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Probabilistic assessment of earthquake insurance premium rates for the Gumusova-Gerede Motorway Section

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ABSTRACT

A probabilistic model is developed for the assessment of the earthquake insurance premium rates for the structures taking place in the Bolu Mountain Crossing in the Gumusova-Gerede Motorway Section. The model requires two types of studies, namely: seismic hazard analysis and estimation of potential damage to structures. The computations are carried out according to the proposed model by using the seismic hazard results obtained from the time-dependent renewal model and the best estimate damage probability matrices developed in the study.

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1. Introduction

Bolu Mountain Crossing, being a stretch of Gumusova-Gerede Motorway project and named as Section 2, has a total length of 27.2 km, in which 25.6 km of it is motorway and 1.6 km is the connection road. Motorway is designed as two by three-laned and covers earthworks, structures, tunnel and pavement works. Bolu Mountain Crossing, being included within the motorway project along Edirne-Istanbul-Ankara route, which is the main artillery of the highway network in the country, and aiming to meet local and international transportation demands, is the sole section of the project which was completed in 2007. When completed and opened to traffic it ensured the integrity of a very important alignment as a high standard and access control road and safe continuous traffic flow along the motorway.

Within the scope of the road there is one tunnel with two tubes of 2.9 km and 2.8 km long, four viaducts of totally 4.6 km long, three bridges of totally 76 m long, one under-bridge and twelve over-bridges of totally 682 m long. Bolu Mountain Crossing starts from Kaynasli, travels towards east along Asarsuyu Valley, crosses Bolu Mountain through a tunnel and ends at Yumrukaya. The commencement date of the project is 19.02.1990 and initially the expected completion date was 15.12.2006. The initial contract price was 570,500,000 US dollars, whereas later the revised new contract value reached to 670,000,000 US dollars. The contractor of the project is Astaldi S.p.A. and the project is financed by foreign credit.

The earthquake of November 12th 1999 hit the motorway system and caused damages at Viaduct 1 and partial collapse of the Elmalık (Ankara) side of the tunnel for a length of 350 m. The insurance company, after negotiations had agreed to reimburse 105 million US dollars for the losses of the client. After making such a high payment, the insurance company refused the renewal of the earthquake insurance coverage. Consequently, the international insurance companies are invited to make offers for the earthquake insurance coverage of the motorway system. Only one insurance company made an offer with an extremely high premium rate. The client found the offer too high and required a realistic evaluation of the pure risk premium.

In this paper a probabilistic model is presented to obtain a realistic estimate of the earthquake insurance premium for the Bolu Mountain Crossing in the Gumusova-Gerede Motorway Section. The model integrates the information on seismic hazard and the information on expected earthquake damage on engineering facilities in a systematic way, yielding to estimates of the earthquake insurance premium rates.

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2. Probabilistic Model for the Estimation of Earthquake Insurance Premium Rates

The assessment of earthquake insurance premium rates requires two types of studies, namely: seismic hazard analysis and estimation of potential damage to structures. In the following, first a brief explanation is provided on these two types of studies and then the model is developed.

2.1. Seismic hazard analysis (SHA)

In the probabilistic sense seismic hazard can be defined as the probability of exceeding different levels of a selected earthquake "severity" or ground motion parameter at a given site and within a given period of time due to expected seismic activity in the region. Many models have been developed for seismic hazard analysis. Most of the earlier models of seismic hazard assessment were based on the assumption that earthquake occurrences are independent events in space and time, and utilized the Poisson model (also known as the classical SHA model) or the extreme value statistics. Later studies considered the temporal or spatial dependence of earthquakes only, like the renewal or Markov models. In recent studies, the occurrence of earthquakes is treated as a space-time process and the spatial and temporal correlations are taken into consideration. A detailed discussion of different stochastic models for seismic hazard analysis is given in (Yücemen and Akkaya, 1996). The probabilistic formulation adopted in this study is based mainly on the time-dependent renewal model. The results obtained based on the classical SHA model are also presented and taken into consideration.

2.2. Estimation of potential seismic damage to structures

Another important component of the model is the assessment of damage to a specified type of structure as a result of earthquakes. Damage is commonly described by a loss ratio that varies with the strength of shaking and type of structure. Due to the uncertainties involved, the damage that may occur during future earthquakes has to be treated in a probabilistic manner. For this purpose damage probability matrices (*DPM*) can be constructed from observational and estimated data (Whitman, 1973; ATC-13, 1985; Gürpınar and Yücemen, 1980; ATC-25, 1991).

