



A STATISTICAL PROCEDURE FOR THE ASSESSMENT OF SEISMIC PERFORMANCE OF EXISTING REINFORCED CONCRETE BUILDINGS IN TURKEY

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SUMMARY

A procedure is developed to assess the seismic performance of low- to mid-rise reinforced concrete buildings using a statistical approach and the seismic damage database compiled from recent earthquakes in Turkey. The database is based on the post-earthquake damage evaluations conducted after the 1999 earthquakes in Turkey and contain detailed information on some selected buildings that suffered various degrees of damage. The detailed information collected for each building were processed and analyzed in order to investigate and establish correlations between the building attributes that are believed to affect the seismic performance and the observed damage. In this procedure, the building to be evaluated is required to be visited to collect data on its structural layout, plan and vertical member dimensions, number of stories and architectural features such as soft stories and overhangs. A damage score, obtained from a discriminant function utilizing the building-specific information, is compared with a cutoff value to arrive at a decision regarding its performance.

Seismic performance evaluation is carried out in two stages, first for life safety and then for immediate occupancy performance levels. The building is then classified as safe or unsafe depending on the results of these evaluations. Since the cutoff values were derived based on the seismic damage database compiled from a particular earthquake and at a particular site, further endeavor was devoted to the improvements and adjustments that would allow the application of the proposed procedure to other regions. For this purpose the variability of ground motion with respect to the soil properties and the distance to source were incorporated into the analysis. The sites are classified according to Turkish Seismic Code's definitions based on the shear wave velocity. The procedure is verified through application to a number of buildings that were subjected to some of the recent earthquakes in Turkey.

INTRODUCTION

The majority of the procedures developed for the vulnerability assessment of building structures have primarily focused on the structural system, building capacity, layout and certain response parameters [1-6]. These parameters would provide realistic estimates of the expected performance if the as-built features

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of the structural system were same as the designed structural and architectural features. In general, the construction practice in Turkey leads to structures that are far beyond reflecting designed configurations and detailing, thus contravene most assumptions of the usual vulnerability assessment procedures. Several recent attempts were made to utilize limited field data in determining the seismic vulnerability, which basically focused on determining the boundaries of demarcations for certain performance levels. The obvious need for procedures that are based mainly on the observed performance has been the motivation for this study. In this context, a statistical analysis technique, discriminant analysis, was used to develop a preliminary evaluation methodology for assessing seismic vulnerability of existing low- to mid-rise reinforced concrete buildings located in Turkey. The main objective is to identify the buildings that are highly vulnerable to earthquake effect, that is their seismic performance is inadequate to survive a strong earthquake. Therefore, damage scores determined based on certain building attributes are obtained from the derived discriminant functions, and are used to classify existing buildings as “safe”, “unsafe” and “intermediate”. The discriminant functions are generated based on the basic damage inducing parameters, namely number of stories (n), minimum normalized lateral stiffness index (mnlstfi), minimum normalized lateral strength index (mnlssi), normalized redundancy score (nrs), soft story index (ssi) and overhang ratio (or).

The building damage database that formed the data set for this study contains 484 buildings in Düzce, which were evaluated by the survey teams after the 1999 Düzce earthquake. The building inventory was formed entirely by low- to mid-rise reinforced concrete buildings. The observed building performances were classified into five damage groups as None, Light, Moderate, Severe and Collapse. Table 1 presents the classification of these buildings according to the number of stories and the observed damage.

Table 1. Building Database Differentiated according to Height and Observed Damage

Number of stories	2	3	4	5	6	Total
Damage Level						
None	7	18	17	17	2	57
Light Damage	13	62	44	31	0	143
Moderate Damage	3	29	59	56	4	136
Severe Damage	0	13	22	21	2	51
Collapse	0	0	15	43	6	57
Total	23	122	157	168	14	444

The description of these parameters and the derivation of discriminant functions are presented briefly in the sections that follow. Details of the statistical procedure and the damage parameters are given elsewhere [7, 8]. In order to extend this procedure to other regions that have different site characteristics than Düzce further analyses were carried out.

DAMAGE INDUCING PARAMETERS

The basic assumption of the procedure is that the seismic intensity level of each building in the database is the same, which is quite reasonable considering the soil profile and distance-to-source of the building locations involved. For this reason, the damage will be evaluated only on the basis of structural parameters rather than including the excitation parameters. Considering the characteristics of the damaged structures and the size of the existing building stock, six parameters were chosen as the basic estimation parameters of the proposed method: number of stories (n), minimum normalized lateral stiffness index (mnlstfi),

minimum normalized lateral strength index (mnlsi), normalized redundancy score (nrs), soft story index (ssi), overhang ratio (or).

