the relationship between ground settlement or lateral spreading and building damage. These uncertainties can only be reduced with detailed information on the foundation type, combined with analysis and empirical relationships.

CONCLUSIONS AND RECOMMENDATIONS

This paper has presented a summary of a review of recent damaging earthquakes, focussing on the damage potential of ground failure hazards such as liquefaction and landslides. A brief summary of the available methodologies for the prediction of these types of losses was presented, with the comments as to the appropriateness of these approaches in the light of the field data. The principle conclusions and recommendations are given below:

- For a regional loss model, seeking a preliminary estimation of building damage only, in most cases it will be sufficient to consider ground shaking hazard only, since in 86% of the earthquakes reviews, ground shaking dominated the regional damage distribution.
- For smaller study areas, it is necessary to consider the influence of secondary hazards such as liquefaction, landslide or fault rupture on the estimated losses, in 46% of the earthquakes these hazards caused notable damage.
- Tsunamis are a rare but highly damaging occurrence which warrant separate consideration.
- For loss models where a reasonable estimation of either transportation or lifeline system losses is required, either for the system managers, for emergency response planning, or for the purposes of estimating business interruption losses, ground failure hazards can be very significant.
- The introduction of the ground failure component creates an additional layer of uncertainty in a loss model, between the uncertainty related to strong-motion prediction and that related to building vulnerability models.
- The common lack of detailed data for regional loss studies means that simplified approaches which do not require large amounts of data collection are required. HAZUS [10] is one of the few methodologies that satisfies this requirement without ignoring ground failure. However, the uncertainties associated with this approach are large and not well defined, and caution is advised in its application, particularly outside the US.
- Even where more detailed data is available, the uncertainties cannot be eliminated, there is a need for further work to better define the relationships between permanent ground deformation and building response and damage levels.
- Specifically there is a clear need for a unified damage scale that relates both structural damage and foundation damage to a damage state and therefore a repair cost, and there is a need for improved capacity and fragility curves for the ground failure components. Without these, the uncertainties associated with estimating losses due to ground failure are so significant that it is difficult to perceive the benefits of introducing this feature into a loss model.

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