A *DPM* expresses what will happen to structures during earthquakes of different intensities. An element of this matrix $P_k(DS, I)$ gives the probability that a particular damage state (*DS*) occurs when the structure of k^{th}-type is subjected to an earthquake of intensity, I, where I denotes a selected earthquake "severity" or ground motion parameter, like modified Mercalli intensity (*MMI*), magnitude, peak ground acceleration (*PGA*), etc. The identification of damage states is achieved in two steps:

- (i) The qualitative description of the degree of structural and non-structural damage by words. In the most general classification five levels of damage states are specified. These are: No damage (N), light damage (L), moderate damage (M), heavy damage (H), and collapse (C) states. The above categorization of damage states is also used in this study.
- (ii) The quantification of the damage described by words in terms of the damage ratio (*DR*), which is defined as the ratio of the cost of repairing the earthquake damage to the replacement cost of the structure. For mathematical simplicity it is convenient to use a single *DR* for each *DS*. This single *DR* is called the central damage ratio (*CDR*). Based on the opinion of experts in charge of damage evaluation and based on similar studies, the damage ratios corresponding to the five damage states are estimated and are shown in Table 1.

Depending on the type of structures, different *DPM*'s exist. In this study *DPM*'s are developed for the different type of structures taking place at the Bolu Mountain Crossing in the Gumusova-Gerede Motorway Section, namely: viaduct, tunnel, cut and cover and "other structures", consisting of box culverts, embankments, slope supports, pavements, landscaping, river training, etc. Damage probability matrices can be obtained in the most reliable way based on the seismic damage data assessed from past earthquakes and also by using subjective judgment of experts. Techniques based on theoretical analyses for developing *DPM*'s are also available (Whitman, 1973). The form of a *DPM* is illustrated in Table 1.

Table 1. Damage probability matrix.

Damage State (*DS*)	Damage Ratio (*DR*) %	Central Damage Ratio (*CDR*) %	Selected Intensity Parameter (*I*)				
			I_1	I_2	I_3	I_4	I_5
None	0 - 1	0	Damage State Probabilities $P(DS, I)$				
Light	1 - 10	5					
Moderate	10 - 50	30					
Heavy	50 - 90	70					
Collapse	100	100					

2.3. Determination of the pure risk premium

The expected annual damage ratio ($EADR_k$) is used as a measure of the magnitude of earthquake damage to a k^{th}-type of structure that will be built in certain seismic zone and is defined as:

$$EADR_k = \sum_I MDR_k \times (I) SH_I \,, \tag{1}$$

where, MDR_k = average damage ratio for the k^{th}- type of structures subjected to an earthquake of intensity I and SH_I = annual probability (seismic hazard) of an earthquake of intensity I occurring and affecting the construction site.

It is to be noted that for the computation of *EADR*, one needs only the *MDR*'s corresponding to different intensity levels, rather than the whole *DPM*. The information contained in the damage probability matrix and in the damage ratios can be combined by defining the MDR_k as follows:

$$MDR_k = \sum_{DS} P_k\,(DS, I) \times CDR_{DS}\ , \tag{2}$$

where, CDR_{DS}= central damage ratio corresponding to the damage state *DS*.

After calculating $EADR_k$, the pure risk premium (*PRP*) is computed based on the insured value of the building (*INSV*) under consideration from the following relationship:

$$PRP_k = EADR_k \times INSV\ . \tag{3}$$

2.4. Determination of commercially charged insurance premium

The commercially charged insurance premium (CP_k) for the k^{th}-type of structure is found by increasing the PRP_k by some margin as follows:

$$CP_k = PRP_k/(1 - LF)\ , \tag{4}$$

where, *LF* = load factor which covers the hidden uncertainties, business expenses and a reasonable profit allowance. A common value for *LF* is 0.4 (Gürpınar and Yücemen, 1980). Thus, the commercially charged earthquake insurance premiums will be obtained by multiplying the pure earthquake insurance premium values by an adjustment factor of {1/(1-0.4)}=1.667.

