SIMPLIFIED PERFORMANCE-BASED SEISMIC DESIGN APPROACH FOR DEVELOPING COUNTRIES, SYRIA AS CASE STUDY

A. ALHOURANI[1*†], M. ONUKI[1], J. DANG[2] and T. KOIKE[3]

[1]*Graduate Student, Department of Civil Engineering, Kyoto University, Japan*
[2] *Program Specific Researcher, Department of Civil Engineering, Kyoto University, Japan*
[3]*Professor, Department of Civil Engineering, Kyoto University, Japan*

ABSTRACT

We propose a simplified approach for seismic design in developing countries considering both economical and seismic conditions. For developing countries in which seismological and earthquake load data is either unavailable or incomplete; a rational and simple seismic design procedure that accounts for seismic hazard level, cost efficiency and real structural performance is crucial. In this paper, the seismic design method in Syria is discussed to establish the shortcomings and problems existing in current seismic design practice. A case study is presented to examine the proposed approach. In addition a seismicity study for Syria and surrounding region is carried out to establish a general understanding of the degree of the seismic activity in the local context.

Keywords: Performance-based seismic design, reduction factor, serviceability limit state, ultimate limit state.

1. INTRODUCTION

In many developing countries, UBC 97 guidelines are directly adopted to seismic design with only minimum revision of seismic load levels, whereas in other countries these guidelines are not always used in the correct manner. Seismic design engineers in developing countries expect seismic design guidelines to be rational and simply applicable to their countries, where seismic load data have not yet been completely established.

When a new seismic design guideline is introduced into a developing country, the following criteria must be taken into account:

1. The seismic design procedure must be clear and easily understood;
2. The design spectrum must be easily constructed reflecting the seismic hazard environment of the country;
3. Safety criterion must be simply defined and its corresponding safety measure are easily estimated; and

* Corresponding author: Email: alhourani.zohir.25r@st.kyoto-u.ac.jp

† Presenter: Email: alhourani.zohir.25r@st.kyoto-u.ac.jp

4. The seismic design guideline is also simply revised when the societal and economic conditions of the country changes in the future.

In order to develop and evaluate the new proposed seismic design approach, the current seismic design method in Syria which is surrounded by major active seismic fault lines will be discussed.

2. SEISMIC DESIGN METHOD IN SYRIA

Internationally two types of earthquake levels are often considered for seismic design commonly referred to as Design Basic Earthquake (DBE) and Maximum Considered Earthquake (MCE). For seismic design, most codes and standards specify DBE of having 10% probability in 50 years (i.e. 475 years return period) and specify MCE of having 2% probability in 50 years (i.e. 2450 years return period) in terms of a single intensity measure such as the Peak Ground Acceleration (PGA). The Syrian seismic design code recently published in 2004 only adopts a seismic hazard map for Peak Ground Acceleration (PGA) with 10% probability of exceeding in 50 years (Return Period 475 years) as shown in Figure 1, which coincide with the definition of DBE earthquake level.

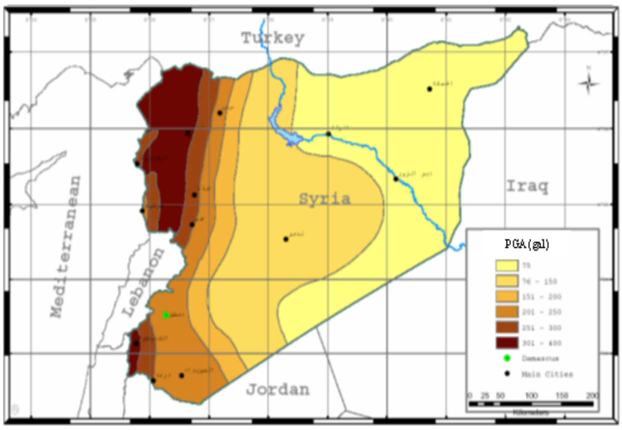


Figure 1: PGA distribution map in the Syrian seismic design code. (Syrian Earthquake Building Code 2004)

