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P25 - Scoring Method for The Collapse Vulnerability Assessment of R/C Buildings

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Abstract

It is historically a fact that Turkey experiences frequent earthquakes, on the order of one damaging earthquake of magnitude 6 to 7 approximately every two years, causing extensive losses to economy, life and limb. Every strong earthquake leaves behind poverty and tens of thousands of homeless people. In order to mitigate especially the losses of life due to earthquakes, a rapid scoring technique called the *P25 - Preliminary Assessment Method,* is proposed herein. The purpose of the method is to determine, for a reinforced concrete framed building, whether there is any vulnerability to collapse during a strong earthquake. By identifying those buildings, which are most likely susceptible to collapse inside a particular building stock, and consequently strengthening or demolishing them, practically no loss of life will occur. In this presentation, details of *P25 - Preliminary Assessment Method* are discussed and the high degree of prediction reliability of the method is demonstrated on 323 case study buildings, which experienced wide ranges of damage during past earthquakes.

Keywords: Zero loss of life, preliminary assessment, collapse vulnerability, P25 - scoring method.

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1. Introduction

Turkey, by virtue of its geographic location, experiences one damaging earthquake about every two years. In fact, the number of earthquakes which have occurred in Turkey, within the last century, with magnitudes greater than $M=5$, is *122*. This is the highest rate of earthquake occurrence in the world. Over a period of one hundred years, a total of *98 000* people died, and about *550 000* buildings were heavily damaged. During the August 17, 1999 Kocaeli earthquake of $M_w=7.4$ and also during the November 12, 1999 Bolu-Duzce earthquake of $M_w=7.2$, a total of *17 500* people died, *45 000* people were wounded. Out of *854 000* residential units, *51 200* residential units representing 6 percent of the total building stock totally collapsed, *59 800* suffered heavy damage beyond repair, *103 400* suffered moderate damages and the remaining *75* percent of the units suffered minor or no damage.

2. P25 - Preliminary Assessment Technique

The method is primarily based on observing and listing the most important structural parameters which affect the seismic response of a building and also scoring them with some weighting factors one after the other in relation to their relative importance. The basis of the P25 - preliminary assessment technique to be explained herein has been proposed initially by Bal et al. 2006 and 2007 and then developed and calibrated through a research project supported by *TUBITAK (Turkish Scientific and Technical Research Council).* The method is applied to *323* R/C buildings with different damage states, located on different soil conditions and subjected to various seismic actions (Bal et al. 2006). The basic parameters of the methodology may be listed as ***(a)*** cross-sectional dimensions of R/C columns, shear walls and infill walls at the critical floor, ***(b)*** storey heights h_i, and the total height H , ***(c)*** outer plan dimensions L_x and L_y of ground floor, ***(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, confinement zones of columns, various structural irregularities such as, soft and / or weak storey, torsion, short column and frame discontinuity, etc.

The proposed *P*25 rapid assessment approach considers the effect of masonry infill walls, as opposed to some previous methodologies (Boduroglu et al. 2004; Yakut et al. 2006). The method considers seven different failure scores P_1 to P_7 and their interactions, if any. The final performance score *P*, of the building is an amalgamation of these seven scores and is graded between 0 and 100, varying from the worst to the best, respectively.

2. Effective Resultant Rigidities

Plan dimensions L_x and L_y are the *x* and y-sides of the smallest rectangle into which the plan of the critical storey *(ground floor)* may be placed. The floor area will be calculated as $A_p = L_x L_y$ and the moment of inertia values will be calculated as $I_{px} = L_y L_x^3 / 12$ and $I_{py} = L_x L_y^3 /12$. The sum of the cross-sectional areas and the moments of inertia of columns, shear walls and masonry infill walls will be divided by the overall floor area and moments of inertia, respectively. This operation is applied to both *x* and *y*- directions and the effective statistical minimum values $C_{A,ef}$ and $C_{I,ef}$ are selected as follows:

$$C_A = 10^5 \ (A_{ef} / A_p), \tag{1}$$

$$C_I = 10^5 \ (I_{ef} / I_p)^{0.2} \tag{2}$$

$$C_{A,ef} = (\cos\theta \, C^2_{A,min} + \sin\theta \ C^2_{A,max})^{0.5}, \tag{3}$$

$$C_{I,ef} = (\cos\theta \ C^2_{I,min} + \sin\theta \ C^2_{I,max})^{0.5}, \qquad (4)$$

$$C_{I,min} = min\ (C_{I,x}\ ,\ C_{I,y}), \qquad (5)$$

$$C_{I,max} = max\ (C_{I,x}\ , C_{I,y}), \qquad (6)$$

in which, θ = the angle of incidence of the dominant direction of earthquake. When in doubt about the possible dominant direction of earthquake in the region, θ is recommended to be a value smaller than *30* degrees. From the view point of statistical probability, $\theta = 30$ appears to be a realistic assumption.

