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THE GROUND FAILURE COMPONENT OF EARTHQUAKE LOSS ESTIMATIONS: A CASE STUDY OF ADAPAZARI, TURKEY

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SUMMARY

Widespread ground failure and associated damage to buildings were observed in Adapazari following the 1999 Kocaeli earthquake. The subsequent building damage survey and extensive geotechnical investigations have highlighted important lessons in the field of liquefaction engineering. In this paper, survey data are used to examine issues relating to earthquake loss estimations in areas susceptible to liquefaction.

Current methodologies such as HAZUS (FEMA, 1999) are reviewed and compared to the observations from Adapazari. Some uncertainties are illustrated through comparison of predicted and observed building damage in liquefied zones. The significance of these uncertainties is compared to other components of loss estimation methodologies (e.g. ground motion estimation; building vulnerability).

Finally, some recommendations for future loss estimations in similar regions are presented. These include the need for a unified damage scale, encompassing both ground shaking induced damage and ground failure induced settlement or tilt of buildings, and the need for a more rigorous approach to modelling building vulnerability to liquefaction, incorporating building aspect ratio and foundation type.

INTRODUCTION

Adapazari, in Turkey suffered the greatest loss of life and damage of all the cities affected by the August 17, 1999 Kocaeli earthquake. One of the most notable features of the damage was the widespread occurrence of ground failure. Many buildings failed as a result of excessive foundation settlement, tilting or sliding. The building damage and the ground conditions in central Adapazari have been extensively investigated over the past five years and some important lessons have been learnt.

This study uses building damage and geotechnical survey data from Adapazari to assess the implications for earthquake loss estimation studies in similar regions. A building that has settled or tilted excessively

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(e.g. see Figure 1) would be demolished after the earthquake, and therefore the repair costs will be equal to the replacement value in the same way as for a structure which has collapsed due to strong ground shaking. However, fatalities, injuries and contents losses may be less for the building in Figure 1 than for a collapsed building. Business interruption losses on the other hand would be just as great. For building owners, insurers or government bodies requiring an accurate picture of expected future earthquake losses, it is evident that the presence of liquefiable soils can affect the nature and distribution of these losses.

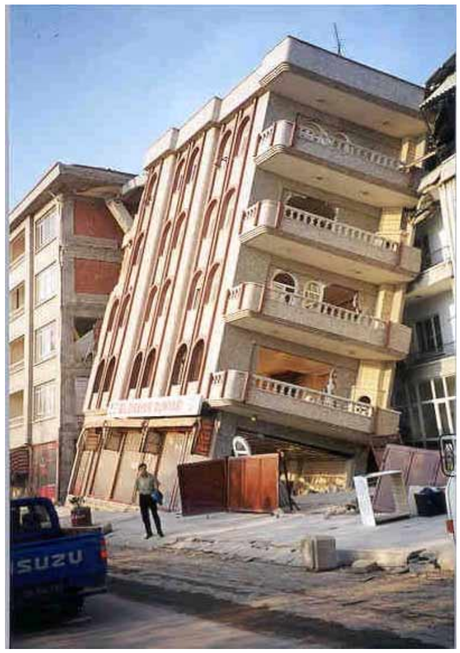

Figure 1: Tilted building due to liquefaction in central Adapazari. ***Courtesy Earthquake Engineering Field Investigation Team (EEFIT), UK***

Post-earthquake field investigations from recent damaging earthquakes around the world, such as Loma Prieta (1989), Luzon, Philippines (1991), Kobe, Japan (1995), Kocaeli and Chi-Chi, Taiwan (1999), clearly show that ground failure continues to be a significant hazard in some environments. In downtown Adapazari, the occurrence of ground failure has the potential to dominate the earthquake damage distribution. To provide an appropriate model of the post-earthquake losses and consequences in such zones, it is therefore necessary to incorporate the effects of liquefaction. This paper presents some of the lessons that can be learnt regarding the incorporation of ground failure, specifically liquefaction, into loss estimation methodologies, making use of the wealth of field data from Adapazari.

ADAPAZARI POST-EARTHQUAKE SURVEYS

The post-earthquake building damage survey for central Adapazari, coupled with the subsequent detailed geotechnical investigations, provide an ideal opportunity to examine the behaviour of a liquefied urban zone.

Geotechnical Investigations

An extensive geotechnical investigation consisting of soil borings with the implementation of the standard penetration test (SPT) and cone penetration tests (CPT) was carried out in Adapazari to investigate the subsurface conditions at sites where ground failure was or was not observed (Bray *et al*. [1]). 90 CPTs and 14 soil borings were performed along the lines surveyed as part of the post-earthquake reconnaissance effort discussed by Bray and Stewart [2] in order to develop the subsurface data required to identify geotechnical causative factors for the observed structural damage and ground failure indices. Most of the site investigation was limited to a depth of 10 m, but some CPT profiles and soil borings were extended deeper to characterise soils to depths reaching down to 30 m. Full details of this site investigation program are presented by Bray *et al*. [3].