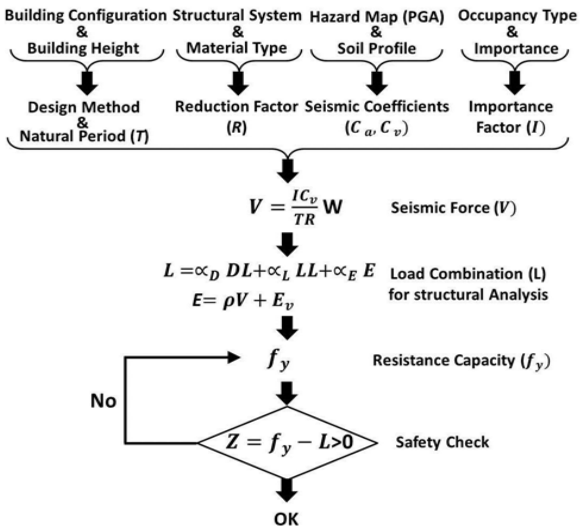


Figure 2: Flow chart of current seismic design approach in Syria.

The use of reduction factor (*R*) when calculating the seismic force *V* for elastic design, see Figure 2, is the main controversial issue in the current design approach. Although *R* in principal reflects the ductile capacity of the structure, the value of *R* in the current code, for convenience, is only related to the building material and on the structural system responsible of resisting the lateral seismic load for DBE type earthquakes. The value of reduction factor *R* in the current code lies between 8~4.5 for common building structures. The corresponding values of ductility ratio μ for *R*=8 is close to 65 (Newmark and Veletsos 1960), which is intuitively unreasonable. Consequently, the reduction factor *R* only represents an empirical value to control construction cost, which is an unavoidable reality in most developing countries.

To obtain the performance-based design framework, it is necessary to investigate the present reduction factor values in relation to structural inelastic behavior and cost efficiency and adopt more convenient values that are more suitable to the national context. The framework will provide a clear simple approach that can be used easily in practice to check the design safety for both DBE and MCE level earthquakes.

3. SEISMIC ACTIVITY IN SYRIA

A seismicity study was conducted by the authors to produce the frequency magnitude distribution (FMD) for Syria and surrounding region, see Figure 3 (Woessner and Wiemer 2005; Wiemer 2001). The study indicates that Syria is prone to three distinguishable levels of earthquakes. The first is Moderate frequent earthquakes with probability of exceedence (p) in the range of 10.8%-3.3% and return periods (T_r) during 50 years of design life cycle ranging from 437-1495 yrs; those values relate to magnitudes ranging from $4.5 \leq M_w \leq 5.5$. The second level is low frequent earthquake with probability of exceedence between 2.9%-1.0% and return periods ranging from 1700-5040 yrs; corresponding to magnitudes ranging from $5.6 \leq M_w \leq 6.5$. The third is very low frequent earthquakes with probability of exceedence in the range of 0.9%-0.3% with return periods ranging from 5685-16747 yrs; related to magnitudes $6.6 \leq M_w \leq 7.5$.

To generate the seismic hazard intensity maps (usually in terms of PGA), the following attenuation equation is commonly used to express PGA in terms of magnitudes (M) and epicentral distances (D) (Esteva and Villaverde 1973):

$$PGA = b_1 e^{b_2 M} (D + 25)^{-b_3} \tag{1}$$

In the case of Syria and the surrounding region, the values assigned to the constants are b_1=837, b_2 =0.89 and b_3 =1.73 (Abdallah et al. 1995). The seismic load of DBE can be then calculated in the form of response spectrum using the following expression:

$$S_A^{DBE}(T) = \beta_A(T) \cdot PGA = \beta_A(T) \cdot \gamma_{soil}(T_G) \cdot PGA_{base-rock} \tag{2}$$

in which $\beta_A, \gamma_{soil}, PGA_{base-rock}$ are respectively, the normalized response spectrum by input acceleration, surface amplification factor and peak ground acceleration at the base-rock. To reflect the uncertainty in the hazard intensity calculations, two sets of the design response spectrum, 90% and 70% non-exceeding level of the envelope curve, can be generated. The statistical parameters for the response spectrum sets are calculated as follows (JWWA 2006):

$$E\left[\ln S_A^{DBE}\right] = \ln S_A^{90} / \left\{1 + \mathrm{cov}\left(\ln S_A^{DBE}\right) \cdot \Phi^{-1}(0.9)\right\} \tag{3.a}$$

$$E\left[\ln S_A^{DBE}\right] = \ln S_A^{70} / \left\{1 + \mathrm{cov}\left(\ln S_A^{DBE}\right) \cdot \Phi^{-1}(0.7)\right\} \tag{3.b}$$

in which S_A^{90} and S_A^{70} are the design response spectra of acceleration which provide the non-exceeding level of 90% and 70%, respectively.