$$A_{ef} = \Sigma\ (A_c + A_s + A_m\ E_m\ /\ E_c), \qquad (7)$$

$$I_{ef} = \Sigma\ (I_c + I_s + I_m\ E_m\ /\ E_c), \qquad (8)$$

where E_m is the modulus of elasticity of masonry infills, E_c is the modulus of elasticity of concrete, A_s, A_c and A_m are the cross - sectional areas of the shear walls, columns and masonry walls, respectively, and finally, I_s, I_c and I_m are the moments of inertia of the shear walls, columns and masonry walls, respectively. For practical purposes (E_m / E_c) may be taken as 0.15.

4. Correction Factor For Height

Since the cross-sectional dimensions of the vertical structural elements at ground floor *(critical storey)* increase with the overall height H of the building, it should also be included as another parameter in the calculations of effective rigidities. A suitable correction factor h_0, is proposed in Eq (9), which represents both the adverse and favorable effects of the building height. The correction factor h_o is given in the form of an inverse parabola, as

$$h_0 = -0.6H^2 + 39.6H - 13.4 \qquad (9)$$

This correction factor is h_0=100 for a *3m* high single storey building *(nominal value)* and becomes h_0=446 for a 5- storey building with H=15*m*. The formula has been obtained by examining generating around 9-thousand buildings having several different design input values.

5. Calculation Of Various Scores, P_1 To P_7

Score P$_1$: Once the effective resultant cross-sectional area $C_{A,ef}$ and the effective resultant flexural rigidity $C_{I,ef}$ of the critical storey are available from Eqs. 3 and 4, and also the height correction factor h_0 is evaluated, the basic score P_1 is obtained from:

$$P_1 = (C_{A,ef} + C_{I,ef})\ (\prod_{i=1}^{14} f_i)/h_0 \qquad (10)$$

in which, f_i represents 14 different correction factors, concerning the status and various deficiencies of the building as listed in Table 1.

Score P$_2$: A *'short'* column is relatively shorter than all the others in a given floor thus leading to increased shear demand and nonductile shear failure during a severe earthquake. There are six different scores for '*short'* columns, varying between 20 and 70 as seen in Table 2.

Score P$_3$: There is an architectural tendency to design for a variety of commercial functions on ground floors, such as show rooms, shopping centers, banks, etc, resulting in relatively higher storey heights and lack of masonry infill walls. This is reflected in score P_3 as follows:

$$P_3 = 100[r_a r_y (h_{i+1} / h_i)^3]^{0.60} \tag{11}$$

$$r_a = (A_{ef,i} / A_{ef,i+1}) \leq 1 \tag{12}$$

$$r_y = (l_{ef,i} / I_{ef,i+1}) \leq 1 \tag{13}$$

in which, r_a and r_r are the relative ratios of the total effective cross-sectional areas and effective moments of inertias of columns, shear walls and infill walls, at two adjacent storeys i and $i + 1$, respectively as shown in Eqs. 7 and 8. The values r_a and r_r are calculated for both x and y- directions and the average of these values is utilized in Eqs. 12 and 13. The power 0.60 used in Eq.11*,* stems from a need to maintain harmony in the magnitudes of the P – scores.

Score P$_4$: The overhang of the structural floor slabs immediately above the ground floor, all along the height of the building, is one of the most traditional characteristics of Turkish residential architecture. This particular overhang feature adversely affects the safe earthquake response of reinforced concrete buildings since it changes the mass distribution, plan regularity and frame action. Bal and Ozdemir, 2006 recently studied this issue on a number of buildings and proposed to consider a decrease in strength, varying between 4% and 54%. Following this proposal the score P_4 is assumed to vary between 50 and 90 as summarised in Table 3.