The number of stories (n) represents the total number of individual floor systems above the ground level. The lateral rigidity of the ground story, which is usually the most critical story, is considered through the minimum normalized lateral stiffness index (mnlstfi). The vertical members that have the ratio of longer cross sectional dimension to the shorter one greater than 7 are considered as structural walls. The mnlstfi is taken as the minimum of the normalized lateral stiffness indexes (I_{nx} , I_{ny}) computed for the two orthogonal directions using Equation 1.

$$I_{nx} = \frac{\sum (I_{col})_x + \sum (I_{sw})_x}{\sum A_f} \times 1000$$

$$I_{ny} = \frac{\sum (I_{col})_y + \sum (I_{sw})_y}{\sum A_f} \times 1000$$
(1)

where;

- $\Sigma(I_{col})_x$ and $\Sigma(I_{col})_y$: summation of the moment of inertias of all columns about their centroidal x and y axes, respectively.
- $\Sigma(I_{sw})_x$ and $\Sigma(I_{sw})_y$: summation of the moment of inertias of all structural walls about their centroidal x and y axes, respectively.
- I_{nx} and I_{ny} : total normalized moment of inertia of all members about x and y axes, respectively.
- ΣA_f : total story area above ground level.

Minimum normalized lateral strength index (mnlsi) reflects the base shear capacity of the critical story. The contributions of the columns, structural walls and unreinforced masonry filler walls are considered. The mnlsi is equal to the minimum of the normalized lateral strength indexes calculated in the two orthogonal directions (A_{nx} , A_{ny}) from Equation 2.

$$A_{nx} = \frac{\sum (A_{col})_x + \sum (A_{sw})_x + 0.1 \sum (A_{mw})_x}{\sum A_f} \times 1000$$

$$A_{ny} = \frac{\sum (A_{col})_y + \sum (A_{sw})_y + 0.1 \sum (A_{mw})_y}{\sum A_f} \times 1000$$
(2)

For a square column, both $(A_{col})_x$ and $(A_{col})_y$ will be the same and are taken equal to one-half of the cross sectional area of the column. For rectangular columns with longer side along the x-direction, $(A_{col})_x$ and $(A_{col})_y$ are taken as equal to the 2/3 and 1/3 of the column cross sectional area, respectively. For structural concrete walls and masonry infill walls, full areas in the direction of the wall are considered only in Equation 2, and the term reflecting the area in the perpendicular direction is taken as zero.

The normalized redundancy score (nrs) takes into account the degree of the continuity of multiple frame lines to distribute lateral forces throughout the structural system. The normalized redundancy ratio (nrr) of a frame structure is calculated by using the following expression:

$$nrr = \frac{A_{tr}(nf_x - 1)(nf_y - 1)}{A_{gf}} \quad (3)$$

In Equation 3, A_{tr} is the tributary area for a typical column, and is taken as 25 m^2 if nf_x and nf_y are both greater than or equal to 3. In all other cases, A_{tr} is taken as 12.5 m^2 . The terms nf_x and nf_y are the number of continuous frame lines in the critical story (usually the ground story) in x and y directions, respectively. And A_{gf} is equal to the area of the ground story, i.e. the footprint area of the building.

The value of nrs is 1 if nrr computed from Equation 3 is between 0 and 0.5, and it is taken as 2 if nrr falls into the range 0.5-1.0, for nrr greater than 1 nrs is assigned a value of 3.

The soft story index (ssi) is defined as the ratio of the height of first story (i.e. the ground story), H_1 , to the height of the second story, H_2 .

In a typical floor plan, the area beyond the outermost frame lines on all sides is defined as the overhang area. The summation of the overhang area of each story, A_{overhang} , divided by the area of the ground story, A_{gf} , is computed as the overhang ratio (or).

DERIVATION OF DISCRIMINANT FUNCTIONS

Method of Analysis

A statistical technique, known as discriminant analysis is employed here in order to make a more rational and systematic evaluation of damage inducing parameters in the prediction of seismic vulnerability of structures. The damage database employed was modified by reducing the damage states into three; none and light damage states were mapped into one category (N+L), moderate damage level was retained (M) and severe damage and collapse states were combined (S+C).

