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TYPICAL BUILDINGS FINAL STRUCTURAL SCORES

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Abstract

Rapid Visual Screening, RVS, of Buildings for Potential Seismic Hazards – A Handbook, is a procedure developed under FEMA 154 Report, originally issued on 1988 and then updated as Edition 2, on March 2002 [1]. The procedure is designed to be implemented without performing structural analysis calculations and enables classification of surveyed buildings in two categories: risk acceptable to life safety and seismically hazardous. The procedure involves the scoring system of the buildings compatible with ground motion criteria in the FEMA 310 Report (ASCE, 1998) [3] and the damage estimation data according to HAZUS damage and loss estimation methodology and fragility curves (NIBS 1999) [4]. Finally cut-off scores are determined; i.e. a building receiving a high score is considered to have adequate seismic performance, whilst a building with low score should be further evaluated by a professional engineer in seismic design. The scoring system utilizes two steps: identification of the primary structural lateral-load-resisting system and identification of building attributes that modify the seismic performance expected of this lateral-load-resisting system.

The Final Structural Score, S, represents an estimate of the probability that the building will collapse if ground motions occur that equal or exceed the Maximum Considered Earthquake (MCE) ground motions. The buildings evaluated to have a cut-off value of S larger than 2, are considered to provide an excess of 90% confidence of being able to withstand earthquake with 2% probability of exceeding in 50 years. The buildings with cut-off score $S \leq 2$, are considered as inadequate and shall be studied further from and earthquake engineer. The S is based on the Basic Structural Hazard Score, BSH, and Score Modifiers, SMs. The BSH represents a generic score for a type or class of building, and is modified for a specific building by Score Modifiers (SMs) specific to that building.

The direct benefits of the procedure include the time efforts to review and investigate in detail a massive number of buildings and identification of unacceptable weak structures to be further analyzed and rehabilitated. The final benefits of the procedure results in saving of lives and prevention of injuries, reduced damage and fewer major disruption of daily lives and businesses.

This study is performed to adopt the procedure, whilst to revise the input parameters for basic structural hazards score and score modifiers to meet the site specific spectral accelerations and capacity curves for the local building typology matrix in city of Pristina, Capital of Republic of Kosovo. Typical Final Structural Scores can be obtained then for the considered building typology matrix, which depending of the final value can be subject to further evaluation from structural earthquake engineer for verification of performance stability.

Keywords: structural score, basic structural hazard score, score modifiers.

1. Introduction

The procedure is implied for a residential/commercial neighborhood, accommodating more than hundred buildings and in general four primary structural lateral load resisting systems. The construction of the neighborhood is subdivided into three categories, namely prior to the initial adoption and enforcement of seismic codes applicable for that building type "Pre-Code", during the period when the first seismic provisions were adopted and enforced "Low Code" and "Moderate Code" when enhancement of seismic code provisions were enforced.

2. Rapid visual screening procedure

The Second Edition of the Rapid Visual Screening of Buildings for Potential Seismic Hazards – A Handbook [1] and Supporting Documentation [2], is considered as appropriate for the purpose, as it can be implemented from wide range of users, namely from professional engineers, municipal authorities, private owners of building blocks, and students as training tool to appropriately trained technicians.

The RVS procedure incorporates a revised scoring system compatible with the ground motion criteria in the FEMA 310 Report, Handbook for Seismic Evaluation of Buildings - A Prestandard (ASCE, 1998) [3], and the damage estimation data according to HAZUS damage and loss estimation methodology (NIBS, 1999) [4]. The principal purpose of the RVS procedure is to identify potentially seismically hazardous buildings needing further evaluation, but the results can also be used to: identify the community's seismic rehabilitation needs, develop the seismic hazard mitigation programs, develop the inventories of buildings for use in regional earthquake damage and loss impact assessments, plan of post earthquake building safety evaluation efforts, etc.

The RVS implements three different Data Collection Forms, depending on seismicity of the considered regions: low, moderate, and high. The inspection of buildings under RVS procedure requires the user to: identify the primary structural lateral-load-resisting system and identify building attributes that modify the seismic performance expected of this lateral-load-resisting system. The procedure is evaluated to take an average of half an hour and as much if the access to interior is possible.