Four typical soil profiles were developed to characterise the subsurface conditions along four lines that traverse four central districts of the city. A correlation was found between the manifestation of ground failure at building sites and soil profiles that were susceptible to liquefaction. Local variations in the characteristics of alluvial sediments in Adapazari appear to have played an integral role in the occurrence and non-occurrence of ground failure and associated building damage (Sancio *et al*. [4]). The degree of ground failure observed in the study area appears to have been principally controlled by soil condition, with ground failure occurring in zones that are susceptible to liquefaction. Ground failure was largely absent from areas having soils that are too clay-rich to be considered liquefiable.

Sancio *et al*. [4] did not find clear evidence that the type of structures significantly influenced the degree of ground failure. However, the localization of observed settlements around buildings, the relative infrequency of observations of liquefaction in open fields, and the higher rate of severe ground failure for buildings with a high height-to-width aspect ratio suggests that ground strains associated with soil-structure interaction may have contributed to the triggering and severity of ground failure.

Building Damage Survey

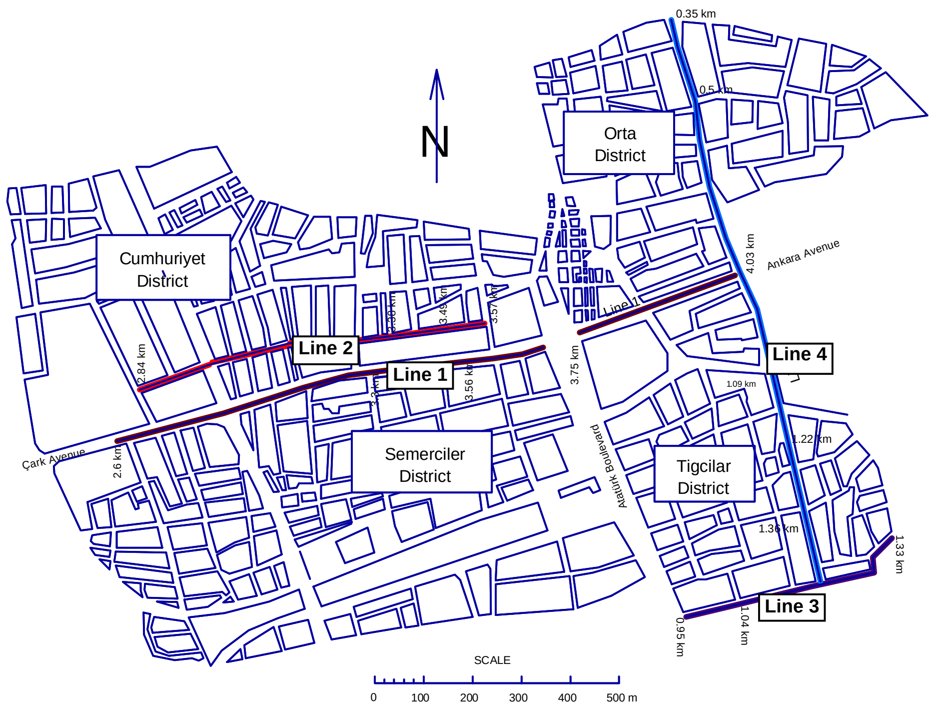

Figure 2: Map of central Adapazari showing portions of survey lines 1 to 4 (after Sancio *et al*. [4]).

Bray and Stewart [2] carried out a survey of building damage in Adapazari within three weeks of the Kocaeli earthquake. The survey covered four lines throughout Adapazari and recorded, on a building-by-building basis; the number of storeys, the presence of basements, the type of building, the amount of structural damage, and the degree of settlement, tilt, or lateral movement. The degree of structural damage was rated using an index originally presented by Coburn and Spence [5] (Table 1), which categorizes damaged buildings according to the extent of cracking and deformation. The locations of the survey lines in central Adapazari are shown in Figure 2.

Damage Scales

The manifestation of ground failure was most commonly in the form of uniform or differential settlement of foundations (e.g. Figure 1). Frequently, in these cases, there was no evidence of building damage and therefore the Ground Failure Index (Table 2) defines the distribution and severity of the foundation damage [2]. Surveyors who attempt to incorporate building tilt or settlement into existing building damage scales such as Table 1, currently do so with a high degree of subjectivity, and whilst they may be correct in identifying a building which is beyond repair due to excessive tilt, the intermediate damage states are much more difficult to define. There is often a large degree of uncertainty in the interpretation of survey results from zones of ground failure. In Adapazari, the two scales defined in Tables 1 and 2 were applied objectively and independently, thus creating an invaluable database of the two types of failure, without which it would be impossible to determine the interaction between ground failure, structural damage, and ground conditions. However, there were numerous cases where it was impossible to apply the ground failure index, because collapsed buildings obscured foundation behaviour. Nonetheless, the use of the Ground Failure Index, [2], in combination with the structural damage index [5], is strongly recommended for future earthquake investigations.

