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# Seismic Risk Assessment of Collapsed Buildings with Different Approaches

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**ABSTRACT:**

After the experiences of demolishing earthquakes in 1999 with a magnitude greater than 7.2 in Turkey, the perspective of the country has been changed about the earthquake preparedness and mitigation policy to alleviate future risk from similar events. Various rapid screening approaches have been developed recently to determine the seismic risk level of existing buildings in Turkey, due to the fact that the building stock is too big for code-based detailed investigation, like in many earthquake prone countries. P25 Scoring and Seismic Safety Screening methods are two of the most popular approaches which have been developed and applied widely to identify the collapse vulnerable structures, in Turkey. In this study, following a brief explanation of the seismic activity experienced in Duzce, the basic concepts of the code-based methods, P25 Rapid Scoring and Seismic Safety Screening methods are presented. These methods have been applied to different reinforced concrete (RC) real building data which were heavily damaged or collapsed in Duzce earthquake. The results obtained are shown to be in good agreement with the real damage-state of the buildings.

## 1 INTRODUCTION

As it is known, Turkey is a seismically active country located in the complex zone of collision between the Eurasian plate and both the African and Arabian plates. Thus, seismic hazard is spread almost all over the country and many demolishing earthquakes have been recorded in Turkey's history. Duzce Earthquake is one of those great seismic activities occurred only 3 months after the August 1999 Kocaeli Earthquake of 7.4 Magnitude.

Following these devastating earthquakes in 1999 and tremendous number of life losses, the Turkish Government was faced with a big financial burden as a result of its statutory obligation to cover the full costs of rebuilding. In order to offset such catastrophic outcomes in future earthquakes, researchers and the local authorities were after some wise and applicable solutions to minimize the earthquake loss. A key element for successful implementation of such a "campaign" of minimizing the losses in near future is the prioritization of the buildings so that the collapse vulnerable structures can be identified to be retrofitted or demolished before the expected earthquake. Until recently, the only way of doing this was using a code-based procedure to check every single building in the area to identify "unsafe" buildings. This is a natural choice for mitigation works because it is fully defined and justified by seismic codes, apart from the fact that it is straightforward and relatively reliable. However, this code-based approach of assessing the whole stock one by one presents financial and time constraints that render almost impossible to complete such an enterprise. Other than too big amount of financial sources are needed which cannot be afforded by a local authority, another major shortcoming is that the time needed for such work will be too long, where if a serious seismic activity is expected in the near future and the building inventory is quite large as for the case of Istanbul. To minimize the losses, many researchers work on some simplified preliminary methods to identify the collapse vulnerable buildings by using certain parameters and making quick observations without using detailed 3D analyses. Starting from 70's some rapid assessment methods are suggested to screen the existing structures in earthquake prone regions. Obviously, methodologies based on such approaches must be 'quick and cheap' but yet 'reliable enough' to identify the collapse vulnerable buildings correctly so that the local authorities can be convinced and transfer their limited sources in order to assess the situation of those critical buildings in more detail.