2.1 Implementation steps of RVS procedure

To implement appropriately the RVS program it is important to plan and realize all the necessary steps so that the results are satisfactory and reliable. In general the screening implementation sequence includes several steps, namely:

- Budget development and cost estimation of the screening;
- Pre-field planning, including selection of the area and buildings to be surveyed, identification of a record-keeping system, and development of maps that document local seismic hazard information;
- Selection and review of the Data Collection Form DCF [respective of region seismicity: low (L), moderate (M), and high (H)].
- Qualification and training of screeners;
- Acquisition and review of pre-field data; including review of existing building files and databases to document information identifying buildings to be screened (e.g., address, lot number, number of stories, design date) and identifying soil types for the survey area;
- Review of existing building plans, if available;
- Field screening of individual buildings (teams consisting of two persons - at least one engineer). Subsequent steps include:
    1. Verifying and updating building identification information, e.g.: number of stories, year built, screener identification and total floor area.
    2. Walking around the building and sketching a plan and elevation view on the DCF,
    3. Determining occupancy class and load,
    4. Determining soil type. If there are no information's, a soil type E should be assumed,
    5. Identifying potential non-structural falling hazards,

6. Identifying the seismic-lateral-load resisting system,
7. Identifying and circling the appropriate seismic performance attribute Score Modifiers,
8. Determining the Final Score, S, and deciding if a detail evaluation is required, and
9. Photographing the building.

- Checking the quality and filing the screening data in the record-keeping system, or database. This phase shall be performed from a design professional with significant experience in seismic design.
- Comments Section.

3. Technical aspects of the RVS methodology

The RVS methodology was developed in such a manner that it can be updated in distinctive manner, regarding all its respective sub-components.

3.1 Seismic hazard

Under current version, the Seismic hazard is selected to consider ground motions with 2% probability of exceeding in 50 years, which corresponds to an earthquake ground motion average recurrence interval of 2475 years. In this study, otherwise the ground motion is selected with 10% probability of exceeding in 50 years, corresponding to an earthquake with recurrence interval of 475 years.

Three fundamental issues are important for quantifying the seismic hazard:

- selection of an appropriate ground shaking parameter;
- selection of a design-earthquake recurrence interval and
- the definition of seismicity level (low, moderate, and high).

The parameter for ground shaking is used the maximum acceleration response instead of peak ground acceleration (PGA) and effective peak ground acceleration.

Seismicity region is defined based on the location of the zone to be screened, assuming NEHRP soil type B, which is defined as rock with an average shear wave velocity between 80 and 160 m/sec. Criteria for specifying seismicity region as a function of short-period and long-period spectral acceleration response are defined for Low, Moderate and High regions of seismicity.

3.2 Building Classification

Classification of buildings is cumulated selecting 15 model building types as per FEMA 178 [5].

Building Classification system is defined according to:

- FEMA 310, Handbook for the Seismic Evaluation of Buildings - A Prestandard (ASCE, 1998) [3],
- FEMA 273 Guidelines for the Seismic Rehabilitation of Buildings (ATC, 1997) [6], and
- FEMA 356 Prestandard and Commentary for the Seismic Rehabilitation of Buildings (ASCE, 2000) [7].

3.3 Basic Structural Hazard Scores

Structural Scoring System is in function of Basic Structural Hazard (BSH) Scores and Score Modifiers (SMs), which are developed for each model building type.

The BSH are developed from different HAZUS-defined earthquake damage states (slight, moderate, extensive, and complete), which are estimated from the building fragility and capacity curves specified in the HAZUS Technical Manual (NIBS, 1999) [4].

Development of BSH is based on the HAZUS fragility curves, that define seismic hazard - selected spectral displacement, in terms of maximum spectral acceleration response. It is defined for every model building type, calculated as the negative of the logarithm (base 10) of the probability of collapse of the building, given the ground motion corresponding to the maximum considered earthquake (MCE), expressed with formula:

$$\mathrm{BSH} = -\log_{10}[\mathrm{P(collapse\ given\ MCE)}] \tag{3.1}$$

In general BSH is typical for particular building model type, and is altered with use of SMs, that are dependent on local conditions of given building. The combination of BSH with SMs, gives the final Structural Score (S) of the respective building:

$$\mathrm{S} = \mathrm{BSH} \pm \mathrm{SMs} \tag{3.2}$$

A Final Structural Score, S, is determined at the end of RVS procedure. The Score is described as probability of building collapse if seismic action equal of greater than maximum considered earthquake strikes. The value of S=2 is considered as a cut-off value, with condition that buildings receiving equal to or lower value are considered as hazardous, and issued for further evaluations from structural seismic engineer. The interpretation for S=2 stands that there is probability of 1/100 or 1% that the building will collapse, if expected maximum earthquake occur.