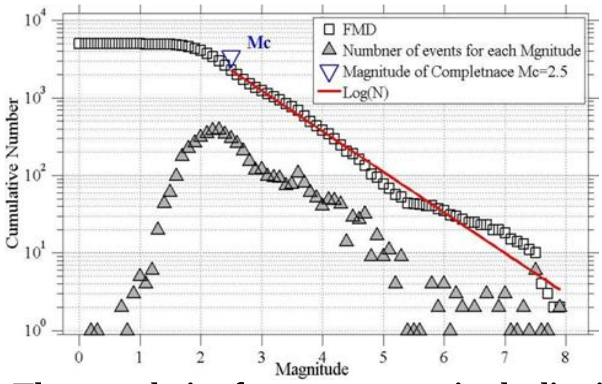


Figure 3: The cumulative frequency magnitude distribution for Syria and surrounding regions.

4. PEFORMANCE-BASED SEISMIC DESIGN APPROACH

The proposed seismic design method checks the seismic performance on the serviceability limit state and the ultimate limit state. The serviceability limit state is controlled by the strength capacity; and the ultimate limit state is controlled by the displacement capacity. In the serviceability limit state, the seismic safety Z^S is assessed as the probability that random load combination $\mathbf{L}^\mathbf{S}$ of dead load *DL*, live load *LL* and seismic Load *E* exceeds the capacity limit $\boldsymbol{f_y}$, see Figure 3. The capacity limit is given by the yield strength. This safety check is carried out for DBE earthquake level.
In a similar manner, the seismic safety Z^U for the ultimate limit state for MCE earthquake level is evaluated as the probability that inelastic seismic response $\boldsymbol{u}$ exceeds the capacity displacement limit $\boldsymbol{u_m}$, see Figure 4.

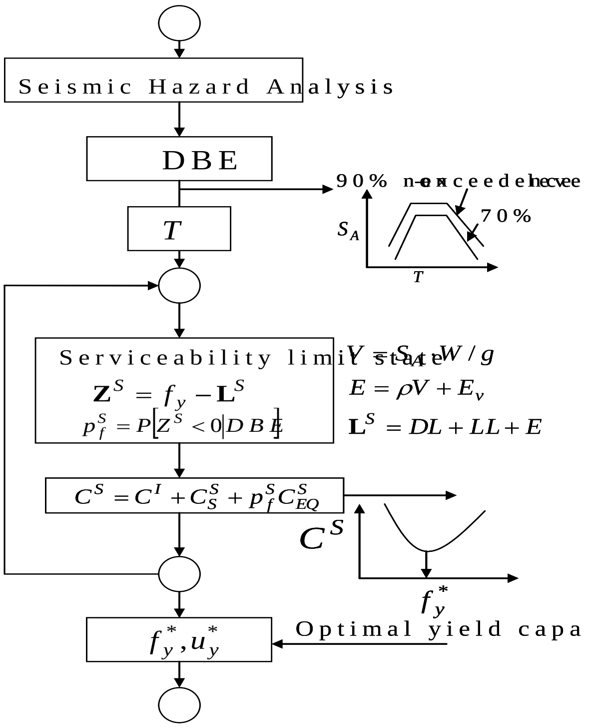
The proposed simplified approach assesses both DBE and MCE earthquake levels considering two components; the previously mentioned limit states accordingly and the minimum life cycle cost. To reach the optimal solution for this assessment, seismic risk analysis will be conducted using the concept of life cycle cost expressed as follows (Koike and Imai 2009):

$$C = C^I + C_S + p_f \cdot C_{EQ} \tag{4}$$

in which all costs are estimated in term of life cycle cost, and C^I: total initial cost for all assets; C_S: total retrofit investment for all the existing structures for minor damage mode, and zero value for newly constructed structures; C_{EQ}: repair cost for minor damage. If risk analysis is applied to a targeted city or region, the above Equation (4) is extended by Equation (5) to include all categories and groups of structures within this city.

$$E\left[C^S\right] = C^I + C_S^S + \int \nu_{Building}(x) \int_0^{C_{\max}} \rho_f^s \left\{q^{-1}(c), x\right\} \; f_{C_{EQ}^S} dc \;\; dx \tag{5}$$

in which $\nu_{Building}, C_{\max}, f_{C_{EQ}^S}$ are the damage rate of the building per unit area. The probability of density function $f_{C_{EQ}^S}$ is defined between two fixed boundaries $[0, C_{\max}]$.