3. Estimation of the Earthquake Insurance Premium Rates for the Gumusova-Gerede Motorway Section

The probabilistic model presented in Section 2 will now be utilized to obtain a realistic estimate of the earthquake insurance premium rates for the structures taking place in the Bolu Mountain Crossing in the Gumusova-Gerede Motorway Section (BMC-GGMS) excluding Viaduct-1. The period of earthquake insurance coverage is assumed to be between January 1, 2003 and the scheduled end of the construction, which was initially set as December 31, 2006, a total period of four years.

3.1. Seismic hazard analysis

In order to use the proposed model for computing the earthquake insurance premium for the structural components of the BMC-GGMS, it is first necessary to carry out a probabilistic seismic hazard analysis for the site where the mountain crossing is located. Extensive probabilistic seismic hazard analyses have been conducted in the past for this site by utilizing the classical seismic hazard model based on the independent Poisson model. These studies are carefully examined and the results of the most recent one (Yılmaz and Erdik, 2000), are summarized in Table 2.

Table 2. Seismic hazard results for the time-independent (memoryless) Poisson process (Yılmaz and Erdik, 2000).

Return Period (years)	*PGA* (g)
9.5	0.084
47.5	0.239
95	0.324
475	0.557
950	0.673
4750	0.985
9500	1.137

In the current study, the probabilistic seismic hazard analysis is conducted based on the time-dependent renewal model, which is believed to represent the current short-time seismic hazard more realistically, in view of the recent major earthquakes that took place in the region. Results of the time-dependent seismic hazard assessment study for the same return periods are presented in Table 3. The details of this seismic hazard analysis can be found in Yılmaz et al. (2003).

Table 3. Seismic hazard results based on the time-dependent (renewal) model.

Return Period (years)	*PGA* (g)	*MMI*
9.5	0.02	IV-V
47.5	0.06	VI
95	0.09	VI-VII
475	0.26	VIII
950	0.36	VIII-IX
2000	0.54	IX
4750	0.60	IX.¼
9500	0.70	IX-X

3.2. Damage probability matrices

In order to compute the *EADR* values from Eq. (1), it is necessary to obtain the *DPM*'s that are applicable for the major structures (i.e. viaducts, tunnel, cut and cover) as well as for the other structures (e.g. box culverts, embankments, slope supports, pavements, landscaping, river training, etc.) taking place in the motorway system. Since no sufficient damage data were available at this site for developing empirical *DPM*'s and the utilization of techniques based on theoretical methods is infeasible, *DPM*'s used in this study are constructed based on expert opinion and *DPM*'s available in the literature for such structures. Although intensity is not a reliable and objective measure of the severity of ground shaking, it is used in this study mainly because earthquake damage to structures is much better correlated with *MMI*. *MMI* scale provides twelve discrete levels of intensity with increasing severity. In this study consistent with the expected seismic activity only the levels V to IX are considered.

In order to estimate damage state probabilities by making use of the subjective judgment of experts, a questionnaire was prepared and sent to seven experienced engineers involved with the design and construction of the "Bolu Mountain Construction Project". Each engineer is asked to fill out the blank *DPM* tables by writing down the subjective probabilities reflecting his opinion on the likelihood of different levels of damage under different intensities.

It is to be noted that in these *DPM*'s two sets of subjective damage probabilities, labeled as UC and NUC, are given. The damage potential for sections under construction (UC) is expected to be considerably higher compared to those that are either completed or not under construction (NUC). This difference is taken into consideration by giving two sets of damage state probabilities under each intensity level. The *MDR* values of these seven engineers are averaged to obtain the "best estimate" subjective *MDR*'s and these are used in the subsequent analysis.

In order to crosscheck the subjective *MDR*'s obtained in this way and to supplement them, a literature survey was conducted. A very useful and dependable reference on this matter is the publications of the Applied Technology Council (ATC), namely ATC-13 (1985) and ATC-25 (1991). The ATC-13 report includes background information, detailed descriptions of the methodology used to develop the required damage/ loss estimates and inventory information, and tables and figures showing the damage/loss estimates developed. Included are damage probability matrices for 78 different facility types as well as estimates of time required to restore damaged facilities to their pre-earthquake usability. In Table G.1 of ATC-13, *MDR* values are given for different intensity levels based on expert opinion for major bridges, tunnels, cut and cover tunnels, highway roadways and pavements and earth retaining structures. The values given in this table correspond to the NUC case.