The procedure for calculating the BSH Scores for the various building types and seismicity regions considered in the second edition of FEMA 154 includes the following steps:

1. Determining the median values of the input short-period and one-second-period spectral acceleration response (from the MCE maps) for the low, moderate, and high seismic regions;
2. Modifying the results from Step 1 to incorporate the effect of site soil amplification and the 2/3 reduction factor (soil type B is assumed for the calculation of BSH Scores);
3. Computing the demand spectrum from the acceleration response spectrum developed in Step 2;
4. Computing the bilinear capacity curve of the model building type - Pushover curve, which is a function of two points: yield and ultimate;
5. Computing the trial intersection point of the demand and capacity curve;
6. Using the trial intersection point found in Step 5 to adjust the demand curve for effective damping (sum of the elastic damping and the hysteretic damping);
7. Computing the next trial intersection point of the capacity curve and the demand curve, which has been adjusted for effective damping;
8. Repeating Steps 6 and 7 until convergence;
9. Determining the probability of collapse by determining the probability of being in the complete damage state, and multiplying the probability of complete damage by the probability of collapse, given complete damage.
10. Computing the BSH Score as the negative log (base 10) of the probability of collapse.

3.4 Score Modifiers

Score Modifiers "SMs" were introduced to account for specific building and site characteristics observed during the rapid visual screening, other than used on general BSH Score (which were calculated for low-rise buildings on soil type B for an assumed seismic design level, which relates to design date, and for performance assumed to be of an “ordinary” structure per HAZUS99).

Score Modifiers are calculated separately to address the specific earthquake resisting performance characteristics of the considered building:

1. Building height: mid-rise and high-rise;
2. Vertical and horizontal irregularities;
3. Design and construction year: pre-code and post-benchmark;
4. Soil type: C, D, and E.

SMs for mid-rise and high-rise buildings were calculated for each seismicity region, soil type D as average between type C and E, and that for low-rise, mid-rise and high-rise.

SMs counting for vertical irregularities are introduced based on expert judgment, because there are so many variations in configuration or deficiencies.

SMs counting for horizontal - plan irregularities are introduced by calculating the effect with increase of seismic load for 50%, respectively of seismic acceleration response.

SMs to account for design and construction dates different from those assumed in the development of BSH for each seismicity region and building type were developed based on the criteria that specifies the assumed seismic code design levels for various time periods, and soil type D.

SMs for Soil Type C, D and E have been developed to adjust the short-period and one-second-period maximal considered earthquake spectral acceleration response ordinates to incorporate the effects of soil on earthquake ground shaking.

4. Case Study

The procedure is implied for a neighborhood with mixture of destination of use - residential and commercial, consisting more than hundred buildings and in general four primary structural lateral load resisting systems.

The considered neighborhood is developed mainly beginning of 1960's and continued for 40 years, implemented with use of design codes that were in power in time of design and construction, subdivided into three categories:

- 1st category: built prior to the initial adoption and enforcement of seismic codes applicable for that building type "Pre-Code",
- 2nd category: built during the period when the first seismic provisions were adopted and enforced "Low Code" and
- 3rd category: built when enhancement of seismic code provisions were enforced "Moderate Code".

In the next page, the characteristic examples of representative buildings with implementation of RVS procedure are shown on typical tabular data form, resulting in determination of respective Final Structural Score, S.

4.1 Steps for calculation of Final Structural Score

Below, is presented the detail procedure for development of BSH Score and SMs, which finally result in determination of Final Structural Score for specific model building type.

The calculation of the BSH Score is based on data and information in the HAZUS99 SR2 Technical Manual, including data from Table 3.18 (Collapse Rates by Model Building Type for Complete Structural Damage) and the Maximum Considered Earthquake (MCE) spectral acceleration response for the high seismicity region.

Step 1. Determination of Input Spectral Acceleration Response Values, S_S and S_1

The input spectral acceleration response values considered in this example are the median short period spectral acceleration response, Ss, and the median one-second period spectral acceleration response, S_1, for an assumed soil type B condition in the high seismicity region.

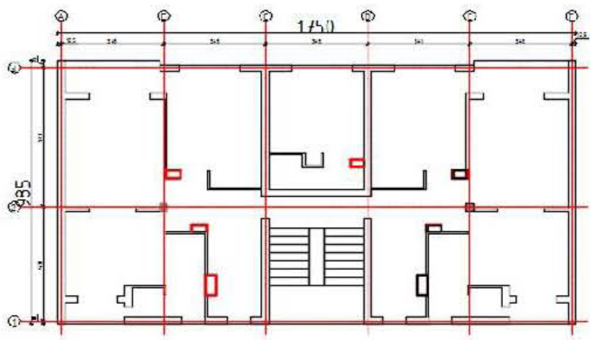
The values of median spectral acceleration response for this region are 0.39g for S_S and 0.12g for S_1.