It is possible to evaluate structures at different performance levels according to different objectives. If the main concern is to identify the buildings that are severely damaged or collapsed, the first three damage states (i.e. N, L and M) can be considered as one group and the severely damaged state and collapsed cases as the other group, reducing the distinct damage states into two. Since the main objective is the identification of severely damaged or collapsed buildings for life safety purposes, this classification can be referred to as “Life Safety Performance Classification” (LSPC). Similarly, if the main concern is to identify the structures which suffer no damage or light damage during an earthquake, the first two damage states (N and L) can be considered as one group and remaining damage states (M, S and C) as the other group, reducing the distinct damage states into two. This identification is named as “Immediate Occupancy Performance Classification” (IOPC) since the main concern is to identify the buildings that can be occupied immediately after a strong ground motion.

In the discriminant analysis method, first the set of estimation variables that provides the best discrimination among the groups is identified. These variables are known as the “discriminator variables”. Then a “discriminant function”, which is a linear combination of the discriminator variables, is derived. The values resulting from the discriminant function are known as “discriminant scores”. The final objective of discriminant analysis is to classify future observations into one of the specified groups, based on the values of their discriminant scores.

The unstandardized estimate of discriminant function based on six damage inducing parameters is obtained for life safety performance classification by utilizing the SPSS [9] software and the database compiled after 1999 Düzce earthquake. Here, DI_{LS} denotes the damage index or the damage score corresponding to the LSPC and the other parameters are as described. The function given in Equation 4 is referred to as the unstandardized discriminant function, because the unstandardized (raw) data are used for computing this discriminant function

$$DI_{LS}=0.620n-0.246mnlstfi-0.182mnlisi-0.699nrs+3.269ssi+2.728or-4.905 \quad (4)$$

In the case of immediate occupancy performance classification, the unstandardized discriminant function, where DI_{IO} is the damage score corresponding to IOPC, based on these variables is:

$$DI_{IO}=0.808n-0.334mnlstfi-0.107mnlisi-0.687nrs+0.508ssi+3.884or-2.868 \quad (5)$$

A convenient statistical parameter for interpreting the contribution of each variable to the formation of the discriminant function is the loadings or the structure coefficients [10]. The structure coefficients that are obtained as an output from the SPSS software revealed that the number of stories above the ground level (n) has the highest loading [8], indicating that it is the best discriminator variable in LSPC. In the case of IOPC, again the number of stories comes out as the best discriminator variable and the normalized redundancy score is the second best.

In order to evaluate the performance of the buildings for which damage scores are calculated using the equations derived above, a cutoff value needs to be determined. This cutoff value is used to rank the vulnerability of buildings by comparing the damage scores computed with the cutoff value determined. The details of this classification methodology are given next.

Performance Classification Procedure

In the proposed classification methodology, buildings are evaluated according to both performance levels, by using Eqs. (4) and (5), and the final decisions for the damage state of the buildings are made by considering the results of the two performance levels simultaneously.

Moreover, the number of stories is the most significant variable in both performance classifications. In order to improve the discriminating contribution of other parameters, cutoff values are selected depending on the number of stories. For this purpose, a functional relationship is derived between the cutoff values and the number of stories, n , by fitting a least squares curve to the available damage data. Two constraints, 70% correct classification rate and the maximum classification error of 5% for life safety, are imposed. The resulting cutoff functions corresponding to the two types of classification are given in Equation 6.

$$\begin{aligned} CF(lspc) &= -0.090 \cdot n^3 + 1.498 \cdot n^2 - 7.518 \cdot n + 11.885 \\ CF(iopc) &= -0.085 \cdot n^3 + 1.416 \cdot n^2 - 6.951 \cdot n + 9.979 \end{aligned} \quad (6)$$

In the proposed classification procedure, first the damage scores are obtained by using Eqs.(4) and (5) for the cases of LSPC and IOPC, respectively. Then by comparing these damage scores with the story dependent cutoff values obtained from Eq. (6), the building under evaluation is assigned an indicator variable of “0” or “1”. The indicator variable “0” corresponds to none, light or moderate damage in the case of LSPC and none or light damage in the case of IOPC. Similarly, the indicator variable “1”

corresponds to severe damage or collapse in the case of LSPC and moderate or severe damage or collapse in the case of IOPC. In the final stage of the classification procedure, the building is rated as “safe” (i.e. “none or light damage”) , “unsafe” (i.e. “severe damage or collapse”) or “intermediate” depending on the values of the indicator variables. The building is classified as “safe” if both indicators from LSPC and IOPC are 0, the classification results in “unsafe” when both indicators are 1, and for other combinations of the indicators the building is classified as “intermediate”. For the buildings rated as “intermediate” the final decision on the seismic safety of the building is left for a more comprehensive seismic evaluation.