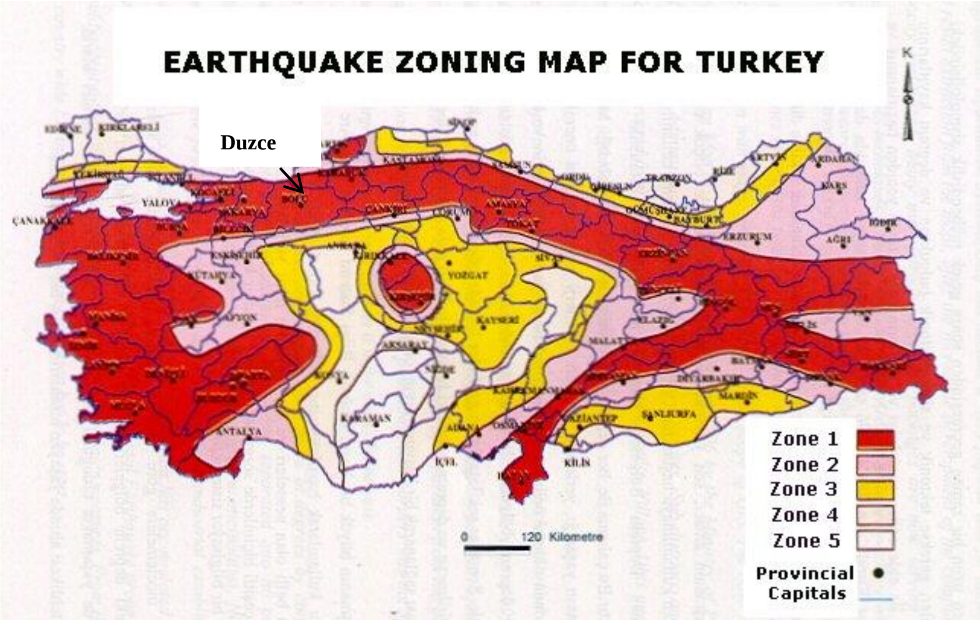


Figure 1 Seismic Hazard Map of Turkey

## 2 DESCRIPTION OF DUZCE EARTHQUAKE

Duzce is a small town of 80.000 population located about 150km away from Kocaeli, Turkey (Fig. 1). On August 1999, the Ms=7.4 Kocaeli Earthquake broke almost 140km long at the Western part of the 1200km North Anatolian Fault. Just after some damage experienced in the town due to this devastating earthquake, another shaking was experienced on November 1999 in Duzce with a magnitude of Mw=7.2, as the continuation of that seismic activity along North Anatolian Fault breaking about 40 km of fault rupture on the segment of the same fault, (Fig. 2). Fortunately, loss of life is somewhat limited since the buildings damaged in August 1999 earthquake were already vacated as compared to the previous shake, nevertheless, causing 894 fatalities and extensive building damage in the province of Duzce.

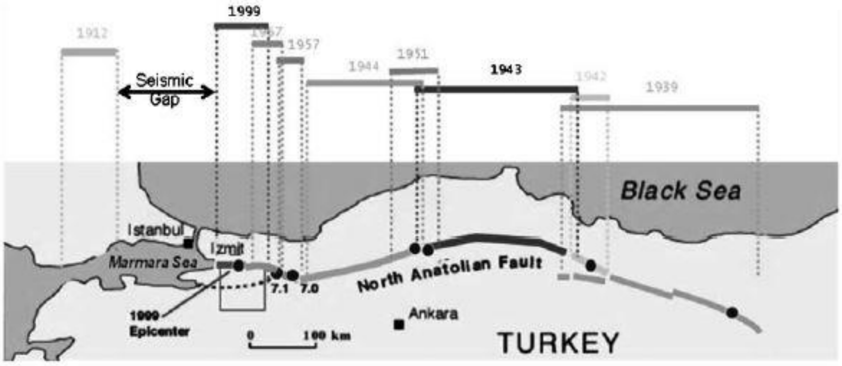


Figure 2 North Anatolian Fault and its Rruptures

## 3 CODE-BASED SEISMIC RISK ASSESSMENT METHODS OF RC BUILDINGS

The Turkish Earthquake Code (2007) (TEC'07) suggests utilizing either force-based linear or displacement-based nonlinear analyses for the determination of seismic performance of RC buildings. In all of these methods, seismic analysis is carried out using effective (cracked) rigidities of the cross-sections with the behaviour factor R=1. The knowledge level coefficient varying from 0.75 to 1.00 is determined with regard to necessary information available about the structural details. Each member has to be defined as brittle or ductile based on the analysis results. Shear and compression failures are categorized as brittle, while the flexural failure is recognized as ductile.