Table 4.1.Typical FEMA-154 Data Collection Form for RVS procedure – Pre Code Category

Rapid Visual Screening of Buildings for Potential Seismic Hazards

FEMA-154 Data Collection Form

MODERATE Seismicity



Scale: _______________

Address: Ulpiana, Prishtina

Zip 10000

Other Identifiers

No. of Stories 5 — Year Built 1962

Screener Fatos Tahiri — Date 09.03.2015

Total Floor Area [m^2] 1020

Building Name A1

Use Residential and Commercial

OCCUPANCY					SOIL TYPE						FALLING HAZARDS			
Assembly	Govt	Office	Number of Persons		A	B	C	D	E	F	☐	☐	☐	☐
Commercial	Historic	Residential	0-10	11-100	Hard Rock	Avg. Rock	Dense Soil	Stiff Soil	Soft Soil	Poor Soil	Unreinf. Chimneys	Parapets	Cladding	Other
Emer. Services	Industrial	School	101-1000	1000+										

BASIC SCORE, MODIFIERS, AND FINAL SCORE, S

BUILDING TYPE	W1	W2	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM
Basic Score	5.2	4.8	3.6	3.6	3.8	3.6	3.6	3.0	3.6	3.2	3.2	3.2	3.6	3.4	3.4
Mid Rise (4 to 7 stories)	N/A	N/A	+0.4	+0.4	N/A	+0.4	+0.4	+0.2	+0.4	+0.2	N/A	+0.4	+0.4	+0.4	+0.4
High Rise (>7 stories)	N/A	N/A	+1.4	+1.4	N/A	+1.4	+0.8	+0.5	+0.8	+0.4	+0.2	+0.4	N/A	+0.6	N/A
Vertical Irregularity	-3.5	-3.0	-2.0	-2.0	N/A	-2.0	-2.0	-2.0	-2.0	-2.0	N/A	-1.5	-2.0	-1.5	-1.5
Plan Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Pre-Code	0.0	-0.2	-0.4	-0.4	-0.4	-0.4	-0.2	-1.0	-0.4	-1.0	-0.2	-0.4	-0.4	-0.4	-0.4
Post-Benchmark	+1.6	+1.6	+1.4	+1.4	N/A	+1.2	N/A	+1.2	+1.6	N/A	+1.8	N/A	+2.0	+1.8	N/A
Soil Type C	-0.2	-0.8	-0.6	-0.8	-0.6	-0.8	-0.8	-0.6	-0.8	-0.6	-0.6	-0.6	-0.8	-0.6	-0.4
Soil Type D	-0.6	-1.2	-1.0	-1.2	-1.0	-1.2	-1.2	-1.0	-1.2	-1.0	-1.0	-1.2	-1.2	-1.2	-0.8
Soil Type E	-1.2	-1.8	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6
FINAL SCORE S															**0.6**

COMMENTS

Data Evaluation Required

YES **NO**

*=Estimated subjective, or unreliable data

DNK = Do Not Know

BR = Braced farme

FD = Flexible diaphragm

LM = Light metal

MRF = Moment-resisting frame

RC = Reinforced concrete

RD = Rigid diaphragm

SW = Shear wall

TU = Tilt up

URM INF = Unreinforced masonry infill

Table 4.2.Typical FEMA-154 Data Collection Form for RVS procedure – Low Code Category

Rapid Visual Screening of Buildings for Potential Seismic Hazards

FEMA-154 Data Collection Form

MODERATE Seismicity

Address: Ulpiana, Prishtina

Zip 10000

Other Identifiers

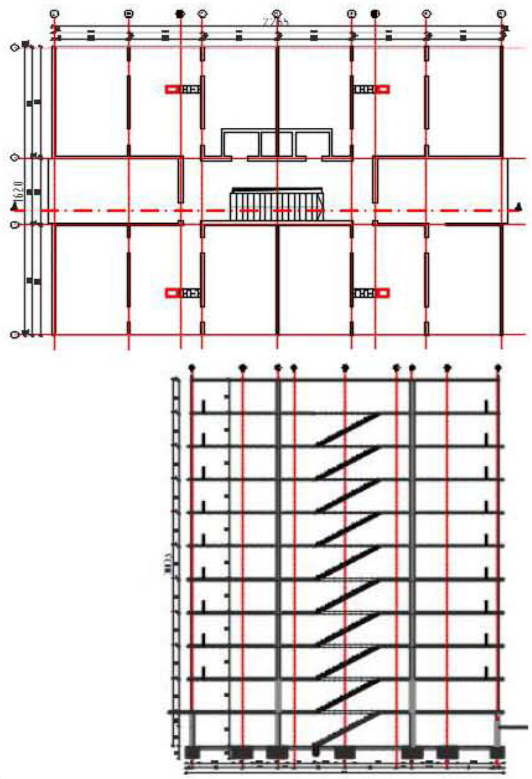
No. of Stories 10 Year Built 1965

Screener Fatos Tahiri Date 18.03.2015

Total Floor Area (m^2) 3670

Building Name S5 - 1

Use Residential and Commercial



Scale:

