Seismic Vulnerability Assessment Methods: A Review

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Abstract. Seismic vulnerability is defined as the tendency of the structure to undergo structural or non-structural damage in case of any seismic event. In such cases, the buildings lose its ability to bear the sudden effects of seismic forces. In risk analysis of a building, the vulnerability assessment of a structure plays a vital role. Over the years various methods have evolved for assessing the seismic vulnerability of a structure. The assessment procedures may be empirical, semi empirical or analytical. The assessment output may be quantitative or qualitative in nature. Seismic vulnerability based on empirical method are evaluated with the help of post-earthquake damage data collected over the years and thereafter the structures are compared with the structural details and typology prior to seismic event. The damage data and statistics are recorded year after year around the globe after every seismic event. On the other hand, in analytical method, the seismic vulnerability can be assessed through deriving numerical model and also performing various types of static and dynamic analyses, mainly the nonlinear analyses. However, some of the said, methods are time consuming and computationally intensive, hence there are various alternative vulnerability assessment strategies proposed by various researchers, which are briefly described in this article. Also, the prerequisite of a suitable seismic vulnerability assessment procedure is discussed.

Keywords: Seismic vulnerability · Empirical · Analytical

1 Introduction

Every year, there are significant amount of losses, including losses of human lives, caused by natural catastrophes like earthquake. This bears a significant impact if considered decade wise. Predicting seismic vulnerability of the built environment is required for saving losses, minimising causalities and also anticipating the extent of damage likely to take place. Vulnerability assessment is a significant component of an overall loss predicting model which identifies the seismic damage for a given scenario. This proves to be very useful for the insurance company for estimating premium and claim settlement. With the ever increase of population suitable vulnerability assessment methods are necessary for quick estimate of future losses and to formulate strategies to mitigate the risk. A successful and timely vulnerability assessment can mitigate the risk to a great extent and the subsequent rehabilitation and retrofitting strategies can be cost effective. Further the seismic vulnerability assessment of the existing building or stock

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of buildings can provide all important details that are to be considered during construction and design of new buildings following the prevalent seismic code including the calibration of the codal guidelines as per requirement. As already defined the seismic vulnerability of a structure is its probable likelihood to damage by a given ground shaking intensity and therefore the structural vulnerability assessment under a scenario earthquake leads to the probability of achieving a prescribed damage level, which can be expressed qualitatively or quantitatively. In this regard various seismic vulnerability assessment methods have been proposed by seismic experts, earthquake engineer and researchers for a given building stock, based on the seismic demand and typology of the structure. This paper will review some of the important vulnerability assessment procedures.

2 Literature Review

Seismic vulnerability as defined is the likelihood of the building to damage during earthquake. It is an important parameter for various field workers, engineers, disaster management authority to know the vulnerability of a building stock before hand in order to anticipate the probable occurrence of damage post-earthquake. In this regard Kassem et al. (2019) proposed an index called Seismic Vulnerability Index (SVI), with its value ranging from 0 to 1. less vulnerable being indicated by 0 and more vulnerable by 1, in qualitative sense. Yakut (2004) proposed an index called basic capacity index method which reflects the probable or anticipated seismic performance of a structure during earthquake based on the structural details of existing RC structure. Japanese Seismic Index method (JBDPA 1990) is another popular method used in Japan since 1975 for existing RC buildings less than six storeys. A combination of empirical method and analytical method for seismic vulnerability assessment is popularly known as hybrid method of vulnerability assessment, Kappos et al. (1995, 1998) have derived damage probability matrices using a hybrid procedure. Bernardini et al. (1990), proposed a method for the vulnerability assessment of unreinforced masonry buildings (URMB) using the fuzzy-set theory and the definition of collapse multipliers. There is another method called FaMIVE which is based on collapse load factor where the most probable mechanism with lowest capacity considering both in plane and out of plane failure of masonry building is taken into consideration as proposed by D'Ayala and Speranza (2002). Calvi (1999) developed a methodology where displacements are considered to be the primary indicator of damage for any seismic event. Meléndez et al. (2018) proposed a probabilistic vulnerability index method which is termed as Vulnerability Index Method probabilistic (VIM_P) for seismic risk and vulnerability assessment of the building stock in Barcelona. Whitman et al. (1973) introduced empirical damage probability matrix for the probabilistic prediction of damage to buildings from earthquakes based on previous earthquake damage data. Spence et al. (1992) have developed continuous vulnerability curves based on parameter less scale of intensity (PSI). Kircher et al. (1997), discussed about the capacity spectrum methods in which the performance point of a structure is derived from the intersection of an earthquake demand spectrum, and a capacity curve (pushover curve), where the demand spectrum representing the ground motion during earthquake.