Member damage levels are classified as ML: Minimum damage, SL: Safety level, CL: Collapse level as shown in Figure 3. The seismic load applied on the structure depends on the required minimum performance level(s) defined as: PIO: Immediate Occupancy, PLS: Life Safety, PCP: Collapse Prevention. The seismic performance of a building is determined by obtaining story-based structural member damage ratios under linear or non-linear approaches. Further details about this procedure can be found in TEC'07 (2007).

Due to the urgent need for the assessment of millions of existing, inadequate buildings in Turkey, the government issued an Urban Transformation Law, in 2013 to be applied to the vulnerable building stock located in most critical areas. With that law, a simplified linear assessment method was also suggested to be applied on the weakest floor of the building, which is referred as the critical floor, thus that investigation of risky or safe state is made for the entire building. In this assessment method, only vertical structural members of the critical floor are examined for the final risk determination. In addition, contribution of the infill walls in the frames also taken into consideration.

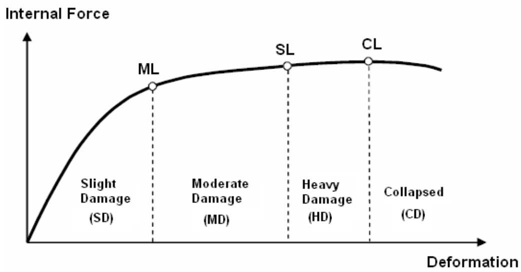


Figure 3 Damage limits of ductile members

### 3.1 **Linear Approach**

The linear assessment is performed by using equivalent static force distribution if the total building height is less than 25m and torsional irregularity is negligible, or otherwise the modal superposition method should be used. The final seismic performance of the building is determined based on the damage distributions of structural components, which are obtained by demand/capacity ratios (DCR). DCR values are simply calculated by using the residual moment capacities of ductile members. The relative lateral displacements of the structural components must also be checked at each storey to evaluate their damage levels.

### 3.2 **Nonlinear Approach**

The displacement-based nonlinear approach defined in TEC'07 aims to obtain the plastic deformation or force demand at each structural member regarding its ductile or brittle behaviour, respectively. These demands are then compared with the strain limit states and the internal force capacities of the member. Plastic rotation demands are obtained from plastically deformed ductile cross-sections. From plastic rotations, total curvature demands are determined. Then, curvature demands are converted to strains occurred at concrete and reinforcement bars. These strain demands are compared with the limit strain values in order to specify the member damage levels. Damage limit states are described as follows: ML: Minimum damage limit is the outer fibre strain of the core concrete to reach 0.0035 or the vertical steel bars to reach to 0.010. Maximum strain values for SL: Safety level are $0.0035+0.01\ (\rho_s/\ \rho_{sm}) \leq 0.0135$ and 0.040 and the limit for CL: Collapse level is $0.0040 + 0.014\ (\rho_s/\ \rho_{sm}) \leq 0.018$ for concrete and 0.06 for steel, respectively. (Here $\rho_s$ and $\rho_{sm}$ stand for the volumetric ratio of the existing and code-required transversal reinforcement, respectively, with the reason that the transversal reinforcement satisfies the conditions of the ductile earthquake resistant design). According to the displacement-based non-linear assessment in TEC'07, the strains at plastic cross-sections are to be verified as contrary to the chord rotations of primary ductile elements must be checked for Eurocode safety verifications. Damage limit states are described according to the damage limits of strain values as ML, SL and CL. Again, code definitions of the performance level of the structure are based on the number of members falling into certain band of limit states.

## 4 RAPID ASSESSMENT METHODS FOR EXISTING RC BUILDINGS

There exists large number of RC buildings that are gravity load designed with insufficient lateral load resistance, in most seismic regions all over the world. Many of these existing structures were not designed adequately or simply designed according to the old seismic codes of that country that may have been upgraded over the years. Most of these buildings urgently need to be reassessed and retrofitted to minimize seismic damage and life loss. In order to overcome this problem, various rapid screening methods have been developed to identify quickly the collapse vulnerable structures without performing elaborate 3D structural analysis procedure.