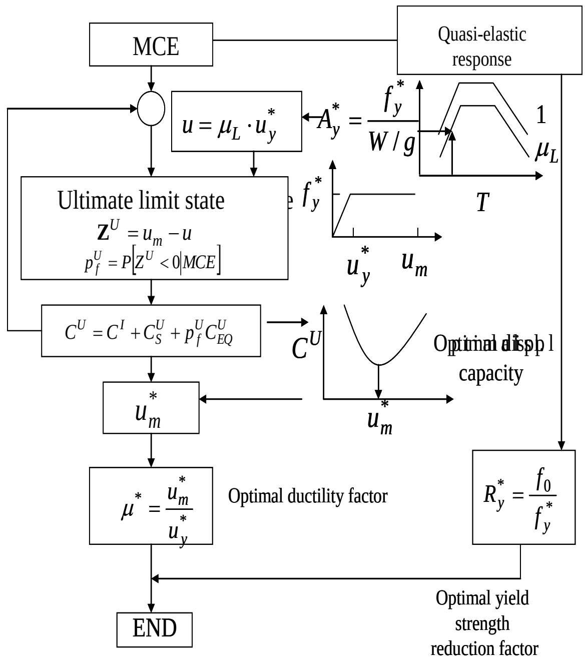


Figure 4: The flow chart to estimate the optimal structural capacity for serviceability limit state.

Figure 5: The flow chart to estimate the optimal structural capacity for ultimate limit state.

The flow chart of Figure 4 and Figure 5, show how to obtain the optimal capacity limit f_y^* for DBE earthquake level and the optimal displacement capacity μ_m^* for MCE earthquake level. The exceedance probability p_f^{target} and several cost data C_S, C_{EQ} must be available to extract the previous optimal values for the two earthquake levels.

In Figure 4 and for a given design response spectrum in DBE level, the seismic load is treated as a random variable in the calculation of load combinations. Using Equation (4), the optimal solution of the yield capacity (f_y^*) is estimated from the minimum value of the life cycle cost utilizing the seismic risk analysis concept.

The ultimate limit state, used in conjunction with MCE earthquake level, is measured by the response displacement of the structural system, see Figure 5. Using a single degree of freedom system with the fixed optimal capacity limit (f_y^*) and a single earthquake accelerogram of MCE, the optimal maximum displacement capacity (u_m^*) is derived as the value corresponding to the minimum cost which is derived in the similar manner from the seismic risk analysis. The optimal yield strength reduction factor R_y^* can be then obtained as follows: $R_y^* = f_0 / f_y^* = A_0 / A_y^*$

where f_0 , A_0 is the maximum force and acceleration value of the elastic response for MCE, and f_y^*, A_y^* is the optimal capacity limit and optimal yield acceleration for DBE. f_0 and A_0 are calculated from the nonlinear acceleration response spectrum with ductility equal to unity. Since the optimal maximum deformation u_m^* is estimated, the optimal ductility factor can be simply calculated as: $\mu^* = u_m^* / u_y^*$

5. CASE STUDY

To examine the reasonable range of reduction factor R an example is presented. In order to consider the uncertainties of DBE and MCE, the seismic loads are given in form of the design spectra of acceleration providing the non-exceeding level of 90% and 70%. Magnitudes of DBE and MCE are chosen to be 4.75 and 6.05 respectively. The previous values correspond to exceedance probability of 10% and 2% for 50 yrs life time following the internationally accepted definitions of DBE and MCE earthquakes. The epicentral distance is assumed as 30 km (which is the distance between Damascus city and the nearest fault segment of the DSFS called Serghaya fault), so that the PGA at interest location is found to be 84gal and 267gal, respectively for DBE and MCE (The previous PGA values are multiplied by 1.5 the soil amplification factor). For Syria, earthquake records regarding MCE are not available, so ten earthquake waves are adjusted to fit the MCE design spectrum determined by PGA=267gal for nonlinear response analysis in MCE level design. The design response spectra defined in the Syrian seismic design code was used in the adjustment process, see Figure 6.