OCCUPANCY					SOIL TYPE						FALLING HAZARDS			
Assembly	Govt	Office	Number of Persons		A	B	C	D	E	F	☐	☐	X	☐
Commercial	Historic	Residential	0-10	11-100	Hard	Avg.	Dense	Stiff	Soft	Poor	Unreinf.	Parapets	Cladding	Other
Emer. Services	Industrial	School	101-1000	1000+	Rock	Rock	Soil	Soil	Soil	Soil	Chimneys			

BASIC SCORE, MODIFIERS, AND FINAL SCORE, S

BUILDING TYPE	W1	W2	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM
Basic Score	5.2	4.8	3.6	3.6	3.8	3.6	3.6	3.0	3.6	3.2	3.2	3.2	3.6	3.4	3.4
Mid Rise (4 to 7 stories)	N/A	N/A	+0.4	+0.4	N/A	+0.4	+0.4	+0.2	+0.4	+0.2	N/A	+0.4	+0.4	+0.4	+0.4
High Rise (>7 stories)	N/A	N/A	+1.4	+1.4	N/A	+1.4	+0.8	+0.5	+0.8	+0.4	+0.2	+0.4	N/A	+0.6	N/A
Vertical Irregularity	-3.5	-3.0	-2.0	-2.0	N/A	-2.0	-2.0	-2.0	-2.0	-2.0	N/A	-1.5	-2.0	-1.5	-1.5
Plan Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Pre-Code	0.0	-0.2	-0.4	-0.4	-0.4	-0.4	-0.2	-1.0	-0.4	-1.0	-0.2	-0.4	-0.4	-0.4	-0.4
Post-Benchmark	+1.6	+1.6	+1.4	+1.4	N/A	+1.2	N/A	+1.2	+1.6	N/A	+1.8	N/A	+2.0	+1.8	N/A
Soil Type C	-0.2	-0.8	-0.6	-0.8	-0.6	-0.8	-0.8	-0.6	-0.8	-0.6	-0.6	-0.6	-0.8	-0.6	-0.4
Soil Type D	-0.6	-1.2	-1.0	-1.2	-1.0	-1.2	-1.2	-1.0	-1.2	-1.0	-1.0	-1.2	-1.2	-1.2	-0.8
Soil Type E	-1.2	-1.8	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6
FINAL SCORE S									**1.2**						

COMMENTS

Data Evaluation Required

YES **NO**

*=Estimated subjective, or unreliable data
DNK = Do Not Know

BR = Braced farme
FD = Flexible diaphragm
LM = Light metal

MRF = Moment-resisting frame
RC = Reinforced concrete
RD = Rigid diaphragm

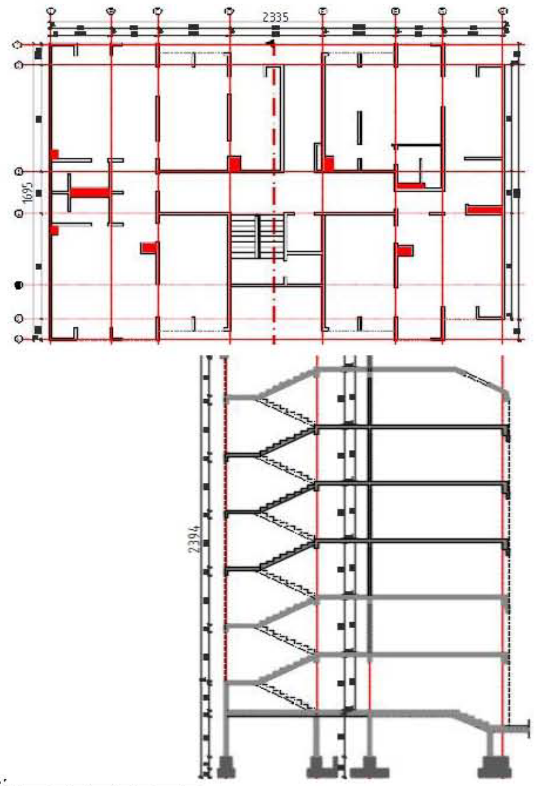
SW = Shear wall
TU = Tilt up
URM INF = Unreinforced masonry infill