While ATC-13 provides the *MDR*'s directly, ATC-25 describes the distribution of expected damage in terms of fragility curves based on *PGA*. However, in the case of bridges and highway tunnels, curves showing the degree of damage versus intensity are given. From these curves the *MDR* values corresponding to different intensity levels are extracted for bridges and highway tunnels.

The *MDR*'s based on expert opinion and those obtained from ATC-13 (1985) and ATC-25 (1991) are combined and modified to form the "best estimate" *MDR*'s corresponding to different intensity levels for the viaducts, tunnel, cut and cover and other structures. Here, because of space limitation only the resulting weighted average *MDR* values are given in a tabular form (Table 4). For the details of the computation of these *MDR* values the reader is referred to Yılmaz et al. (2003).

Table 4. "Best estimate" *MDR* values (%) (UC: Under Construction; NUC: Not Under Construction).

Structure Type	*MMI* = V		*MMI* = VI		*MMI* = VII		*MMI* = VIII		*MMI* = IX	
	UC	NUC	UC	NUC	UC	NUC	UC	NUC	UC	NUC
Viaducts	0.003	0	0.014	0.0021	0.66	0.146	3.91	1.02	15.26	10.19
Tunnel	0	0	0.81	0.10	1.79	0.325	4.53	1.16	13.87	5.20
Cut and Cover	0	0	0	0	0.83	0.19	3.26	1.22	14.01	5.72
"Other" Structures	0	0	0	0	0.83	0.25	3.26	1.30	14.01	6.03
Viaducts	0.003	0	0.014	0.0021	0.66	0.146	3.91	1.02	15.26	10.19

Note: UC=Under Construction; NUC=Not Under Construction

3.3. Computation of expected annual damage ratios

In computing the expected annual damage ratios (*EADR*) for the different components of the system, the best estimate mean damage ratio values (Table 4) and the seismic hazard values obtained from the time-dependent model (Table 3) are to be used. The seismic hazard is assumed to be the same at the whole site where the components of the system are located. The resulting *EADR* values, computed from Eq. (1), can be interpreted as the pure risk premiums (*PRP*) to be charged per annum for every one million dollar of insured "property" and are shown in Table 5. The computations are also carried out based on the seismic hazard values obtained by using the independent Poisson model (Table 2). These *EADR* values are also shown in Table 5. As expected the memoryless Poisson model yields higher *EADR* values (about 3 times more) compared to those obtained from the time-dependent renewal model for the UC and NUC cases and for all components of the system. The *EADR* values corresponding to the sections of viaduct, tunnel, cut and cover and other structures that are under construction are respectively, about 2.2, 4.4, 2.8 and 2.5 times higher than the *EADR*'s estimated for the sections that are not under construction in both of the seismic hazard models. This difference in the *EADR*'s is due to the fact that during the construction phase, the viaducts, the tunnel, the cut and cover and the "other" structures will be more vulnerable to earthquake excitation.

As observed in Table 5 the *EADR* values (and consequently the premium rates) are sensitive to the assumptions on seismic hazard analysis and damage probability matrices. In the case of seismic hazard analysis, we believe that the values obtained from the time-dependent model describe the current level of seismic hazard as well as the hazard for the next four years more realistically compared to the independent Poisson process. This is due to the fact that the Poisson model, because of its memoryless stochastic mechanism, ignores completely the large magnitude earthquake that occurred in the region during the year 1999, whereas the time-dependent (renewal) model takes into consideration the past seismic activity.

In view of the above discussion, it was decided to find a weighted average *EADR*. In other words, although the time-dependent model is preferred to the Poisson model, the more conservative seismic hazard values obtained from the Poisson model are not completely disregarded. A weight of 80% is assigned to the *EADR*'s obtained from the time-dependent (renewal) model and 20% to the *EADR*'s calculated based on the Poisson model. The resulting *EADR*'s are called as our "best estimate" values and are also shown in Table 5.

Table 5. "Best estimate" *EADR* values based on the renewal and Poisson models.