3 Description of the Methods

3.1 Seismic Vulnerability Index Method

A simpler method using nonlinear parametric analysis and subsequently deriving the seismic vulnerability index for the seismic vulnerability assessment of reinforced concrete (RC) was proposed by Kassem et al. (2019) (Fig. 2). The authors developed this approach to study the seismic vulnerability of a school building at Ranau, Malaysia post Ranau earthquake in 2015. However this method is useful to determine the vulnerability classes of building stock by classifying the buildings based on seismic resistant design capacity as Low, Medium or High ERD (ERD-Earthquake Resistant Design). The authors have further proposed eight types of parameters to finally derive the vulnerability index of each vulnerability class. The eight parameters considered are: connections at beam-column joint, support type at foundation level, types of horizontal diaphragm, soil type of the building foundation, ductility of the building, structural irregularity in terms of mass ratios and grade of concrete. A series of nonlinear static analysis and nonlinear dynamic analyses are performed to evaluate the weightage of each parameter mentioned. Seismic Vulnerability Index (SVI) is thus determined from the Eq. (1). SVI value is deterministic and it ranges from 0 to 1.

$$SVI_{Building} = \frac{1.5\sum N_i^c x_i + 1.0\sum N_i^b x_i}{\sum N_i^c + \sum N_i^b x_i} \quad (1)$$

where, Ni^c and N_i^b denotes the number of plastic hinge(s) formation- in columns and beams respectively, and 'i' represents number assessing the performance level, where 'i' ranges from 1 to 6. x_i is the weightage factor of the beams and columns. For performance level (PL) < B, x_i = 0.000; PL:B-IO, x_i = 0.125; PL:IO-LS, x_i = 0.375; PL:LS-CP, x_i = 0.625; PL:CP-C, x_i = 0.875; PL: C-D, D-E, > E, x_i = 1.000, as proposed by Kassem et al. (2019) (Fig. 1).

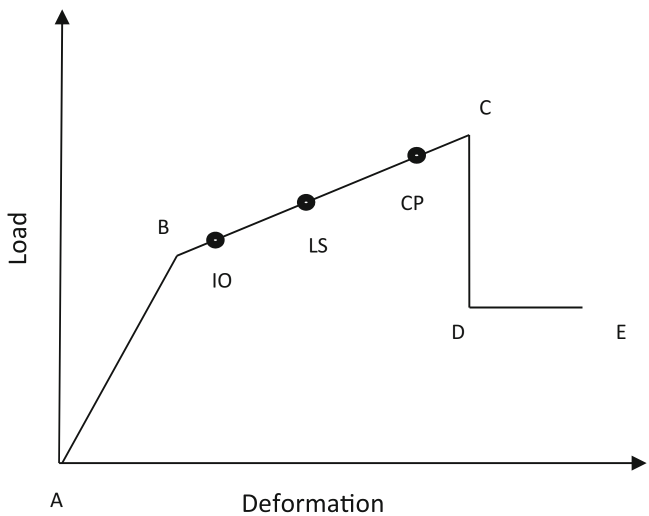

Fig. 1. Load-deformation curve indicating various performance level for the weight factor x_i.