Although the decision parameters of the proposed classification method described above are derived from the Düzce damage database, the classification method is applied to the same database in order to check its correct classification efficiency. Out of the 484 buildings forming the seismic damage database, 99 buildings (37+11+51) that correspond to 20.5 % of the entire database, are classified as “intermediate” and left for further detailed evaluation. Among these 99 buildings, only two of them had an IOPC indicator variable of “0” and a LSPC indicator variable of “1”. This result actually indicates the success of the discriminating ability of the parameters used in the analyses. Out of 122 severely damaged or collapsed buildings, 98 buildings are correctly classified, 13 of them are misclassified and 11 of them are left for further detailed seismic analysis. Thus, the efficiency in identifying the severely damaged or collapsed buildings is increased to 80.3% and among the 484 buildings evaluated only 13 of the severely damaged or collapsed buildings are rated as safe. Thus, the misclassification that may lead to life loss is only 2.7%, i.e. $13/484=0.027$.

Application of the Proposed Methodology to Other Seismic Damage Databases

It is desirable to check the validity of the proposed statistical model by examining the correct classification rates in cases of different databases compiled from different earthquakes. For this purpose, the proposed methodology and the accompanying discriminant functions were applied to damage data assessed from the 1992 Erzincan earthquake and the damage data compiled after 2002 Afyon earthquake [8].

The classification results according to the proposed classification methodology demonstrate that the correct classification rate for severely damaged and collapsed buildings is quite high. On the other hand, the correct classification rate for none and a light damage state is found to be 96.4 % for the Erzincan database and 75.0 % for the Afyon database. Only 3 buildings forming 9.3 % of the Erzincan database and 22.2 % of the Afyon database cannot be judged. These buildings are identified as “intermediate” and they are the buildings that require further detailed investigations [8].

Considering the existence of various random factors (such as geotechnical parameters) and sources of uncertainties, these rates are found to be quite satisfactory and support the predictive ability of the proposed statistical model.

INCLUSION OF SITE CHARACTERISTICS

The cutoff values developed earlier are considered to be valid for damaging earthquakes ($M_w > 6.4$) and the regions that have similar distance-to-source and site conditions to that of Düzce. To apply this procedure to the sites, which have different distance-to-source and soil properties than Düzce, further modifications must be made to improve the procedure that is presented in the preceding sections.

The purpose of the improvement is to capture the relative variation of the ground motion intensity with the distance-to-source and the soil type. The spectral displacement value was selected as the damage inducing ground motion parameter, as it is a widely used parameter for expressing the vulnerability of buildings.

The general trend of a damage curve suggests that the variation of damage with S_d follows the form of an exponential function [11]. This inference is used to link the change in S_d to the change to be imposed on the cutoff values obtained for Düzce. The spectral displacement can be obtained from elastic site spectra computed using available attenuation relations. A number of relations, available in the literature, can be employed to relate inelastic spectral displacement to the elastic one. Although the expressions seem quite different, their influence on the cutoff modifications is shown to be insignificant, especially in the range considered in this study [12]. For this reason, equal displacement rule is considered to be reasonable.

The proposed procedure is developed on the basis of several assumptions, which are listed below:

- The earthquake magnitude in the region to which the method is applied is similar to the one that affected the reference site, i.e. Düzce.
- Attenuation relations are believed to represent the variation of the ground motion adequately.
- Construction practice does not show regional variations.
- Damage pattern observed in the reference site would be the same for other sites that have same distance-to-source and soil type.

The steps involved in this procedure can be outlined as follows;

Step 1: Obtain site-specific response spectra using an appropriate attenuation model.

Step 2: Calculate spectral displacement at the fundamental periods of interest.

Step 3: Plot spectral displacement/n as a function of the fundamental period (or n), n representing number of stories considered in the Düzce study.

Step 4: Convert spectral displacement to a damage index (cutoff value) by assuming an exponential relation.

Step 5: Normalize all damage indexes at different sites and distances with the damage index obtained for the reference site, i.e. Düzce.

Step 6: Modify Düzce cutoff values by multiplying them with the cutoff modification coefficients, i.e. normalized values calculated in Step 4.