Table 1: Structural damage index of Coburn & Spence [5], adopted for the Adapazari damage survey by Bray & Stewart [2]. The final column shows damage descriptions used in the loss estimation calculations described herein, and their approximate correlation to the survey data

Structural Damage Index	Description	Descriptive term
D0	None; No observable damage.	None
D1	Light damage; architectural damage only	Slight
D2	Moderate damage; some cracks in load-bearing elements	Moderate
D3	Heavy damage; cracked load-bearing elements with some deformation across the cracks	Extensive
D4	Partial collapse; collapse of a portion of the building	Complete
D5	Collapse; complete collapse of a structure or loss of a floor	Complete

The structural damage index defined in Table 1 is more or less directly related to the building repair or replacement costs, in that D0 correlates to zero repair costs and for D4 and D5 the losses will be equal to the full replacement cost. The intermediate damage states can be approximated to a percentage of the full replacement costs. This is the approach used in loss estimation models. The GF Index does not directly relate to the building repair costs, and the structural damage index does not include foundation failure. In order to include losses due to ground failure in loss models, there is a clear need for a unified damage scale which relates the degree of ground failure to the repair cost of the structure by aligning the damage descriptions of Tables 1 and 2.

Table 2: Ground Failure Index [2]

Index	Description	Interpretation
GF0	No observable ground failure	No settlement, tilt, lateral displacement, or boils
GF1	Minor ground failure	Settlement, $\Delta < 10$ cm; tilt of > 3-storey buildings < 1^{o}; no lateral displacements
GF2	Moderate ground failure	10 cm < Δ < 25 cm; 1^{o} < tilt < 3^{o}; small lateral displacements (< 10cm)
GF3	Significant ground failure	Δ > 25 cm; tilt > 3^{o}; lateral displacements > 25 cm

Damage distributions in central Adapazari

Almost 2% of the population of Adapazari died as a result of the earthquake, and some 12% of the city's buildings suffered heavy damage or collapse [6]. Close proximity to the fault rupture (7km) and deep alluvial sediments beneath the city centre contributed to the catastrophic damage. Visible structural damage was in the form of cracks, deformations or collapse (Figure 3); and foundation damage was in the form of uniform or differential settlement, often accompanied by bulging of foundation soil (Figure 4) or occasionally, lateral foundation displacements of up a metre.

Figure 3: View of damaged buildings along Çark Avenue (Line 1, Figure 2) *Courtesy Earthquake Engineering Field Investigation Team (EEFIT), UK*

Figure 4: View of ground failure in Adapazari, Bray & Stewart [2]

The damage survey by Bray & Stewart [2] included reinforced concrete (RC) frame buildings, timber frame with brick infill, timber, and unreinforced masonry (URM) buildings. For simplicity, this study considers only RC frame buildings, of which there were almost 600 surveyed. Figure 5 summarises the survey data. There were a greater number of low-rise buildings (1 to 3 storeys) in the lower damage states, and more mid-rise buildings (4 to 7 storeys) suffering either *extensive* or *complete* damage. The distribution in Figure 5 reflects the particular vulnerability of mid-rise RC frame buildings in the Kocaeli earthquake, due to their poor construction, often with storeys added after the initial completion of the structure, the presence of soft storeys, and the possible coincidence of their fundamental frequencies with the dominant frequency of the ground shaking.

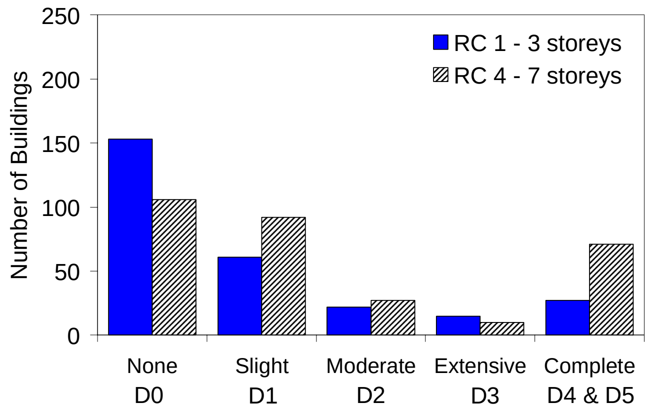

Figure 5: Distribution of building damage to RC frame buildings in central Adapazari survey zone. See Table 1 for definitions of damage states

Figure 5 compares the Adapazari damage data with survey data from Gölcük coastal zone and an area of Izmit. Features of each survey zone are briefly compared in Table 3.