Score P$_5$: Pounding of any two adjacent buildings may be either eccentric or concentric type (Athanassiadou et al. 1994; Tezcan and Ipek, 1996)**.** The concentric pounding occurs if the line connecting the centers of the plan areas of the two adjacent buildings pass through the mid-point of the common sides along which the two buildigs are expected to hit each other. There are 16 different scores of pounding as shown in Table 4*,* depending on the types of positions of buildings. The most favourable pounding occurs (score of 75) if the two adjacent buildings are of the same height, their slabs are at the same elevations, and they experience concentric pounding. Incidentally, the last building within a row of adjacent buildings, experiences the worst hit.

Scores P_6 and P_7 : The liquefaction score, P_6 is given in Table 5 to vary between 10 and 60*,* depending on the level of *GWT*=ground water table and the calculated liquefaction risk potential to be 'low' , 'medium' or 'high' (Tezcan and Ozdemir, 2004)**.** Soil bearing capacity failure score P_7 is given in Table 6 to vary between 10 and 100 depending on the soil type and depth of *GWT.*

Final Score, *P:* The final score, P*,* is calculated by selecting P_{min} which is the smallest score among P_1 to P_7 as follows:

$$P = \alpha \beta P_{min}, \tag{14}$$

$$\alpha = (1 / I)(1.4 - A_0)\ [1 / (0.4n + 0.88)]\ t \tag{15}$$

where the correction factor, α , is defined in accordance with the values of I = building importance factor, A_o = effective ground acceleration, n = level of participation of live loads and t = topographic effects. The level of effective ground acceletarion, A_0*,* varies between 0.10 g and 0.40g for four different earthquake zones in Turkey. Normally, the live load participation factor, n = 0.30 is used for residential buildings. The correction for topographic effects is assumed as $t = 0.7$ if the building is on top of a hill, while $t = 0.85$ if the building is on a steep slope and $t = 1$ for buildings on lower elevations. The degree of increase in earthquake damage due to topographic effects has been based on two earlier studies (Celebi, 1987; Sholtis and Stewart, 1999). The correction factor, β is calculated by considering the weighted interaction among seven scores from P_1 to P_7. The minimum of these seven scores is considered as $P_{min.}$ The weighting factors for other scores are shown in Table 7. The weighted score, P_w, is then calculated as

$$P_w = \Sigma (w_i P_i) / \Sigma w_i \tag{16}$$

$$\left.\begin{array}{lll} \beta = 0.70 \text{ ....} & \text{for} & P_w \le 20 \\ \beta = 0.55 + 0.0075\, P_w & \text{for} & 20 \le P_w \le 60 \\ \beta = 1.00 \text{ ....} & \text{for} & P_w \ge 60 \end{array}\right\} \tag{17}$$

The interaction correction factor, β , represents the degree of interaction and the possibility of triggering an interactive failure and is recommended, based on the value of the weighted score, P_w , as follows:

6. Interpretation of The Final Score

The application of the *P*25 *Method* on 323 real case study buildings, which experienced certain degrees of damage during past earthquakes shows that the high risk band is between the scores of $P = 0$ and 25 and the performance score of $P = 34$ can then be considered as the safety-limit, as shown in Fig. 1. Actually, no building was in a *'collapsed'* state with a score of $P = 30$ or greater. Therefore, to consider the value of $P = 25$ as an upper score for the occurrence of the collapsed state is on the very safe side indeed. Buildings in the high risk band of $P = 0$ - 25 are regarded as certain candidates for collapse. Those buildings, which acquire a questionable score of $P = 26$ to 34, should be further investigated and assessed in detail utilising push over analysis by expert engineers in order to verify their possible level of performance. If a building is scored equal to or higher than $P = 35$, it should be regarded as safe against total collapse. In fact, no building was ever in the '*collapsed state'* with a score equal to or higher than $P = 30$.

7. Comparison with Other Methods

The need for a rapid screening of buildings for potential seismic hazards, was recognised by (FEMA 155, 1988), as early as in 1988. However, the technical criteria used by FEMA 155, are not altogether useful and suitable for the types of reinforced concrete frame buildings existing outside the USA. An alternate rapid assessment procedure was presented by Hasan and Sozen 1997, considering the damage patterns of low - rise R/C frame buildings in Turkey. A similar procedure was also introduced by Gulkan and Sozen 1999, using also the structural data from Turkish earthquakes. Similarly, Boduroglu, *et al.* 2004 also introduced slightly different techniques for the seismic and collapse vulnerability assessment of existing buildings in Turkey. A rapid seismic screening system has also been proposed by the National Research Council of Canada, Ottawa (NRCC, 1993), in the form of a manual for buildings existing in Eastern and Western European Cities. The Japan Building Disaster Prevention Association in Tokyo prepared a series of standard forms and methods of calculation of seismic indices for the performance assessment of existing R/C buildings (JBDPA, 1990).