Site Classification and Attenuation Models

Two major parameters used for site classification are the “distance-to-source (d_s)” and the “soil type (ST)”. The sites were characterized by a pair of d_s and ST bins. Five d_s bins were selected considering the variation in the response spectra with the distance. ST bins were determined based on the shear wave velocity (V_s) of the soil types employed by the Turkish Seismic Code [13]. Twenty different site classes were obtained from the combination of d_s and ST bins, which are illustrated in Table 2. Note that type C2 represents the reference site (Düzce). This way, any region with a certain d_s and ST is assigned a site class according to Table 2, excluding the sites located farther than 50 km from the source. The number of sites can easily be increased by incorporating other distance ranges and soil types (i.e. $V_s > 1000$ m/s).

Table 2. Site Classification

Soil Type	Shear Wave Velocity (m/s)	Distance to Source (km)				
		0-4	5-8	9-15	16-25	26-50
A	701-1000	A1	A2	A3	A4	A5
B	401-700	B1	B2	B3	B4	B5
C	201-400	C1	C2	C3	C4	C5
D	<200	D1	D2	D3	D4	D5

Three attenuation relationships that are suitable for the source mechanism of the North Anatolian Fault were considered. The models developed by Boore et al. [14], Gulkan and Kalkan [15], and Abrahamson and Silva [16] were used to generate site-specific response spectra for all twenty sites included in Table 6. Boore et al. [14], and Gulkan and Kalkan [15] are the most convenient ones because they use the shear wave velocity directly to account for the soil type. For Abrahamson and Silva [16], however, NEHRP amplification functions were applied on the rock motion to obtain site response spectra. Since the uncertainty in attenuation models can be substantial, using different attenuation models is believed to give a better representation of the actual condition. Among the ones selected, Gulkan and Kalkan's model has been developed based on the local data recorded in Turkey. These models are compared at different distances as shown in Figure 1. Although at short distances Gulkan and Kalkan's model suggest lower estimates as compared to others, at far distances the situation is the other way around.

Calculation of Spectral Displacement

Since the reference cutoff values were obtained as a function of the building height (number of stories), modification factors were also intended for the discrete height levels included in the database. Hence, a relationship between number of stories and the fundamental period was established based on the Turkish Seismic Code formulae. The mean values of the period against the number of stories were obtained for the buildings contained in the Düzce seismic damage database: the mean periods for 2, 3, 4, 5 and 6 stories are 0.275, 0.355, 0.433, 0.504 and 0.529 seconds, respectively. Although the variation and dispersion of the period with number of stories is large for the buildings in the database, this would not significantly affect the modification factors as will be shown later.

An examination of the computed site-specific response spectra using various attenuation relationships revealed that the variations in the spectral ordinates are insignificant within the distance bins that were selected in this study [12]. Spectral displacement values were obtained from the calculated spectral accelerations at all mean periods given above for each of the twenty site classes. The spectral displacement normalized with number of stories (corresponding to the building period) is plotted against the number of stories as shown in Figure 2.

This normalization was done to obtain a similar term that would mimic the average drift. The change of S_d with the site class is also evident from these plots. When a linear regression is used to represent data a constant line develops, this is the simplest and the most convenient choice because it leaves out the number of stories. The influence of the attenuation functions on the calculated response for site C3 is shown in Figure 3. Abrahamson and Silva [16] yields similar results to that of Boore et al. [14], Gulkan and Kalkan [15], however, provides lower estimates of S_d at all periods.