Table 3: Features of surveys compared in Figure 4

Survey Zone	Survey teams	Fault Distance (km)	Typical soil conditions
Adapazari	Bray & Stewart [2]	7	NEHRP D/E
Gölcük Coast	AIJ [8]	1	NEHRP D
Izmit	EEFIT [9]	4.5	NEHRP D

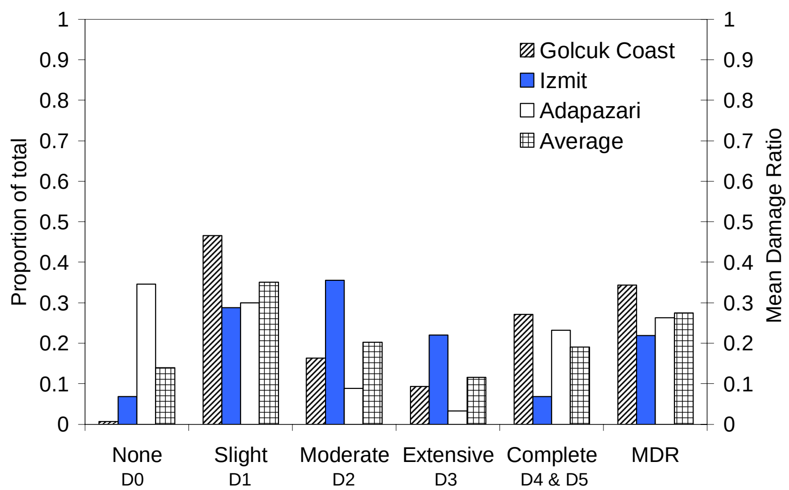

Figure 6: Comparison of Adapazari structural damage to Gölcük coastal zone and Izmit survey area. Mean damage ratio, MDR assumes 2% loss for *slight* damage, 10% for *moderate* damage, 50% for *extensive* damage and 100% loss for *complete* damage (Bommer *et al*. [7]).

The three zones are comparable to some extent, all being located on soft soil and in the near-fault region, and the building stock was largely similar. The Gölcük survey area was closer to the fault, but forward-directivity effects would have been more intensive in the more easterly location of Adapazari. Despite the similarities, there are some significant differences between the three distributions which could be related to differences between the survey teams' methodology, or particular local features such as subsidence and fault rupture in Gölcük and widespread liquefaction in Adapazari. The Mean Damage Ratio (MDR), a composite number intended to represent the overall damage cost, appears to be less sensitive to these differences. A possible interpretation of Figure 6 is that for small study areas, local features such as the presence of liquefiable soils can strongly influence the damage distribution. For wider study areas, as indicated by the average results, the individual features are smoothed out to some extent. It is suggested that the larger the study area is, the more the damage patterns will be dominated by the common cause of damage, i.e. ground shaking. Another observation from Figure 6 is the relatively high proportion of undamaged buildings in Adapazari; possible explanations, which include the robust, thick mat foundations of buildings in Adapazari as well as the infill walls, are discussed later.

ESTIMATING EARTHQUAKE LOSSES DUE TO GROUND FAILURE

Existing methodologies

There are various options currently available to loss modellers with respect to incorporating ground failure. In increasing order of complexity (Bird *et al.* [10]), these are:

1. Omit liquefaction from the model based on the assumption that ground shaking will be the predominant cause of damage.
2. Adopt a simplified approach, whereby the ground shaking demand is increased for susceptible soils, effectively subsuming the effects of liquefaction into stronger ground shaking.
3. Use a published methodology such as that of HAZUS [11].
4. Use in situ geotechnical data to evaluate the probability of liquefaction (e.g using Seed *et al*. [12]); the expected permanent ground deformation (e.g. Shamoto *et al*. [13]; Youd *et al*. [14]), and, according to the foundation type, relate this to the expected building damage.

Further discussion and explanation of these options is presented by Bird & Bommer [15]. Clearly the final option provides the most rigorous approach. However, the requirements, in terms of input data, analysis and time, are significant, often prohibitively so. Loss estimations are very frequently based upon very crude data, not only geotechnical, but also relating to the building portfolios for which the estimation is required. A simplified approach for ground failure, such as that proposed in the HAZUS methodology [11], wherein the level of input data and the simplicity of the analysis are commensurate with other aspects of the study, undoubtedly often answers the needs of loss modellers. Nonetheless, simplified approaches still require validation and definition of the uncertainties, and this is one of the objectives of this case study of Adapazari.