Using the purposed framework (Figure 4 and Figure 5) the seismic safety for serviceability limit state (DBE earthquake level) and ultimate limit state (MCE earthquake level) are assessed. In order to consider the social and economic conditions, retrofit investment C_S^S, C_S^U and repair cost C_{EQ}^S, C_{EQ}^U are used to calculate the life cycle cost C^S, C^U for serviceability and ultimate limit states, respectively. The values of the optimal yield capacity f_y^* and the optimal maximum displacement u_m^* are shown in Figure 7.

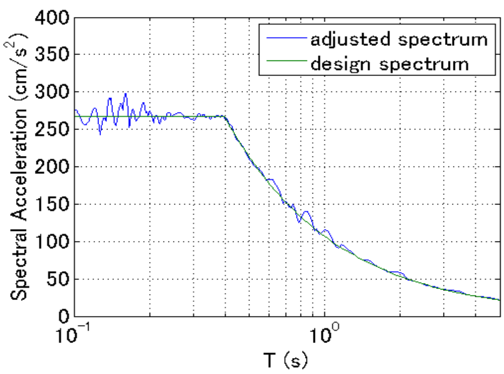


Figure 6: Example of adjusting El-Centro spectrum to the design spectrum in the Syrian code.

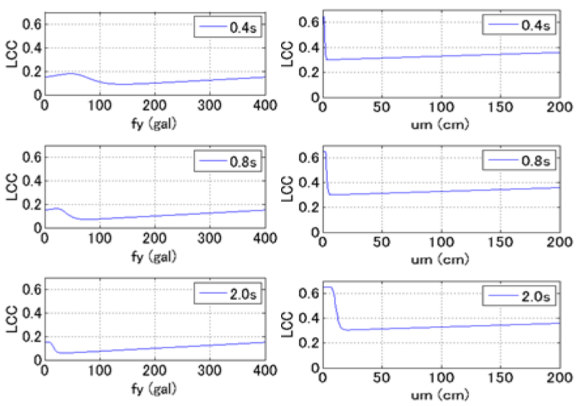


Figure 7: Optimal calculation by minimum life cycle cost.

The optimal values of R_y^* show little unevenness for different earthquake waves, see Figure 8. This is expected as all earthquakes are adjusted to fit the same design response spectra, which means all input earthquakes share the same frequency to intensity characteristic. The only variable left to affect the results of R_y^* is the phase angle, still it can be seen from Figure 8 that even the phase angle influence on R_y^* values is considered small.

Furthermore, the $R_y^* \sim T$ relationship for each earthquake wave shown in Figure 8 shows that the optimal values of R_y have a decreasing tendency for longer natural period. In addition, values of

R_y^* generated using the proposed simplified approach lie in the range of 1.5-2.5 this is because the PGA corresponding to exceedence probability of 2% (MCE earthquake level) in the Syrian context is very small. For the usual definition of DBE and MCE, it can be also seen that the nonlinear response is small, the value of the optimal ductility factor $\boldsymbol{\mu^*}$ is about 3 to 5, see Figure 9. For this case, the ductility demand can be easily satisfied, as long as the limit values of structural geometric coefficients such as reinforcement bar area rate, slenderness, shear-span ratio etc. have been met.

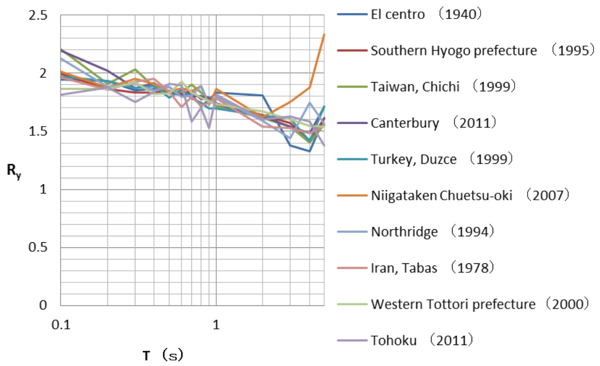


Figure 8: R^*_y ~ T Curves for Different Earthquake Waves.