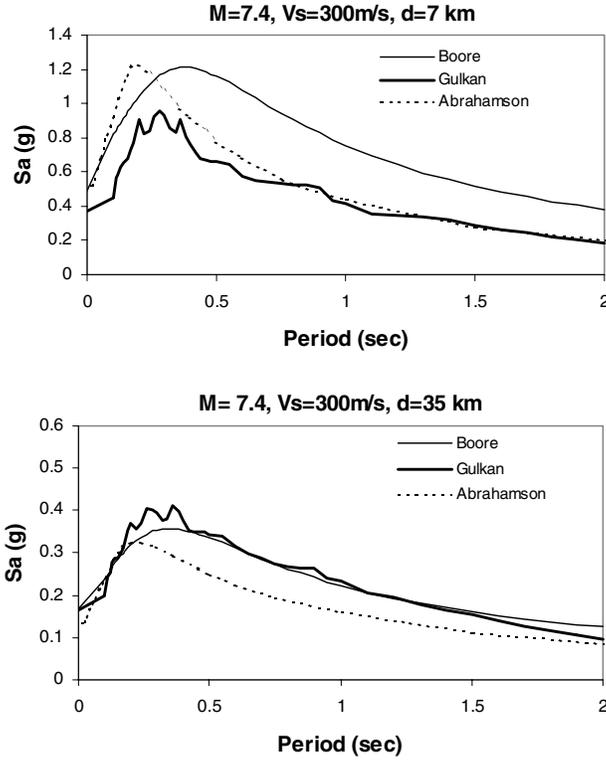


Figure 1. Comparison of the Attenuation Models

Calculation of Modification Factors

The computed S_d values for all sites are then translated into damage terms. In the vulnerability assessment procedure developed for Düzce, there is a reverse relationship between the cutoff value and the damage score of the evaluated building. In other words, as the cutoff value is raised the number of “unsafe” buildings decreases. In view of this relation, the change of the cutoff value (CV) with the normalized spectral displacement was assumed to follow a similar trend observed between damage and S_d/H . Thus, the following function is assumed to reflect the relation between the CV and the normalized spectral displacement (S_d/n);

$$CV = f \left[\frac{1}{1 - e^{-S_d/n}} \right] \quad (7)$$

Since the objective is to obtain cutoff modification coefficients (CMC) to be applied to the reference cutoff values (CV_r), the function in Equation 7 can be used to get CMC values. The calculated CMC values are presented in Table 3 for the three attenuation models employed.

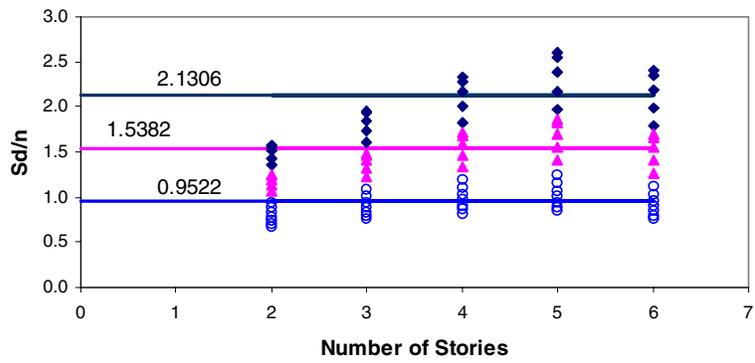
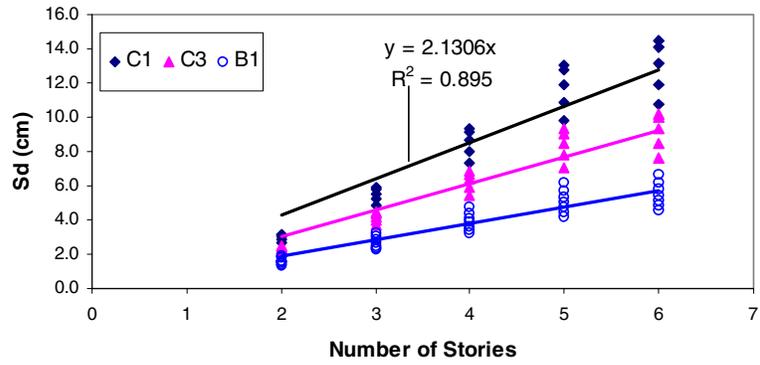


Figure 2. Normalized S_d versus Number of Stories (Linear Representation)

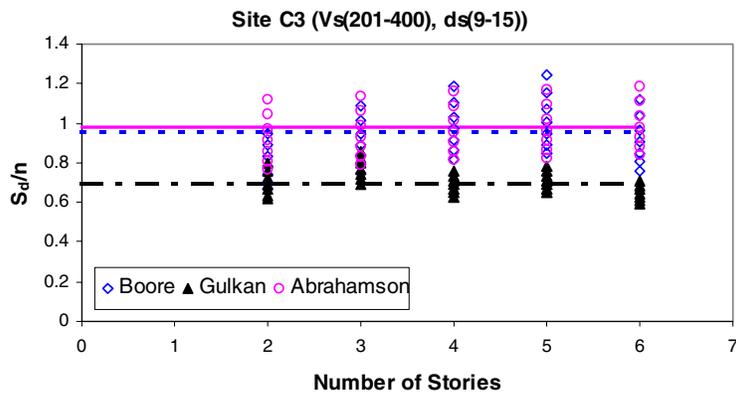


Figure 3. Influence of Attenuation Relation

The CMC can take values between 0.78-3.90, 0.79-2.14, and 0.83-3.03 for Boore et al., Gulkan and Kalkan, and Abrahamson and Silva, respectively. Moreover, among all attenuation models, the one by

Gulkan and Kalkan led to narrower range of modification values, meaning that performance differences of the buildings between the sites would be less. The CMC value for reference site class C2 is 1.0 because of the normalization with respect to this site. Obviously, at better site conditions and farther distances cutoff values should be larger. These CMC values were multiplied with the respective reference cutoff values to obtain the cutoff values for other site classes. Modified cutoff values are computed from $CV = CV_r + ABS(CV_r) * (CMC - 1)$, which can handle negative as well as positive values of reference cutoff values.