A rapid screening method was first proposed with ATC 21 in 1988 and the new versions were also issued by FEMA in 2002, (FEMA 154-155, 1988, 2002]. Several researchers have then worked on alternative methods to define the collapse risk of existing buildings by using certain parameters that affect response of RC buildings. Seismic Index Method (Ohkubo, 1990) is one of those developed for the assessment of inadequate Japanese buildings. P25 Scoring Method is another recently developed preliminary assessment method, which was developed and calibrated with many buildings affected in different past earthquakes through a research project (Gülay, et al, 2008).

All of these preliminary assessment techniques do not usually require heavy analytical work, whereas they are based on some basic factors adversely influencing the earthquake behaviour of buildings, like presence of soft story or/and, weak story, short columns and heavy overhangs, pounding effects, type of soil profile, etc.

### 4.1 **P25 Rapid Screening Method**

P25 Method was initially suggested by Bal (2005) and then it was developed and calibrated with many heavily, moderately, slightly or undamaged buildings in different past earthquakes experienced in Turkey, through an intensive research project supported by TUBITAK (Gülay, et al, 2008). As shown in Figure 4, the method predicts correctly the collapse risk of existing RC buildings.

P25 Method is primarily based on calculation of ratios related to cross-sectional characteristics of structural members and infill walls, as well as on observing and scoring the most important structural parameters which affect the seismic response of buildings. The basic parameters of the methodology may be listed as (a) cross-sectional dimensions of RC columns, shear-walls and infill walls at the critical floor, which is usually the basement or ground floor (b) storey heights, $h_i$, and the total building height, H, (c) outer plan dimensions of ground floor $L_x$, and $L_y$ (d) typical beam dimensions, (e) effective ground acceleration, (f) building importance factor, (g) soil conditions and soil profile, (h) other observational or measurable parameters like material quality, stirrup spacing or confinement zones of columns, pounding effect, topographic conditions. Various structural irregularities and their levels are also considered in the method such as, existence of short columns, torsion, soft storey, frame discontinuity, etc. either by observing or performing quick calculations.

The method considers 7 different failure criteria $P_i$ (i=1, 2,,7) and their interaction. The first one ($P_1$) is related to the basic structural characteristics (i.e. column and wall area and inertia ratios, material properties, irregularities etc). The second failure mode ($P_2$) is short-column induced mechanism, decided according to the short -column length and the level of occurrence of short columns at the critical floor. $P_3$ is soft- and/or weak-storey mechanism which is determined by the difference in succeeding storey heights and strengths. $P_4$ includes possible weaknesses due to over-hanged upper floors and lack of perimeter beams which causes frame discontinuity. $P_5$ failure mode is based on the pounding effect induced by the adjacent structures. $P_6$ and $P_7$ are related to liquefaction and other soil failures, respectively. The interaction among these failure criteria has also been included in the calculations. The final performance scores of the buildings are graded between 0 and 100, varying from the worst to the best, respectively.

Studies on some hundreds of buildings affected by different earthquakes show that the high risk band is between the scores of 15 and 40 and the performance score of 30 can then be considered as the safety-limit (Fig. 4). Buildings within the high risk band are strongly recommended to be assessed in detail by expert engineers (Gulay, et al, 2008).