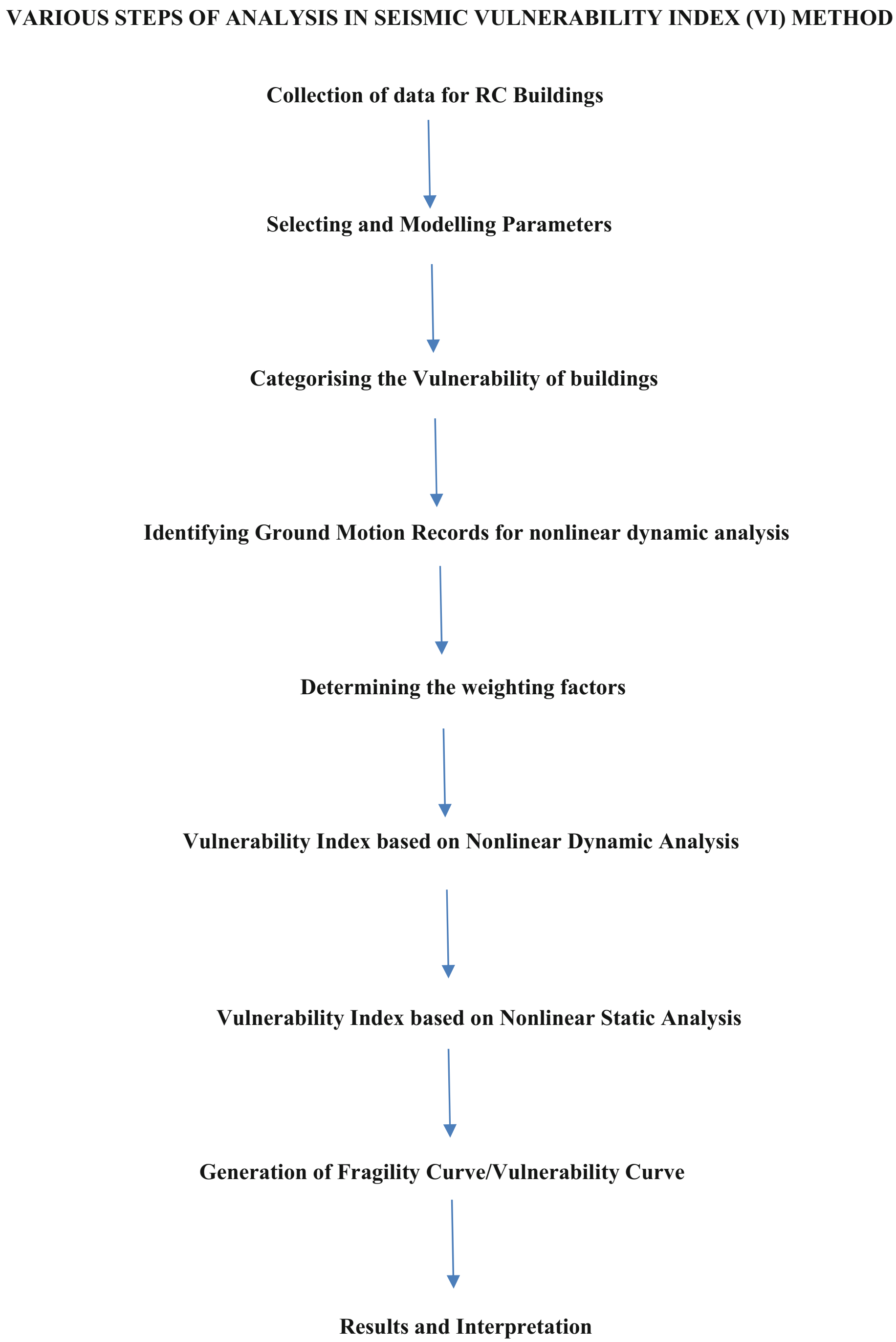

Fig. 2. Various steps of Seismic Vulnerability Index (SVI) method as per Kassem et al. (2019).

Once the seismic vulnerability index (SVI) value is determined, the mean damage grade (μ_D) (where, ($0 < \mu_D < 5$)) is evaluated for each building under study. For this purpose, a mean vulnerability function correlating seismic hazard with the said damage relating the SVI and the corresponding seismic intensity (PGA) is expressed. Subsequently using the SVI approach vulnerability curves relating mean damage grade vs. PGA can also be developed. This method may serve as an alternative to rapid visual screening method, as it is based on judgements and opinions of the experts, and previous damage record data. This method is analytically derived for vulnerability assessment of RC buildings, unlike the procedure from the Italian GNDT and European Macro seismic (EMS) approaches which were mainly focused on empirical data and vulnerability of masonry structures and steel structures. This method also serves as an effective tool to determine the economic damage index which is defined as the ratio of repair/renovation cost to replacement cost. The more is the index value the more is the economic losses. It also accounts for the rate of loss of human lives and other damages.