Table 3. Cutoff Modification Coefficients (CMC)

		Boore et. al. [14]					Gulkan and Kalkan [15]					Abrahamson and Silva [16]				
		Distance (km)														
n	Vs (m/s)	0-4	5-8	9-15	16-25	26+	0-4	5-8	9-15	16-25	26+	0-4	5-8	9-15	16-25	26+
2-3	0-200	0.78	0.82	0.93	1.13	1.54	0.79	0.84	0.93	1.08	1.36	0.83	0.92	1.08	1.36	1.89
	201-400	0.86	1.00	1.24	1.64	2.41	0.93	1.00	1.13	1.33	1.71	0.87	1.00	1.22	1.58	2.24
	401-700	0.97	1.18	1.53	2.10	3.18	1.03	1.11	1.26	1.51	1.95	0.92	1.08	1.34	1.77	2.54
	701+	1.08	1.36	1.81	2.53	3.90	1.12	1.21	1.38	1.65	2.14	1.00	1.21	1.54	2.07	3.03
4-6	0-200	0.78	0.82	0.93	1.13	1.54	0.79	0.84	0.93	1.08	1.36	0.83	0.92	1.08	1.36	1.89
	201-400	0.86	1.00	1.24	1.64	2.41	0.93	1.00	1.13	1.33	1.71	0.87	1.00	1.22	1.58	2.24
	401-700	0.97	1.18	1.53	2.10	3.18	1.03	1.11	1.26	1.51	1.95	0.92	1.08	1.34	1.77	2.54
	701+	1.08	1.36	1.81	2.53	3.90	1.12	1.21	1.38	1.65	2.14	1.00	1.21	1.54	2.07	3.03

The procedure outlined earlier can be used to determine vulnerability of a given building stock located in high seismic areas in Turkey. The cutoff value obtained from Equation 6 needs to be modified using Equation 8 and proper values from Table 3 depending on the site class.

APPLICATION TO ISTANBUL

An exercise was undertaken to test the efficiency of the procedure as well as to see the extent and relativity of the expected damage or the layout of the risk within Istanbul. In this application, the major assumption of having similar construction practices in Duzce and Istanbul is reasonable and valid because all buildings in Düzce database were assumed to portray buildings all over Istanbul rather than dealing with the actual building inventory. It suits the purpose and provides results that indicate the use of discriminant functions along with the cutoff modification coefficients (CMC) obtained.

A uniform exposure that is identical to the compiled database for Düzce, is assigned to all districts of Istanbul. The earthquake scenario “Model A” and shear wave velocity estimates of JICA study [17] were employed to model the fault and to classify the sites. The modified cutoff values were applied and all buildings were identified as “safe”, “unsafe” or “intermediate” in all districts of Istanbul. It should be pointed out that “safe” buildings represent the structures that would experience none or light damage states, “unsafe” buildings include those that are expected to suffer severe damage or would collapse, and “intermediate” buildings might encompass buildings with all degrees of damage, that can not be clearly identified.

The ratios of the buildings classified as safe, unsafe and intermediate buildings to the total number of buildings were obtained using the attenuation relationship of Boore et al. [14] in all-districts of Istanbul. Figures 4 and 5 show the distribution of unsafe and intermediate buildings. The visual plots indicate some spotty areas, which reflect the local soil profile. The effect of distance to source is clearly observed.

The range of safe buildings varies from 38% to 60% depending on the site class. Unsafe buildings constitute 1-40 % and buildings identified as intermediate, which represent buildings that could not be clearly classified as safe or unsafe, have a share of 21-39%. Of the indeterminate buildings, around 50% were moderately damaged, 38% had light or no damage and 10% were severely damaged in Düzce.