Adapazari case study

A comparison of observed damage patterns in central Adapazari to predicted damage patterns was carried out (Bird *et al*. [10]). The ground shaking component of the model was based upon an earthquake loss model developed for the Turkish Catastrophe Insurance Pool (TCIP) (Bommer *et al*. [7]), which used an adaptation of the HAZUS methodology calibrated to Turkish conditions. For the ground failure component, each of the three options described above were considered. Results are presented for one building classification, mid-rise reinforced concrete (RC) frames with masonry infill walls. The main steps of the damage estimation are as follows:

1. Define the demand curve for ground shaking in central Adapazari. The bedrock accelerations are defined at PGA (T = 0s), T = 0.3s and T = 1.0s, and soil amplification is incorporated using the NEHRP amplification factors [16]. Site conditions in central Adapazari are best represented by an intermediate site classification of D/E [10].
2. Define the vulnerability parameters for the mid-rise RC frame buildings. A recent study by Spence *et al*. [17] calibrated the capacity curves to observed damage distributions in the cities of Gölcük and Izmit in 1999, and the findings of that study were incorporated. The best estimate model parameters reflected the observed contribution of infill walls to lateral resistance of infill walls.
3. Estimate the damage distribution due to ground shaking, from the intersection of the demand and capacity curves, using the fragility curves defined for the TCIP model (Bommer *et al*. [7]).
4. Estimate the additional damage due to liquefaction, using the simplified HAZUS methodology and combine the two results (Bird *et al*. [10]).

Although the HAZUS methodology has been developed specifically for application within the USA, it is judged that there are sufficient similarities between the Northern Anatolian fault Zone and the western USA to justify the use of a US-based methodology in the absence of specific approaches for Turkish conditions. One of the primary differences between the two regions is the building stock, in that the buildings in Adapazari are designed and constructed very differently to those that would be allowed in seismic areas of the USA. However, since the HAZUS ground failure component considers only two building classifications (either *shallow* or *deep* foundations) in its ground failure component [15], this difference does not have a significant influence on the results.

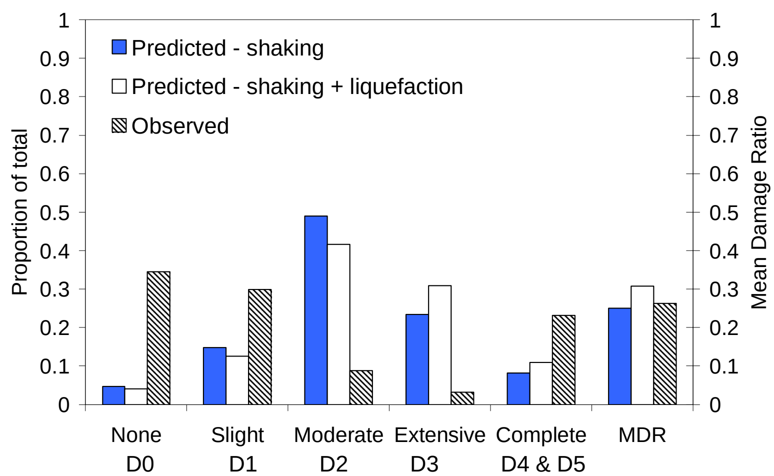

Figure 7: Predicted vs. observed damage to mid-rise RC frame buildings in central Adapazari.

The correlation between observed and predicted damage patterns is reasonable although there is potential for improvement. The estimated MDR agrees particularly well with the observations. Particular features for consideration are the under-estimation of the proportion of undamaged and slightly damaged buildings and the under-estimation of completely damaged buildings.

The under-estimation of the proportion undamaged buildings in Adapazari highlights the particular importance of the damage state definitions used in loss models, discussed previously. According to HAZUS [11], 'Slight' structural damage of a concrete frame building with unreinforced masonry infill walls comprises "*diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces*". In Adapazari over one third of the buildings that suffered either slight or no damage suffered some degree of ground failure. Therefore by combining the damage states for future damage surveys, many of those buildings recorded as undamaged or slightly damaged would be redistributed into other categories as a function of the foundation damage.

The under-estimation of the proportion of completely damaged buildings is thought to be a reflection of the inability of the current vulnerability model to reflect the particular vulnerability of the 5-6 storey apartment blocks in Turkey, due to their poor construction, often with added-on floors and soft-storeys. Although the model reflects the lateral resistance of the infill walls, it does not correct for the brittle behaviour of these walls.

IMPLICATIONS FOR LOSS ESTIMATION MODELLING

Significant variables observed in Adapazari damage patterns

Building vulnerability functions in loss estimations typically define a building's susceptibility to damage according to its classification. Building classifications are based upon the structural system, construction material, age, and height. The combination of these variables can approximately represent a building's behaviour under earthquake loading. In the liquefied zones of Adapazari, where damage was also related to foundation failure, some of the factors observed to correlate closely to the degree of damage are presented in Table 4.