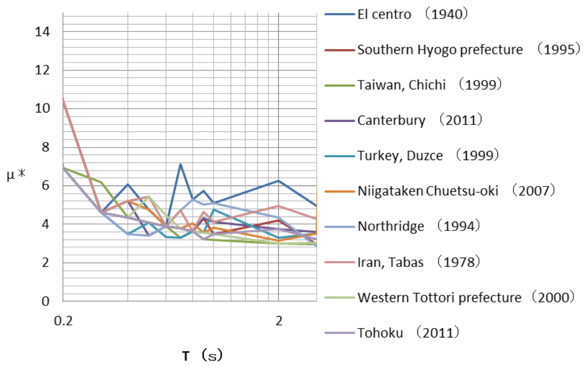


Figure 9: μ^*~ T Curves for Different Earthquake Waves.

However, the well documented historical seismic records indicate that large earthquakes with magnitudes of 7 – 7.5 are likely to occur. In seismic design, engineers should also consider such cases, even though there exceedence probability is less than 2%, in order to prepare for the extreme damage that might occur. The November 1759, a magnitude M=7.5 earthquake along the Serghaya fault which struck Damascus city, the capital of Syria, is considered as the most recent major earthquake to hit a major city in Syria. The $R_y^* \sim T$ and $\mu^* \sim T$ relationship for different earthquake waves have been regenerated using the M=7.5 earthquake as a representative of MCE earthquake level, see Figure 10 and Figure 11. The 7.5 magnitude corresponds to 0.3% exceedance probability

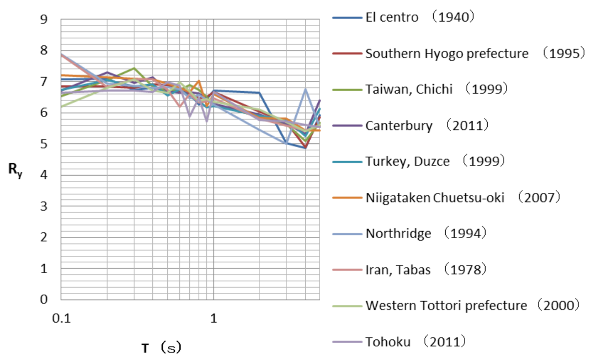


Figure 10: R^*_y ~ T Curves for Different Earthquake Waves using M_{MCE}=7.5.

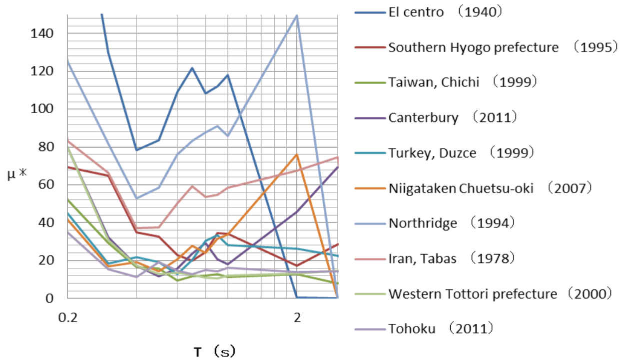


Figure 11: μ^*~ T Curves for Different Earthquake Waves using M_{MCE}=7.5.

Figure 10 displays that for typical buildings in Damascus City, with natural periods 0.4 to 1.3 sec, the reduction factor R_y values lie between 5 to 7. These values are much more reasonable and rational as they consider both the effective seismic protection cost and seismic safety against high seismic hazard levels (M_{MCE}=7.5). On the other hand, the values of the ductility factor $\boldsymbol{\mu^*}$ are somewhat extreme, see Figure 11, this is influenced by the stiffness model (force-displacement relationship) usually used to describe the stiffness degradation of structural components and not a whole structure.

The previous cases illiterate the influence of both the seismic hazard level and seismic protection cost on the values of the reduction factor. Thus these influences must be accounted for during seismic design to avoid underestimation of the seismic design force when using the reduction factor *R* especially for cases of extreme seismic hazard levels.

CONCLUSIONS & FUTURE WORK

Due to current advances in probabilistic methods for hazard and risk analyses, it is desirable for developing countries to adopt more advanced and reliable approaches for seismic design. The proposed framework applies the probabilistic methods in the form of cost estimation to generate more reliable data to be used in seismic design. The clear and coherent flow of the proposed framework makes this approach easy to understand and apply in developing countries. Additionally, according to the seismicity study for Syria, the occurrence of MCE is genuine. The proposed approach offers a more accurate assessment of seismic design force that considers all possible hazard levels. The current study presents the concept and general outlines of the new approach and as importantly explains the reasons behind its formulation.

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