Table 4.3.Typical FEMA-154 Data Collection Form for RVS procedure – Moderate Code Category

Rapid Visual Screening of Buildings for Potential Seismic Hazards

FEMA-154 Data Collection Form

MODERATE Seismicity



Scale: ______________

Address: Ulpiana, Prishtina

Zip 10000

Other Identifiers

No. of Stories 7 Year Built 1978

Screener Fatos Tahiri Date 09.03.2015

Total Floor Area [m^2] 2520

Building Name Y - B2

Use Residential

OCCUPANCY					SOIL TYPE						FALLING HAZARDS			
Assembly	Govt	Office	Number of Persons		A	B	C	D	E	F	☐	☐	☐	☐
Commercial	Historic	Residential	0-10	11-100	Hard Rock	Avg. Rock	Dense Soil	Stiff Soil	Soft Soil	Poor Soil	Unreinf. Chimneys	Parapets	Cladding	Other
Emer. Services	Industrial	School	101-1000	1000+										

BASIC SCORE, MODIFIERS, AND FINAL SCORE, S

BUILDING TYPE	W1	W2	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM
Basic Score	5.2	4.8	3.6	3.6	3.8	3.6	3.6	3.0	3.6	3.2	3.2	3.2	3.6	3.4	3.4
Mid Rise (4 to 7 stories)	N/A	N/A	+0.4	+0.4	N/A	+0.4	+0.4	+0.2	+0.4	+0.2	N/A	+0.4	+0.4	+0.4	+0.4
High Rise (>7 stories)	N/A	N/A	+1.4	+1.4	N/A	+1.4	+0.8	+0.5	+0.8	+0.4	+0.2	+0.4	N/A	+0.6	N/A
Vertical Irregularity	-3.5	-3.0	-2.0	-2.0	N/A	-2.0	-2.0	-2.0	-2.0	-2.0	N/A	-1.5	-2.0	-1.5	-1.5
Plan Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Pre-Code	0.0	-0.2	-0.4	-0.4	-0.4	-0.4	-0.2	-1.0	-0.4	-1.0	-0.2	-0.4	-0.4	-0.4	-0.4
Post-Benchmark	+1.6	+1.6	+1.4	+1.4	N/A	+1.2	N/A	+1.2	+1.6	N/A	+1.8	N/A	+2.0	+1.8	N/A
Soil Type C	-0.2	-0.8	-0.6	-0.8	-0.6	-0.8	-0.8	-0.6	-0.8	-0.6	-0.6	-0.6	-0.8	-0.6	-0.4
Soil Type D	-0.6	-1.2	-1.0	-1.2	-1.0	-1.2	-1.2	-1.0	-1.2	-1.0	-1.0	-1.2	-1.2	-1.2	-0.8
Soil Type E	-1.2	-1.8	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6	-1.6
FINAL SCORE S									**2.8**						

COMMENTS

Data Evaluation Required

YES **NO**

* =Estimated subjective, or unreliable data	BR = Braced farme	MRF = Moment-resisting frame	SW = Shear wall
DNK = Do Not Know	FD = Flexible diaphragm	RC = Reinforced concrete	TU = Tilt up
	LM = Light metal	RD = Rigid diaphragm	URM INF = Unreinforced masonry infill

Step 2. Modification of S_S and S_1 to Compute Modified Response, S_{DS} and S_{D1}

The modified spectral acceleration response input values for short-period and one-second-period were computed using equations 5.1 and 5.2, as follows:

$$S_{DS} = \left(\frac{2}{3}\right) F_a x S_S = \left(\frac{2}{3}\right)(1.0)(0.39g) = 0.26g \tag{4.1}$$

$$S_{D1} = \left(\frac{2}{3}\right) F_a x S_1 = \left(\frac{2}{3}\right)(1.0)(0.12g) = 0.08g \tag{4.2}$$

Where F_a and F_v, are the site soil amplification coefficients, equal to 1.0 for soil type B (FEMA 310, *Handbook for the Seismic Evaluation of Buildings - A Prestandard*).