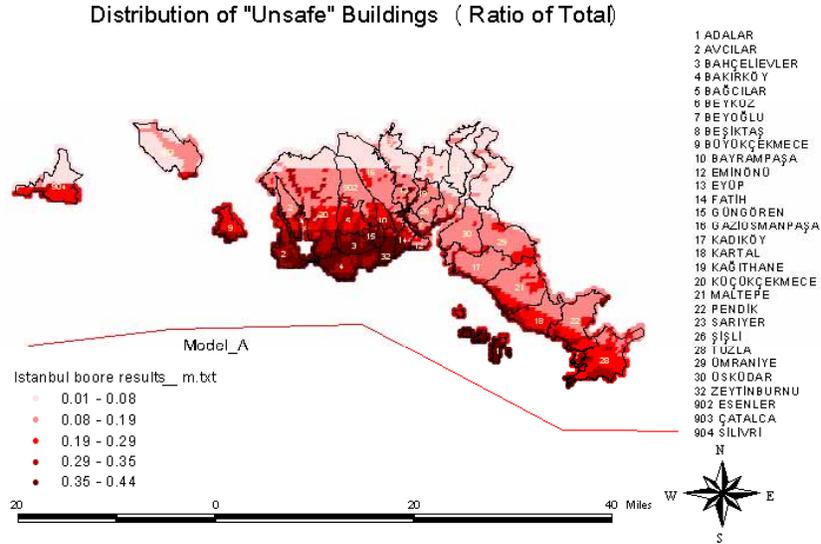


Figure 4. Identification of Unsafe Buildings

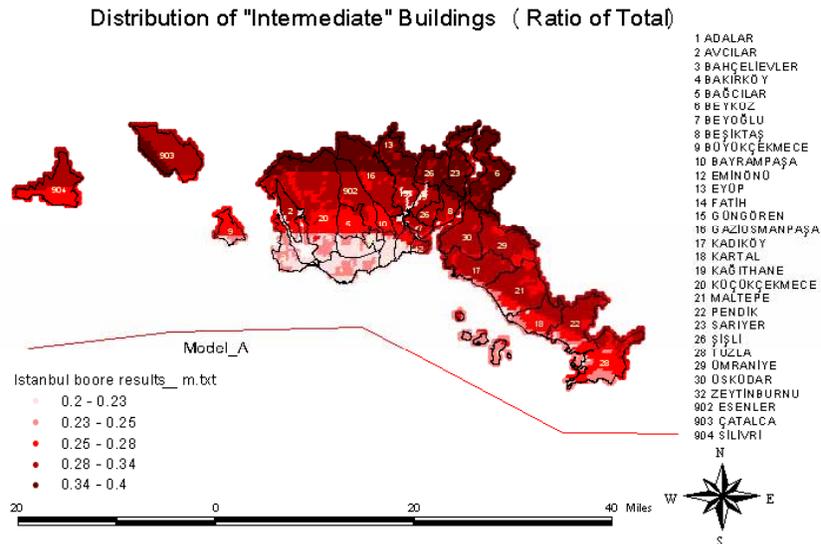


Figure 5. Identification of Intermediate Buildings

CONCLUSIONS

The procedure proposed for the preliminary assessment of the seismic vulnerability of existing reinforced concrete buildings is developed using a statistical analysis technique and a damage database compiled in Düzce. Six estimation parameters, namely number of stories, existence of soft story, normalized redundancy score, degree of overhang, the minimum normalized lateral stiffness and minimum normalized lateral strength indices, are considered for the assessment of seismic vulnerability. Among these parameters the number of stories is found to be the most discriminating parameter for existing low-to mid-rise reinforced concrete buildings. The building to be evaluated is classified based on a damage score computed using all estimation parameters and comparing it with the corresponding cutoff values. Buildings are assigned three classifications as “safe”, “unsafe” or “intermediate”. Further detailed evaluations are recommended for buildings classified “intermediate”.

It has been shown that vulnerability assessment procedures based on observed damage from a particular region can be extrapolated to other sites having similar construction practices and building stock. The variation of ground motion parameters that have known relationship to the damage of buildings are captured using attenuation models that reflect the properties of the sites, i.e. the distance to source and soil type.

The procedure can be applied to other regions to identify reliably high-risk areas and vulnerable locations. This would help determine the rank of regional vulnerability and the mitigation priorities, especially for the mega city of Istanbul for which a large earthquake is due.

This technique is a reasonable theoretical approach that uses available tools to predict the spatial variation of ground motion. Further improvements to the procedure can be made, especially in the intermediate steps, but the end results, which are the modification coefficients, would not be influenced considerably. Besides, the assumptions and approximations already introduced are far beyond the accuracy that would be gained this way.

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