3.2 Basic Capacity Index Method

Capacity Index (Yakut 2004) is a method suited for low rise to mid-rise RC buildings. The method is of the concept that the higher the contribution of the concrete in a structural element, the higher would be the shear capacity of the reinforced concrete buildings and less will be the corresponding vulnerability. In this method, the capacity depends on the size, material property and the direction in which the capacity is computed for individual member, since as the direction changes the dimensions of individual structural element changes, and thus the shear strength capacity also changes for longitudinal direction and transverse direction for any RC buildings under considerations. The yield base shear capacity V_y generally does not take into account the effect of masonry infill walls, however one may relate the presence of masonry infill wall and its contribution to the shear capacity by calculating V_{yw} which is related to V_y by the equation

$$V_{yw} = V_y\left(46\frac{A_w}{A_{tf}} + 1\right) \tag{2}$$

where A_w indicates the total area of the infill wall and A_{tf} indicates the total floor area of the building under consideration. The V_y is then used to calculate the V_c, the concrete base shear capacity which in turn is used to determine the Basic Capacity Index (*BCPI*). The *BCPI* (also known as yield over strength ratio) value is generally theoretical and is calculated as per Eq. (4). It does not consider the structural irregularities and the uncertainties in standard construction practices. To overcome this, the CPI is calculated by taking into consideration the limitations of *BCPI* and is calculated as per Eq. (6). The CPI_{limit} value is set by expert observation after survey and the calculated *CPI* value is expected to be of higher value than the CPI_{limit}, so that the building can have adequate life safety performance.

Following equations are used in finding the capacity index of the building:

$$V_y = (0.37n + 0.30)V_C \tag{3}$$

$$BCPI = \frac{V_y}{V_{code}} \tag{4}$$

$$CPI_{limit} = 0.05n + 0.45 \tag{5}$$

$$CPI = C_A \times C_M \times BCPI \tag{6}$$

where,

V_c = The concrete base shear capacity.
V_y = The yield base shear capacity.
N = No. of stories.
V_{code} = The base shear capacity as per codal provision.
$BCPI$ = Basic Capacity Index.

The CPI value has been taken by considering the architectural features and irregularity denoted by C_A and the variation in the standards of workmanship/construction practice denoted by C_M. CPI value is compared with the CPI limit value to know the probable performance of the structure. CPI limit values as already mentioned should be ideally smaller than the CPI value calculated. The higher the difference ($CPI\text{-}CPI_{limit}$) the better is the performance expected from a building and lower will be the vulnerability. This method is based on strength based concept and the results may be inaccurate compared to the displacement based procedure. However quick vulnerability assessment of the large building stock is possible without detailed computation.

3.3 Japanese Seismic Index Method

As the name suggests, this method is widely used in Japan, for identifying the seismic performance of existing Reinforced Concrete buildings less than 06 (six) storeys. This method is prevalent in Japan since 1975 (JBDPA 1990). The performance of a building during a seismic event is evaluated by an index namely seismic performance index, Is, which is calculated for individual storey in all possible frame direction within the particular building under study using the following equation:

$$I_S = E_0 S_D T \tag{7}$$

where E_0 indicates the basic structural performance representing the energy dissipation capacity during the seismic event, S_D represents the index indicating the structural configuration for the particular building, and T is the index representing the time deterioration of the building under consideration. E_0 can be calculated by the product of the shear force coefficient 'α' and the ductility 'μ' of the particular storey, under performance evaluation. Both S_D and T are empirically derived non-dimensional index. S_D takes into account the vertical or horizontal irregularity of a structure, the damage concentration of a structure, and the cumulative damage sustained by the structure.

The building deterioration and the development of cracks over time after the seismic event is accounted under the empirical index *T,* which is based on actual field survey data.

3.4 Hybrid Methods

Hybrid methods are the combination of empirical method and analytical method that are used to derive vulnerability curves. In this method the empirical data from previous earth quake record set along with damage statistics are used to simulate the numerical model of a particular building typology. It can be particularly useful where the empirical data reduces the computational effort to generate an analytical vulnerability curve using damage probability matrix. Kappos et al. (1995, 1998) in their study developed the damage probability matrices using hybrid methods, where the damage value against the respective intensity levels are selected using the previous ground motion record set following the Vulnerability Index method proposed by Benedetti and Petrini (1984).