Table 4: Implications from Adapazari damage patterns for loss modelling

Variable	Observation in Adapazari	Comparison to HAZUS assumptions
Height	Settlement and tilt was more common and more severe for taller buildings	Building height not considered in ground failure component.
Aspect ratio	The occurrence and extent of foundation tilt and settlement was greater for those buildings with a high aspect (height/width) ratio	Foundation width not considered or even included in inventory data, not an easily available parameter
Soil profile	A strong correlation was revealed between the extent of ground failure and the details of the soil profile, with ground failure occurring where shallow, loose, saturated low-plasticity silts were present [6].	Ground failure component uses a very simplified site classification, based upon Youd & Perkins [13]. More detailed soil profiles require large volumes of input data.
Foundation type	Thick well-reinforced concrete mat foundations appeared to limit the structural damage to buildings on liquefied ground.	Only 2 foundation types; *shallow* and *deep* considered.

The incorporation of some or all of the variables in Table 4 would improve the liquefaction model. Clearly the amount of input data required would also increase significantly which is an important consideration. Nonetheless, by understanding some of the shortcomings associated with a simplified approach, the uncertainties related to a simplified loss model can be better defined, which is the main objective of this study.

Interaction of ground shaking and ground failure

This is an important and complex issue in carrying out regional studies where there is potential for liquefaction. The simplest option is to assume that damage is due to either ground shaking or ground failure, and therefore that one or the other hazard will dominate in any given location. The more complex approach would be to assume that any building can be moderately damaged by ground shaking and moderately damaged by ground failure, resulting in extensive overall damage.

Discussion of building damage in liquefied zones, including Adapazari, frequently refers to the phenomenon known as 'base-isolation' due to the presence of a liquefied soil layer reducing the overall strength of the ground shaking and thus limiting the structural damage due to strong ground shaking within liquefied zones (e.g. Erdik [18]). Although this is a possible explanation for some of the observations in Adapazari (and, incidentally, would greatly simplify the damage estimations) there are some important qualifications. Where buildings have completely collapsed, it is often impossible to determine the occurrence or absence of ground failure. The intersecting grade beams and mat foundations of the buildings in Adapazari (often 1.5m thick) minimised many of the damaging effects of liquefaction. For the remaining buildings, as indicated in Figure 8, there is only a moderate correlation between high structural damage indices and high ground failure indices. A more detailed discussion of the relationship between structural damage and ground failure is presented by Sancio *et al*. [19].

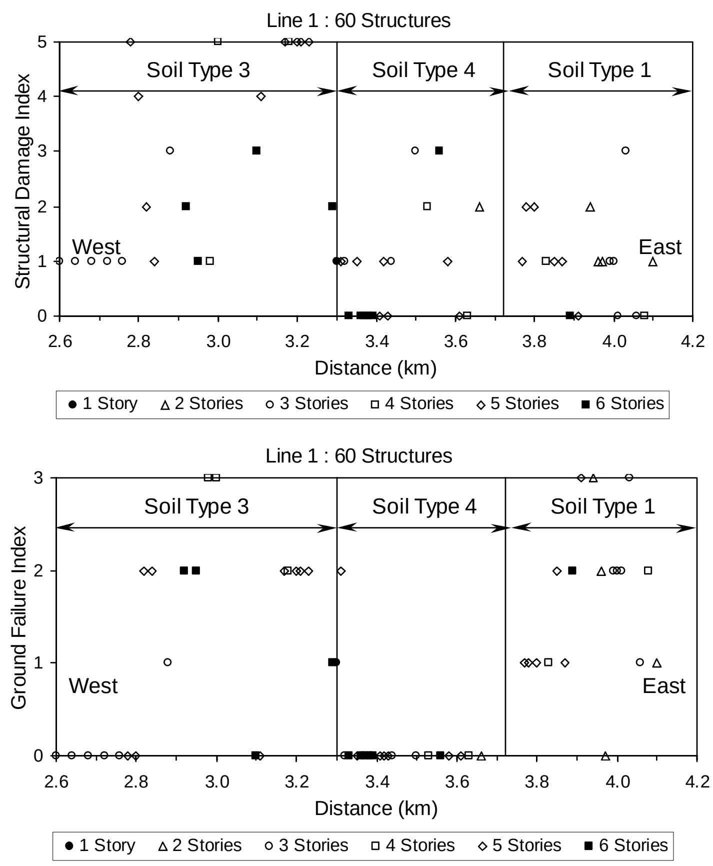

Figure 8: Correlations between structural damage index (Table 1) and ground failure index (Table 2) for a portion of line 1 of Bray & Stewart's [2] survey data (Figure 2).

For a site-specific design, it is advisable to consider all design scenarios, including only ground-shaking, only liquefaction, and a combination of both. For a loss estimation study this is unlikely to be realistic given the crudeness of the input data and the additional costs that such a rigorous approach requires. In consideration of the observations in Adapazari, a suggested approach would be to consider two cases, either with or without liquefaction. By calibrating building vulnerabilities to liquefaction with field observations the complexities of the hazard interaction would be to some extent implicit in this approach.