Step 3. Development of a Demand Response Spectrum

The demand response spectrum, formatted with spectral displacement response as the x-axis and spectral acceleration response as the y-axis, was developed through the use of the following equations, as taken from the HAZUS99 *Technical Manual*:

At short periods (acceleration domain), $0 < T \leq T_S$:

$$S_A(T) = S_{DS} / R_A \tag{4.3}$$

At long periods (velocity domain), $T_S < T \leq T_{VD}$:

$$S_A(T) = \left(\frac{S_{D1}}{T}\right) / R_V \tag{4.4}$$

At very long periods (displacement domain), $T > T_{VD}$:

$$S_A(T) = \left(\frac{S_{D1} \cdot T_{VD}}{T^2}\right) / R_V \tag{4.5}$$

$$S_D(T) = S_A(T) \cdot 10^3 \left(\frac{T}{2\pi}\right)^2 \tag{4.6}$$

where:

$S_A(T)$ - spectral acceleration response in g at period, T;

$S_D(T)$ - spectral displacement response in cm at period, T (the factor of 10^3 converts to cm);

$T_S = \left(\frac{S_{D1}}{S_{DS}}\right) \cdot \left(\frac{R_A}{R_V}\right)$ - the transition period between the constant acceleration and the constant velocity regions of the response spectrum;

$T_{VD} = 10^{\left(\frac{M-5}{2}\right)}$ - transition period between the constant velocity and the constant displacement region of the response spectrum;

M = moment magnitude of earthquake

$R_A = 2.12 / \left(3.21 - 0.68 \cdot \ln(\beta_{eff})\right)$ - reduction factor in acceleration domain (4.7)

$R_V = 1.65 / \left(2.31 - 0.41 \cdot \ln(\beta_{eff})\right)$ - reduction factor in velocity domain (4.8)

(derivation of RA and RV according to Newmark and Hall, 1982)

β_{eff} - effective damping, which is the sum of elastic damping, β_E, and hysteretic damping β_H.

The elastic damping β_E is dependent on structural type (HAZUS99 Technical Manual).

The hysteretic damping β_H, is dependent on the amplitude of response, and is based on the area enclosed by the hysteresis loop, considering the potential degradation of energy-absorption capacity of the structure during cyclic earthquake loading:

$$\beta_H = \kappa \cdot \left(\frac{\text{Area}}{2\pi \cdot D \cdot A}\right) \tag{4.9}$$

where:

Area = Area enclosed by the hysteresis loop, as defined by the symmetric building capacity curve between peak positive and negative displacement, ±D.

D = Peak displacement response of the push-over curve.

A = Peak acceleration response at the peak displacement, D.

κ = Degradation factor that defines the effective amount of hysteretic damping as a function of earthquake duration. It is assumed in FEMA-154, Second Edition, that the MCE earthquake has a long duration. The degradation factors for different model building types are defined in the HAZUS99 Technical Manual.

Step 4. Development of the Capacity Curve for the Building Type and Seismic Region Under Consideration

The reinforced concrete frame with unreinforced masonry infill considered in this example, model building type (C3), urban block named E31–2 with total floor area 1450 m^2, under mid-rise category (6 stories) and designed to low-code level (year built 1969) for the moderate seismic region.

The seismic performance is obtained through building Capacity Curve, that represents a lateral force-displacement plot prescribing inelastic deformation of the structure through step by step formation of plastic hinges on constituting frame members, expressed with relationship Top Displacement/Height of the Building vs. Base Shear/Building Weight (%) or Roof Displacement (Δr in cm) vs. Base Shear (V in kN). The Base Shear force. Seismic Base Shear and its Vertical Shear Distribution is obtained from Nonlinear Static Pushover Analysis and compared with values obtained as per IBC 2000 Specification, with use of equivalent lateral force procedure for regular multi-level building/structural systems [8].

Lateral deformation of the structure is obtained through application of uniform lateral acceleration on the structure, applying in this way the lateral forces proportional to the node tributary masses. The capacity curves are developed by superposition of each incremental displacement of each respective story.

The Capacity Curve of the building is the converted to the Capacity Spectrum format, representing a lateral Spectral Acceleration-Spectral Displacement plot, obtained from conversion of V-Δr capacity curve by using dynamic characteristics of the structure in terms of fundamental period of vibration (T), mode shape (ϕ_x) and lumped floor mass (m_x). This conversion is done by treating the floor masses with only one whole mass M plus incorporation of effective mass ratio α, while the conversion of top displacement to spectral displacement is done by introducing a roof participating factor ($PF\phi_R$) expressing the ratio of top displacement to the displacement of the mass (S_d).

Yield Capacity: S_d = 2.37 cm and S_a = 0.23g

Ultimate Capacity: S_d = 4.66 cm and S_a = 0.29g

The building capacity curve is assumed to bilinear when the spectral displacement is less than yield displacement and is assumed to remain plastic past the ultimate point. The transition from yield point to ultimate point of the capacity curve is assumed to be elliptical of the following form:

$$\left(\frac{S_D - D_U}{C}\right)^2 + \left(\frac{S_A - A}{B}\right)^2 = 1 \tag{4.10}$$

where S_D and S_A are defined above and A, B, C are constants of the equation.