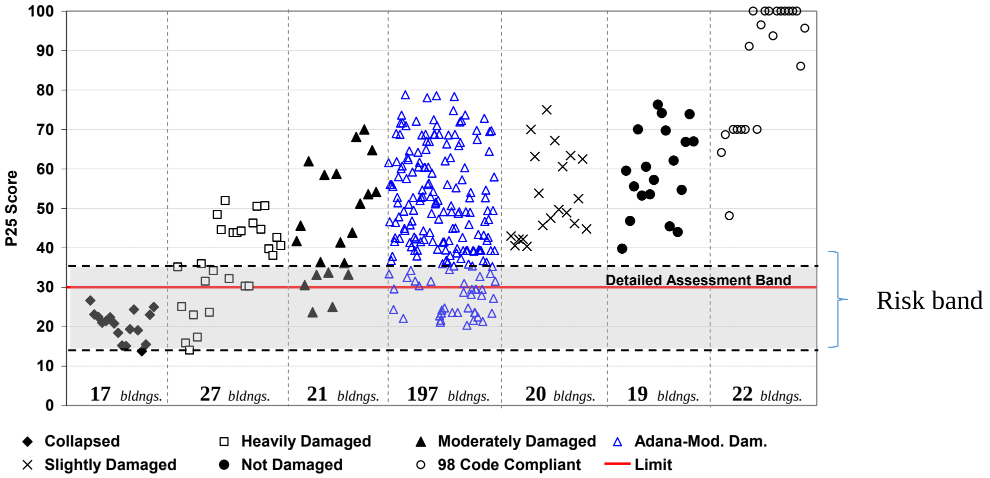


Figure 4 The results obtained with the application of the P25 Method on 323 real RC buildings

## 4.2 Seismic Safety Screening Method (SSSM)

Seismic Index Method (Ohkubo 1990) is one of the rapid assessment methods which has been modified, calibrated and named as 'Seismic Safety Screening Method: (SSSM)' by Boduroglu, et al (2004) to be used in Turkey after the devastating earthquakes, in 1999. The method is used for rapid seismic safety evaluation of RC structures with 7 or fewer stories. Buildings having very unusual geometry, or having too low quality material, older than 30 years or exposed to fire could not be tested with this approach. Actually, a three level evaluation is utilized in the Seismic Safety Screening Method (SSSM) from simple to more sophisticated.

First step of investigation involves the examination of the structural system, age and physical conditions of the building. After this examination, the performance index $I_s$ of the existing building is calculated by using Eq. (1).

$$I_S = E_O \times S_D \times T \qquad (1)$$

Here, $E_o$ is the basic structural performance index. For the calculation of $E_o$ index, vertical structural members are examined in three distinct groups as columns, short columns and shear walls. If the ratio of the clear height to the cross-sectional depth is bigger than 2 ($h_0/D>2$), then the member is defined as column. If the ratio of the clear height to the cross-sectional depth is equal or smaller than 2 ($h_0/D=2$), then the member is defined as short column. The calculation of $E_o$ Index differs when contribution of short columns is neglected or not. $S_D$ is an index to evaluate the physical properties and the geometry of the structure, like the irregularity in plan, length-width ratio of the plan, clearance of the expansion-joints, atriums, eccentricities in plan, irregularity of story heights, existence of piloti, etc. For example if the building has a symmetric plan, $S_D$ can be considered as 1.0. However, if the building has an irregular plan, then $S_D$ should be considered as 0.9. T is an index, which is determined according to the existing damage of the building due to environmental effects, aging effects, etc. which can be selected between 0.8 and 1.

Then, reference or demand index $I_{so}$ is determined with Equation 2 below:

$$I_{SO} = E_S \times Z \times G \times U \qquad (2)$$

In this equation Z is zone factor, which has to be considered as 1.0 for the areas of high seismic risk, or Z can be reduced according to the seismicity of the region. However, in any case Z should be considered as greater than 0.7. G soil coefficient is related with the local conditions having values between 1.0 and 1.1 with lower values represent better soil conditions. U usage coefficient is related with the importance and usage of the buildings, like residential buildings, hospitals, schools, fire stations, etc., it is convenient to use U as 1.0 for usual buildings. $E_s$ basic reference index can be considered as 0.8 for this first stage analysis. However, according to the statistical data for typical existing buildings in Turkey, this coefficient may be subjected to alterations.

Comparing this performance index $I_s$, with the adequate reference or demand index $I_{so}$ the seismic safety of the building can be estimated. This comparison should be repeated for all critical stories and for two principal directions. Actually, if for all comparisons $I_{so} < I_s$ then the building may be assumed to be safe against earthquakes. If for any of the comparison cases $I_{so} > I_s$ then it is concluded that the behaviour of the structure is indeterminate then, further analysis is needed to determine its seismic vulnerability against earthquakes.