For purposes of comparison, various structural parameters considered by each of the above mentioned assessment techniques are listed in Table 8 which indicates the superiority of the P25 – Method.

8. Conclusions

1. The *P*25 - preliminary assessment method to determine the collapse vulnerability of R/C buildings as part of the risk management projects outlined above, enables the central and /or local governments to reduce the loss of life to a theoretical *'zero'* value, simply by strengthening only those buildings, which are assessed as *'candidates for total collapse'*.

2. It is possible to predict rapidly, whether a particular building is vulnerable *to collapse or* not, within a time period of about one hour. The P25 - method is considered to be highly reliable in predicting the collapse vulnerability of a building, as already attested by predicting correctly the damage states of 323 real case study buildings subjected to past earthquakes.

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Appendix

Table 1 : Correction Factors of Irregularity (f_i)

Factor	*Irregularity*	*Degree of irregularity*		
		High	*Medium*	*None*
f_1	***Torsional irregularity***	0.80	0.90	1.00
f_2	***Slab discontinuity***	0.84	0.92	1.00
f_3	***Vertical discontinuity***	0.70	0.85	1.00
f_4	***Distribution of mass***	0.75	0.85	1.00
f_5	***Corrosion***	0.75	0.85	1.00
f_6	***Heavy facade elements***	0.75	0.85	1.00
f_7	***Mezzanine floor*** *(γ=Mezzanine floor / Full area)*	0.80 $\gamma \geq 0.25$	0.90 $0 < \gamma < 0.25$	1.00 $\gamma = 0$
f_8	***Unequal levels of floor***	0.80	0.90	1.00
f_9	***Concrete quality*** (1)	$f_9 = (f_c / 20)^{0.5}$		
f_{10}	***Strong column criterion*** (2)	$f_{10} = [\,(I_x + I_y) / 2\,I_b\,]^{0.15} \leq 1.0$		
f_{11}	***Lateral tie spacing*** (3)	$f_{11} = 0.60 \leq (10 / s)^{0.25} \leq 1.0$		
f_{12}	***Soil type***	0.80 (Z_4)	0.90 (Z_3)	1.00 (Z_2, Z_1)
f_{13}	***Foundation type***	0.80 - 0.90 (singular)	0.95 (continuous)	1.00
f_{14}	***Depth of foundation, D***	0.90 ($D < 1$ m)	0.95 ($1 \leq D \leq 4$ m)	1.00 ($D > 4$ m)

(1) f_c = 28th day strength of concrete in MPa.
(2) I_x, I_y = average column moments of inertia values, whilst I_b is the moment of inertia of a typical beam.
(3) s = tie spacing within the confinement zone in cm.

Table 2 : Short Column Score, P_2

n=Ratio of the number of Short Columns	*Short Columns Height / Critical Storey Height* (1)	
	$>2/3$	$\leq 2/3$
A few $n < 15\,\%$	70	50
Some $0.15 \leq n \leq 0.30$	50	30
Many : $n > 0.30$	45	20

Table 3 : Score for discontinuity of peripheral frame

Beams	**Location of overhang**		
	At single facade	**At two facades**	**At all facades**
Existing	90	80	70
None	70	60	50

Table 4 : Pounding Score, P_5

Type of impact	**Concentric impact**		**Eccentric impact**	
	Slabs at equal level	**Slabs at different level**	**Slabs at equal level**	**Slabs at different level**
The last block within a row	60	30	40	25
Two unequal buildings	55	30	35	25
Low rise next to high rise	75	40	50	35
Two identical buildings	75	50	65	45

Table 5 : Liquefaction Score, P_6

GWT *(m)*	Calculated Liquefaction Potential		
	Minor	Medium	High
> 10 m	60	45	30
2.0 m – 10.0 m	45	33	20
< 2.0 m	30	20	10

Table 7 : Weighting Factors for P_1 to P_7

Weighting factor	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_{min}
w	4	1	3	2	1	3	2	4

Table 6 : Soil Movements Score, P_7

Soil Type	GWT *(m)*	P_7
Z_1, Z_2	–	100
Z_3	GWT ≤ 5.0	25
	GWT > 5.0	35
Z_4	GWT ≤ 5.0	10
	GWT > 5.0	20

Not : Soil types Z1 – Z4 are almost the same as soil types A to D of the Uniform Building Code of the USA.