Step 5. Calculation of the Trial Intersection Point of the Demand and Capacity Curves

The performance point is estimated for mean building bilinear capacity spectrums defined according to induced ground acceleration [$(U_X+U_Y)/2$].

The demand spectra's is plotted in ADRS format with mean capacity curve obtained from acceleration proportional to the mass of the structure.

Performance point is calculated according to the procedure defined for bilinear approximation of capacity spectrum.

Because the intersection-performance point was beyond the yield capacity of the structure of 0.29g, the demand spectrum needed to be modified to account for the hysteretic energy dissipated by the building resulting from displacement response in the inelastic range.

Step 6. Adjustment of the Demand Spectrum to Account for Effective Damping

The hysteretic damping, $\boldsymbol{\beta_H}$, was calculated, using Equation 2.8 and $\boldsymbol{\kappa}$ value taken from the HAZUS99 Technical Manual).

The Area enclosed by the hysteresis loop was calculated by numerical integration using 100 segments and the trapezoidal rule. The effective damping for the demand spectrum was adjusted by summing the elastic and hysteretic damping.

Step 7. Re-Calculation of the Trial Intersection Point of the Demand and Capacity Curves

The ordinates of the demand spectrum were recalculated using a damping value of 15% of critical and the resulting spectrum was overlain on the capacity curve, and the values of S_D and S_A at the trial intersection point were compared to those from the previous trial intersection point to determine if they met the convergence criteria of having an S_D value within 0.001 cm of the prior S_D value.

Step 8. Iteration of Step 6 and 7 Until Convergence

After several iterations of Steps 6 and 7, convergence was reached when the intersection point of the demand spectrum and building capacity curve was at spectral displacement, S_D =2.4cm, and spectral acceleration, S_A = 0.245g. The effective damping, β_{eff}, at this peak displacement of the structure was 15%.

Step 9. Determination of the Probability of Complete Damage

The probability of complete damage was determined from the complete damage state fragility curve for building type C3. Hence the probability that the structure is in the complete damage state is 0.3. This was obtained by calculating the lognormal probability of being in the complete damage state, given the spectral displacement is the same as the peak structural displacement of 2.4 cm.

Step 10. Calculation of the Basic Structural Hazard Score

BSH Score is calculated as the probability of being in the complete damage state x the percentage of buildings that collapse in the complete damage state.

From Step 9, the probability of being in the complete damage state is 0.0048.

From the HAZUS99 SR2 Table 3.18, the percentage of C3 buildings in the complete damage state that collapse is 15%.

$$\mathrm{BSH} = -\log_{10}[\mathrm{P(collapse\ given\ MCE)}] = -\log_{10}[0.0048 \text{ x } 0.15] = 3.2 \tag{4.11}$$

5. Conclusions

The adopted methodology for quick assessment of buildings seismic performance is based on RVS procedure developed under FEMA 154 Report. It can be seen as a useful tool to implement the initial step toward identifying the potentially hazardous buildings in the zone. The identified hazardous buildings shall then be evaluated in detail from an experienced structural seismic engineer in second phase, with aim to confirm the capacity and vulnerability of the building. The detail analysis on the second phase may not comply with structural score obtained through RVS procedure, this due to the nature of the procedure itself, a fast and visual, with obstacles coming from impossibility to access the interior during the screening process, insufficient information's on soil category and also budget constraints that limit the depth and extend of investigation.

The methodology can be used also to design the seismic hazard mitigation programs for a community and develop the inventories of buildings for use in regional earthquake damage and loss impact assessments, etc.

A Case Study is used to illustrate the procedure for calculation of the Basic Structural Hazard Score for model building type of the zone. Detail structural analysis is performed for the purpose, with aim to determine the capacity of the building and intersection with appropriately demand spectra to obtain the trial intersection point through iterative process until the convergence criteria is fulfilled. With convergence of spectral displacement value, the probability of complete damage was determined from the complete damage state fragility curve by calculating the lognormal probability of being in the complete damage state, given the spectral displacement is the same as the peak structural displacement. The Basic Structural Hazard Score is determined then as probability of being in the complete damage state times the % of buildings that collapse in that damage state.

The impression of the authors is that the resulting structural scores obtained from the methodology are in line with expectations from expert judgment. Further work is needed to refine the Basic Structural Hazard Scores and Score Modifiers for the typical building structures on the respective region, in order to enable enforcement of the methodology for use in wider urban plots.

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