According to the calibration study by checking the moment ($M_r/M_d$) and shear ($V_r/V_d$) ratios of the members, where $M_r$, $V_r$ represent bending moment and shear capacities, and $M_d$, $V_d$ represent bending moment and shear demands, respectively, on many vulnerable or damaged Turkish buildings performed by Boduroglu, et al (2004), it is indicated that if the ratio $I_s/I_{s0}$ is 0.40 or greater, then the building can be used safely since very probably the total collapse of the building will be prevented (Figure 5), although it does not mean that the structure will not be damaged, or otherwise if $I_s/I_{s0}$ is smaller than 0.40 then it is not safe to use those buildings and urgent serious measures should be taken.

At the second level of the investigation, carrying capacity and the ductility levels of columns and shear-walls are calculated more precisely and elaborately. Although the second and third levels of the Seismic Index Method can give more realistic results about the seismic safety of the building, only the first level is considered in this study, since anyone of which can be applied independently and the primary concern was on rapid seismic safety evaluation.

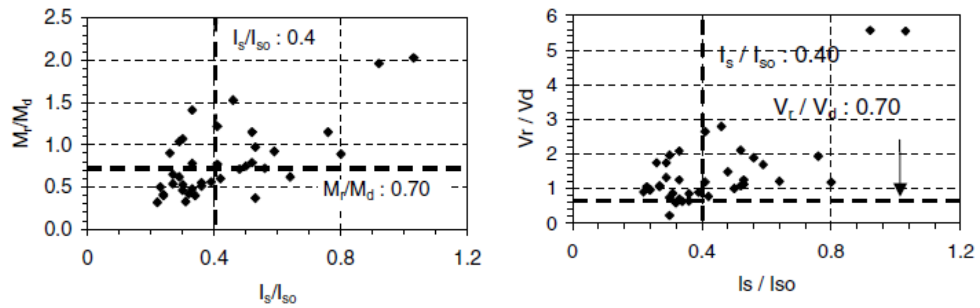


Figure 5 Relationships of moment and shear capacity/demand ratios with $I_s/I_{s0}$ (Boduroglu,et al, 2004)

## 5 DESCRIPTION OF CASE STUDY BUILDINGS

The seismic assessment procedures have been applied to 7 different RC buildings in order to examine the correlation with the real damage states. These buildings were all collapsed or heavily damaged in Duzce earthquake, except the code numbered [01-IST] building which is located in Istanbul and have not exposed to serious seismic action yet. All buildings were located in the 1$^{st}$ degree of earthquake zone (i.e. 0.40g effective PGA) on soil type either Z1 or Z3. Note that according to the TEC’2007 soil type is getting worse from Z1 towards Z4. Average concrete strength is assumed as 10.000 kN/m$^2$, steel yield strength is 220.000kN/m$^2$.The distributed live load is assumed as 2kN/m$^2$. They are all residential buildings, however since ground floors are used for commercial purpose, most of them have soft story and weak story irregularities. The knowledge level is taken as 0.75 in all of the calculations and it is assumed that 8 mm diameter transverse reinforcements are used with 200 mm spacing without any confinement zone in beams and columns. The ages of the buildings were all less than 25 years and they had never experienced a fire. They are all framed structures with infill walls without shear walls or with very small amount of wall around the lifts. Their properties like construction dates, story numbers (n), building plan area (A), total height (H), height of the ground floor ($h_G$), regular story height ($h_i$) of the structures and information about the existence of basement (B) and mezzanine floor (MF) are given in Table 1.