Uncertainties in loss estimations

Uncertainties in loss models are significantly greater than those related to single site risk assessments. This is a function of the large area covered and the corresponding need to simplify the range of site conditions, hazard scenarios, building types, occupancy categories, populations, building value, etc within the study area into manageable groups. These simplifications compound the already significant uncertainty related to estimating seismic hazard. When liquefaction is added into a loss model, additional layers of uncertainty are added in terms of the likelihood of occurrence of liquefaction, the expected ground deformation if it does occur, and the relationship between ground deformation and damage. This increased uncertainty does not however imply that a model which fails to incorporate liquefaction is more reliable; the incorporation and quantification of model uncertainty is an essential component of any hazard or risk study. With respect to the uncertainty related to the ground failure component, there is very limited empirical data for the validation of assumptions made or the calibration of theoretical models.

Estimated ground motion

The uncertainty related to the estimated shaking demand in central Adapazari is significantly less than it would be for many studies of future losses, because the magnitude and location of the earthquake are known, there was a strong-motion recording station within 4km of the study area, and the local soil conditions have been investigated. Nonetheless, without a strong motion record directly from the site of interest, it is difficult to accurately characterise the ground shaking.

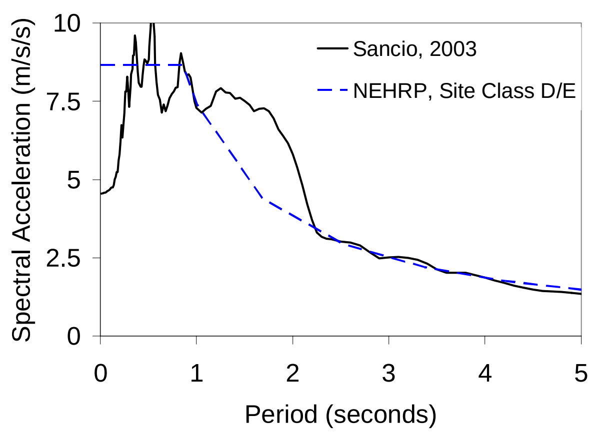

Figure 9: Uncertainty in demand; 5% damped elastic response spectra for downtown Adapazari

For the Adapazari study area, the ground motions have been estimated in two different ways: the first used the Turkish attenuation relationship of Gülkan and Kalkan [20], combined with NEHRP [16] soil amplification factors for a site classification of D/E [10]. The demand was defined by an elastic response spectrum for 5% damping, anchored to spectral accelerations at T = 0.3s and T = 1.0s. This approach has uncertainties relating to the scatter of the attenuation relationship and the simplification of soil amplification. An alternative approach (Sancio [21]) used the average of eight strong-motion records from the Kocaeli earthquake, scaled to 0.3g, the estimated bedrock peak ground acceleration in central Adapazari, plus the soil profile from the geotechnical investigations and the site response analysis program SHAKE91 [22] to estimate the surface response. In this case the uncertainties are primarily related to the scaling and selection of the input motions, as well as soil variability and the selection of appropriate dynamic soil parameters. Figure 9 shows that these two independent models agree very well, with the exception of some potential unconservatism in the simplified NEHRP approach between 1 and 2 seconds. This comparison suggests that in this case study the uncertainty related to the demand curve is relatively small.

Building vulnerability model

The building vulnerability model used to define the shape of capacity curve considered three categories: *poor* seismic design, *good* seismic design, and a *shear wall* model, which incorporates the contribution of infill walls to the lateral resistance in many Turkish buildings. It was concluded by Spence *et al*. [17] that the shear wall model reflected the observed behaviour the most accurately, but the sensitivity of the results to the vulnerability model are illustrated in Figure 10.

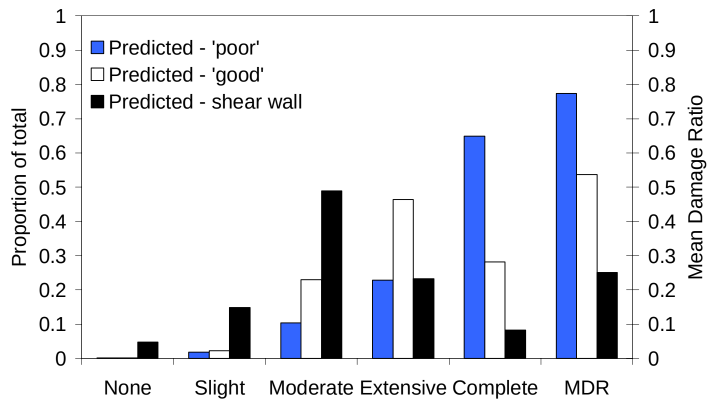

Figure 10: Sensitivity of damage estimations to building vulnerability model for mid-rise RC frame buildings using best estimate ground shaking demand (no liquefaction).

Liquefaction component

In comparison to the vulnerability model, the incorporation of liquefaction into the damage estimation model (Figure 11) applying the HAZUS methodology has a relatively small effect on the predicted damage distribution.