System Component	*EADR* for NUC (10^{-6})			*EADR* for UC (10^{-6})		
	Renewal	Poisson	Best Estimate	Renewal	Poisson	Best Estimate
Viaducts	134.11	428.92	193	298.84	954.06	430
Tunnel	127.37	376.58	178	576.59	1591.45	780
Cut and Cover	99.39	320.13	144	276.07	879.10	397
"Other" Structures	113.49	358.52	163	276.07	879.10	397

Note: UC=Under Construction; NUC=Not Under Construction

3.4. Computation of the pure earthquake insurance premiums

Using the best estimates *EADR*'s given above and the insured values (*INSV*) of the "property", the pure risk premium (*PRP*) values can be computed from Eq. (3). For this purpose the monetary values given by Astaldi S.p.A. are taken as the inputs for the insured values and distinction is made between the work that is completed and work under construction according to the construction schedule. The resulting pure risk premium values corresponding to sections under construction (UC) and sections completed (NUC), as well as the total pure risk premium values are shown in Table 6 for the viaducts, tunnel, cut and cover and "other" structures for each year of the construction period in US dollars. The sum of the annual pure insurance premiums to be paid during the period of 2003-2006 is calculated as 473,811 US dollars.

Table 6. Pure earthquake insurance premium values (in US dollars) for the viaducts, tunnel, cut and cover and other structures corresponding to the different years of construction.

	2003		2004		2005		2006	
Viaducts	*INSV*	*PRP*	*INSV*	*PRP*	*INSV*	*PRP*	*INSV*	*PRP*
NUC	35,385,001	6,830	58,608,961	11,312	112,209,953	21,657	170,479,915	32,903
UC	23,223,960	9,987	53,600,992	23,049	58,269,962	25,056	827,498	356
Total *PRP*		16,817		34,361		46,713		33,259
Tunnel	*INSV*	*PRP*	*INSV*	*PRP*	*INSV*	*PRP*	*INSV*	*PRP*
NUC	127,327,630	22,665	145,012,196	25,813	191,527,234	34,092	241,886,927	43,056
UC	17,684,566	13,794	46,515,038	36,282	50,359,693	39,281	18,252,897	14,238
Total *PRP*		36,459		62,095		73,373		57,294
Cut And Cover	*INSV*	*PRP*	*INSV*	*PRP*	*INSV*	*PRP*	*INSV*	*PRP*
NUC	0	0	12,867,211	1,853	18,631,805	2,683	18,631,805	2,683
UC	12,867,211	5,109	5,764,595	2,289	0	0	0	0
Total *PRP*		5,109		4,142		2,683		2,683
"Other" Structures	*INSV*	*PRP*	*INSV*	*PRP*	*INSV*	*PRP*	*INSV*	*PRP*
NUC	108,672,475	17,714	110,358,330	17,989	128,246,419	20,905	138,512,810	22,578
UC	1,685,855	670	17,888,088	7,102	10,266,391	4,076	19,619,379	7,789
Total *PRP*		18,384		25,091		24,981		30367
Total Pure Risk Premium:		76,769		125,689		147,750		123,603

Note: *INSV*=Insured Value; *PRP*=Pure Risk Premium; NUC=Not Under Construction; UC=Under Construction

4. Conclusions

Using the best estimate seismic hazard values together with the best estimate *MDR* values, the total earthquake insurance premium for the period of 2003-2006 is computed as 473,811 US dollars. This amount corresponds to the pure risk premium, reflecting only the risk of damage due to earthquakes and has to be increased to account for hidden uncertainties, business expenses and a reasonable profit allowance for the insurance firm. This adjustment can be done by using Eq. (4) with a load factor, $LF = 0.4$, yielding to an adjustment factor of 1.667. With this adjustment, the corresponding commercially charged earthquake insurance premium value for the period of 2003-2006 will be: 789,843 US dollars.

The best estimate *EADR* values computed in this study and the resulting earthquake insurance premiums obtained under different assumptions are within our expectations and are consistent among them. We also emphasize on the existence of two favourable factors that have decreased the seismic risk of the system and consequently the insurance premiums, namely: the upgrading of the seismic design criteria after the 12 November 1999 Düzce earthquake has reduced the seismic vulnerability of the system considerably and also the probability of a large magnitude earthquake occurring in the region during the next four years (construction period) has decreased significantly due to the energy released by the 12 November 1999 Düzce earthquake (Lettis and Barka, 2000).

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