Table 1. Properties of the investigated buildings

| Build. Code | 01-IST | 02-DUZ | 03-DUZ | 04-DUZ | 05-DUZ | 06-DUZ | 07-DUZ |
|---|---|---|---|---|---|---|---|
| Soil type | Z1 | Z3 | Z3 | Z3 | Z3 | Z3 | Z3 |
| Const. Date | 1985 | 1992 | 1997 | 1989 | 1992 | 1995 | 1990 |
| n | 4 | 7 | 5 | 5 | 6 | 7 | 6 |
| A ($m^2$) | 109 | 405.6 | 225 | 524.4 | 239 | 582 | 485 |
| H (m) | 12.50 | 19.60 | 17.50 | 15.00 | 17.50 | 19.50 | 17.30 |
| $h_G$, (m) | 3.50 | 3.15 | 3.5 | 3.50 | 3.5 | 3.20 | 3.30 |
| hi (m) | 3.00 | 2.80 | 2.80 | 2.80 | 2.80 | 2.80 | 2.85 |
| B, MF | - | B, MF | B, MF | B | B | B, MF | B |

# 6 EVALUATION AND COMPARISON OF THE BUILDING PERFORMANCE LEVELS

## 6.1 Performance Evaluation with Rapid Assessments

Using the architectural and reinforcement drawings of the considered buildings, the rapid assessment methods P25 and SSSM have been applied on those buildings to obtain a quick estimation of their seismic vulnerability prior to the conduct of detailed analysis, (Pour, H.H. 2011). As it is seen in Table 2, all of the investigated buildings have P25 scores lower than 30 which is proposed as the safety limit (collapse limit) by (2006, Bal, et al and 2008, 2008a, Gulay, et al, ), it means they are all collapse vulnerable except the 01-IST coded building located in Istanbul. This building has not exposed to a big seismic action yet, however it is at critical level in terms of seismic risk, thus it must be analysed in detail by expert engineers. The $I_s/I_{s0}$ ratios in X and Y directions of each building have been calculated at each story for the application of SSSM and the minimum of those values are tabulated in Table 2 in order to check if they are greater than 0.40 as proposed the collapse limit value by Boduroglu, et al (2004). As it is presented in Table 2 they all have been found to be collapse vulnerable and need urgent measures. Unfortunately, all those buildings were already collapsed (or heavily damaged) during 1999 Duzce earthquake and thus the obtained performance levels proved that the real damages of the case study buildings are predicted quite successfully.

## 6.2 Performance Evaluation with Code-based Assessments

The case study buildings have been evaluated with the aforementioned code-based approaches with ETABS Package(2011) using their architectural and reinforcement plans, though the buildings except the first one, had already been demolished. The knowledge level is assumed as 0.75 for Duzce buildings and 0.90 for 01-IST building, since it was investigated in situ.

For the linear assessments; DCR values have been calculated, assuming members do not have confinement. The relative lateral displacements of the structural components have also been checked (Relative story drift limits are taken as ML:0.01, SL:0.03 and CL:0.04) at each storey to evaluate their damage levels. As it is observed in Table 2, the performance levels of all buildings are found to be as PCL (Collapsed) though they should satisfy PLS (Life safety) level. The performance levels for the nonlinear analyses, which are somewhat parallel to the results of linear analyses are also presented in Table 2, using simplified traditional pushover analyses. Modal capacity curves are obtained in order to determine target displacements under corresponding seismic actions. Then, plastic deformations and internal force demands at target displacements have been calculated. Total curvature demands are determined from plastic rotations and converted to strains occurred at concrete and reinforcement bars that have been compared with the limit strain values to specify the member damage levels.