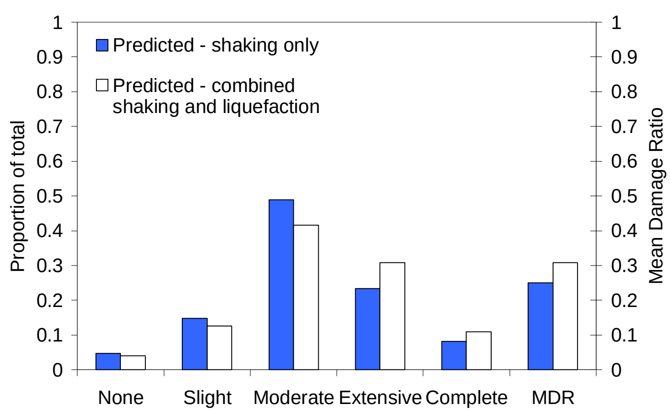

Figure 11: Sensitivity of damage estimations to the incorporation of liquefaction induced damage for mid-rise RC frame buildings with infill walls.

DISCUSSION AND CONCLUSIONS

This paper presents a brief summary of the extensive geotechnical and structural damage survey data collected in Adapazari following the 1999 Kocaeli earthquake. Earthquake loss estimations are a relatively new field, and the use of earthquake data to calibrate current methodologies is important. The ground-failure component of earthquake loss estimations is currently less advanced than the ground-shaking aspect, and therefore, the quality and quantity of data from downtown Adapazari, a zone of extensive liquefaction, is invaluable for the advancement of this field.

Earthquake loss estimations have a high degree of associated uncertainty, due in part to the crudeness of the input data, the necessary simplifications and assumptions that must be made for a regional study, and the inherent uncertainty associated with the estimation of earthquake hazard and risk. The incorporation of ground failure into a model creates an additional layer of uncertainty. An understanding of the relative contribution of this uncertainty and of the significance of the assumptions made to include ground failure is an essential step towards developing a sound methodology for estimating losses due to ground failure.

There are limited options available for the incorporation of ground failure into a loss estimation model. HAZUS [11] provides a simplified approach without requiring excessive amounts of additional input data. The alternative approach, which is to use in situ geotechnical and geological data to model the likelihood and consequences of ground failure, is very demanding in terms of data, time, and resources, often prohibitively so. Although the HAZUS approach meets the requirements of loss modellers, it is as yet uncalibrated, and the influence of some of the assumptions and simplifications upon which it is based has been considered in this study.

The Ground Failure Index (Table 2) was developed for the damage survey in Adapazari, because existing building damage scales do not incorporate some of the consequences of ground failure such as building settlement, tilt, and lateral movement. The use of such a scale is strongly recommended in future earthquake reconnaissance in order to create a database of ground-failure related damage. Additionally, an independent survey of foundation performance, which could then be combined with the ground failure and structural damage surveys, is also recommended.

Current loss estimation methodologies relate damage scales, similar to that presented in Table 1, to the expected repair cost for a damaged building. Presently there is no scale which relates building settlement, tilt, or lateral movement to repair costs in the same way. For many buildings in central Adapazari, these effects were the only damaging consequences of the earthquake and the failure to represent them would clearly lead to unrealistic loss estimation. There is a need for a unified damage scale incorporating both structural and foundation damage with equivalent repair cost ratios.

A comparison of observed and predicted (using a HAZUS-based approach) damage patterns for central Adapazari showed significant potential for improvement in the predicted distributions. The mean damage ratio (MDR), a composite number that reflects the approximate damage costs, did agree particularly well with the observations, although from this limited study it is not possible to determine the reliability of this observation. Potential explanations for the disparities between the damage distributions include: shortcomings in the vulnerability model, which may not correctly represent the particular vulnerability of 5-6 storey reinforced concrete frame buildings, and the damage state definitions discussed above, whereby buildings reported as ‘undamaged’ in Adapazari would more realistically be adjusted into higher damage states due to the tilt or settlement that they suffered.

A number of variables were observed to influence the damage due to liquefaction in Adapazari, including; the building height; building height-to-width aspect ratio; the soil profile; and the foundation type. More detailed consideration of some or all of these factors would improve the accuracy of the liquefaction-induced damage estimation.

The complex issue of ground shaking and ground failure interaction was briefly considered. It was concluded that no clear patterns emerge from the Adapazari data. However, a suggested approach for future studies is that by calibrating assumed building vulnerabilities to ground failure with field observations, the interaction of the two hazards should be, to some extent, implicitly included.

The choice of building vulnerability model has a very significant influence on the results; a variation of almost 50% in the estimated MDR was calculated for different potential models. Therefore it is essential to resolve this uncertainty as far as possible before introducing secondary effects such as liquefaction into a loss model.

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