Table 8 : Parametric comparisons of various assessment techniques

Parameters Considered	FEMA 155 1988	Hassan 1997	Yakut et al. 2004	Yakut et al. 2006	NRCC 1993	JBDPA 1990	P25
A_{col}, A_{wall}	-	A	A	A	A	n	A
I_{col}, A_{wall}	-	-	A	n	A	n	A
A_m = *Infill wall areas*	-	-	A	-	A	-	A
I_m = *Infill wall rigidities*	-	-	A	-	-	-	A
N = *No of storeys*	S	A	A	A	A	A	A
Torsional irregularity	S	A	-	A	A	A	A
Floor Openings	S	A	-	A	-	A	A
Discontinued wall / column	S	-	-	A	A	A	A
Mass irregularity	-	-	-	-	-	A	A
Corrosion	-	-	-	-	-	-	S
Heavy facade panels	S	-	-	-	S	-	S
Unequal floor levels	-	-	-	-	-	-	A
Concrete quality	-	A	-	A	-	A	A
'Strong' column criterion	-	S	-	-	-	-	A
Column tie spacing	-	-	-	-	-	-	A
Short column effect	S	S	-	A	A	-	A
Soft / Weak storeys	S	A	A	A	A	A	A
Pounding of bldgs	S	A	-	-	S	-	A
I = Importance factor	-	A	-	-	A	-	A
n =Live load factor	-	-	-	-	S	A	A
Soil Type	A	A	-	-	A	A	A
Liquefaction risk	-	-	-	-	-	-	S
Land slide risk	-	-	-	-	-	-	S
Earthquake zone effect	-	-	-	-	-	-	A
Topographic location	-	S	-	-	A	-	A
Case studies tested	n	n	484	89	n	**2**	**323**
Prediction in heavily damaged bldgs (%)	n	n	80	91	n	100	**100**
Prediction in collapsed bldgs (%)	n	n	n	n	n	n	**100**

S = Subjective scoring, A = Analytical scoring, n = not applicable

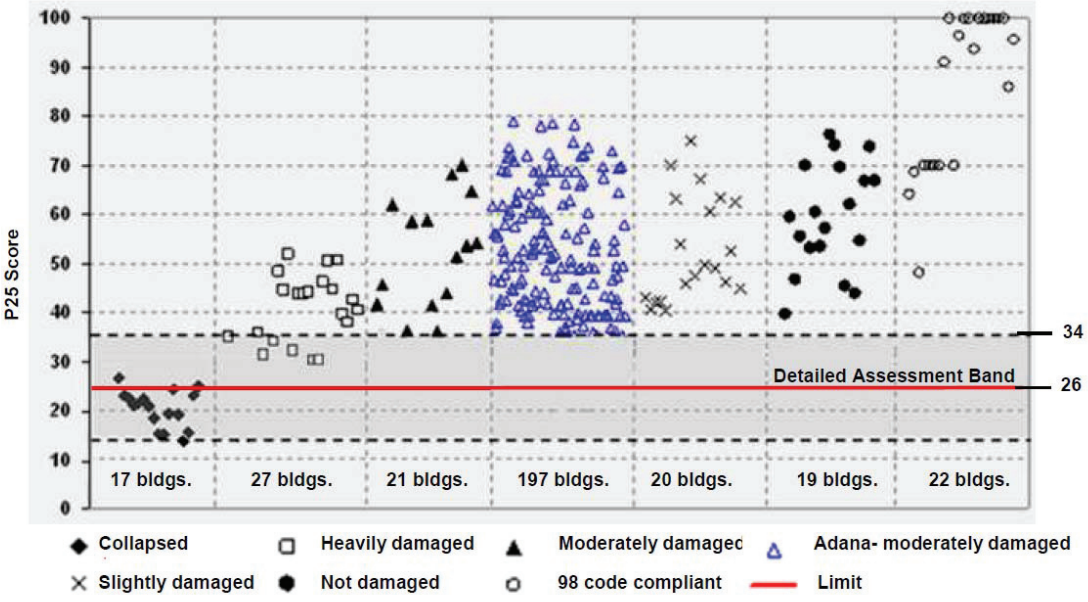

Figure 1: *P25* scores for *323* case study buildings experienced wide range of damages