Table 2. The real damage states and required and computed performance levels of the buildings

| **Building Codes** | **Required Performance** | **Real Damage State** | **Linear Approach** | **Nonlinear Approach** | **P25 Score** | **Min.Is/$I_{s0}$ in X-Y** |
|---|---|---|---|---|---|---|
| 01-IST | PLS | No seismic activity | PCL | PCP | 34 | 0.11 |
| 02-DUZ | PLS | Collapsed | PCL | PCL | 18 | 0.24 |
| 03- DUZ | PLS | Collapsed | PCL | PCL | 23 | 0.14 |
| 04- DUZ | PLS | Heavy Damaged | PCL | PCL | 23 | 0.14 |
| 05- DUZ | PLS | Collapsed | PCL | PCL | 19 | 0.16 |
| 06-DUZ | PLS | Collapsed | PCL | PCL | 15 | 0.09 |
| 07-DUZ | PLS | Collapsed | PCL | PCL | 16 | 0.19 |

## 7 CONCLUSIONS

After a short presentation of the seismic risk evaluation approaches, seven RC case study buildings have been evaluated with code-based and the rapid screening methods and the results are compared with real damage states. Both linear and nonlinear approaches, together with the rapid scoring methods are found to be in good agreement with the real damage states of the buildings. Thus, the low performance levels proved that the collapse vulnerability of the six case study buildings which suffered from 1999 earthquake have been predicted quite successfully. The main insufficiencies most probably caused the buildings' failures are the existence of soft and weak stories, plan irregularity, heavy overhangs, frame discontinuity, lack of confinement and low material quality. Although both rapid screening methods have been proved to be able to categorize successfully the real seismic performances of the buildings, the authors strongly propose to utilise especially P25 Method prior to detailed analysis step, in order to save human lives, time and money, that can be more effectively and practically used rather than the SSSM approach, in order to support the efforts of the governments to mitigate the consequences of future earthquake events. Furthermore, the preliminary evaluation of the buildings with P25 approach would prevent local authorities from wasting their limited sources in an attempt to examine the whole building stock but instead, they would be directed to focus on the buildings having higher risk of collapse resulting in loss of life during the earthquake.

## 6 REFERENCES


Bal, I, E. 2005. "Rapid assessment techniques for collapse vulnerability of reinforced concrete buildings", *M.S. Thesis*, Istanbul Technical University, Institute of Science and Technology, (*in Turkish*).

Bal, I.E., Tezcan, S.S. and Gulay, F.G. 2006. "Advanced applications of the P25 scoring method for the rapid assessment of R/C buildings*" Proceedings of 1st ECEES*, 3-8 Sep. 2006, Geneva, Switzerland, Paper No: 67.

Boduroğlu, H., Ozdemir, P., et al 2004. Paper No.1452, "Towards a Modified Rapid Screening Method for Existing Medium Rise RC Buildings in Turkey" *13th WCEE August 1-6, 2004, Vancouver, Canada.*

ETABS 2011. Extended 3D Analysis of Buildings Systems, *Comp.and Struct. Inc.*, Berkeley California.

FEMA 154, 155 – ATC-21 1988, 2002. Rapid Visual Screening of Buildings for Potential Seismic Hazards:A Handbook, Federal Emergency Management Agency; FEMA 500 C Street, SW Washington, D.C.

Gulay, F.G., Bal, İ.E., Tezcan, S.S. 2008. Calibration of the P25 Scoring Method developed for the seismic safety of RC buildings and its application on a pilot region. TÜBITAK *(Turkish Scientific and Technical Research Council)* Research Project No 106M278, Final Report (in Turkish).

Gulay, F.G., Bal, I.E., and Gokce, T. 2008a. Correlation between detailed and preliminary assessment techniques in the light of real damage states. Journal of earthquake engineering, 12 (1), 129–139.

Ohkubo, M. 1990. The method for evaluating seismic performance of existing reinforced concrete buildings. *Seminar in Structural Engineering*, Dept. of AMES, University of California, San Diego, USA.

Pour, H.H. 2011. 'Seismic Safety Evaluation of Collapsed Buildings in Duzce', *M.S. Thesis*, Istanbul Technical University, *M.S. Thesis*, Institute of Science and Technology, (*in Turkish*).

TEC'07:Seismic Code of Turkey, 2007. Ministry of Public Works, Official Newspaper No: 26454, Ankara, Turkey, (in Turkish).