3.5 Collapse Mechanism-Based Methods

Bernardini et al. (1990) proposed collapse mechanism-based methods by using 'collapse multipliers' for analytically assessing the vulnerability of a masonry building. The failure mechanism of the building during earthquake determines the value of collapse multipliers. It is calculated numerically for an in-plane shear failure during a seismic event and is denoted by I_1, where I_1 can be defined, to be the ratio of the minimum value of shear strength considering both the directions x and y to the total weight W of the building.

$$I_1 = \frac{\min\left(V_x, V_y\right)}{W} \tag{8}$$

where V_x and V_y are the shear strengths at mid-storey level of the ground floor considering the x and y directions. The minimum value of V_x and V_y is considered for determining the collapse multiplier as the minimum shear strength will led to the cause of the early collapse of the masonry facade wall. The collapse mechanism occurring out of plane is defined by the collapse multiplier I_2 where, I_2 is the ratio of flexural strength of the facade/external wall to the total weight of the structure (W)

$$I_2 = \frac{\min(F_H + F_V)}{W} \tag{9}$$

where F_H and F_V are the minimum flexural strength of the horizontal and vertical strips of the most critical external wall.

3.6 Failure Mechanism Identification and Vulnerability Evaluation (FaMIVE) Method

FaMIVE as the name suggests is a procedure which identifies failure mechanism of the masonry structures mainly the URM (unreinforced masonry) buildings and the subsequent vulnerability evaluation. This method yields collapse load factor for each and every types of failure mechanism or collapse mechanism. A total of thirteen nos. of different failure mechanism are considered for the facade wall depending on the type of constraints between the facade wall and the rest of the structural members of the building. The said thirteen failure mechanism involves both in-plane failure mechanism, out of plane failure mechanism and the combined mechanism. The load factor is calculated for every individual facade of the building, and depending upon the masonry properties and connections between the structural members, the most probable failure mechanism is identified. It therefore helps in repair and renovation of the structure so as to mitigate or avoid the possible failure. It applies the pushover analysis for subsequent generation of the capacity curve and to locate the performance point graphically. Thus, this procedure helps to generate vulnerability functions for various masonry structures. This method has been used worldwide on various structures of historical importance for countries like India, Nepal, Italy etc. D'Ayala and Speranza (2002) have also used this procedure for vulnerability assessment of URM buildings.

3.7 Fully Displacement Based Method

This method as the name suggests is based on displacement of the structure due to seismic input, which serves as the damage indicator. It was first proposed by Calvi (1999), who proposed displacement as a damage parameter and developed seismic demand spectra for displacement. It is inspired by the principle introduced by Priestley (2003), who preferred direct displacement based design over strength based design approach of the framed structures. The multiple degree of freedom generally present in a framed building is simplified and modelled as a single degree of freedom (SDOF) structures (Fig. 3). In this approach K_e effective stiffness is considered instead of initial stiffness K_i unlike force based design approach. This method is non-iterative or very less iteration is required, hence it provides the displacement limit profile directly without any intensive computation for any given building stock. It is an effective tool for vulnerability assessment specially for a large building stock by estimating the losses in a cost-effective manner.

3.8 Rapid Visual Screening Method

This method was used for the first time in the year 1988 in the United States. It is basically an empirical method with a preliminary vulnerability approach without involving any detailed calculation and investigation. It is later on modified by introducing suitable modifications and assigning scores against each parameter detailed in FEMA P 154, 2015 (Third Edition). This procedures involves only visual inspection of the structures by a trained personnel while merely walking around the structures and collecting data. This procedure is not suitable for buildings having complex details, however can provide a basic guidance for further detailed analysis and disaster mitigation process.

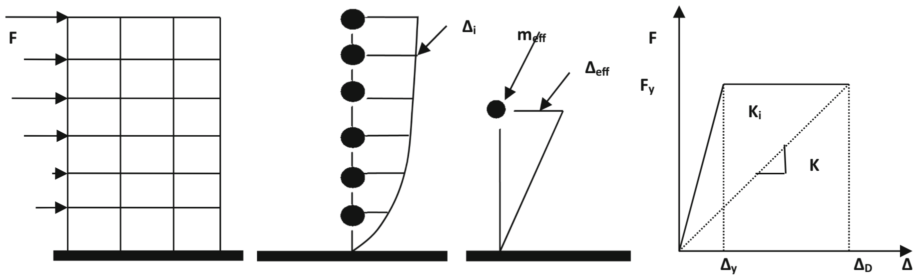

Fig. 3. Equivalent SDFOF system.

3.9 The Analytic Hierarchy Process (AHP)

This method is the process of developing a hierarchy model to decide the most effective criteria and their relative weights to finalise a complex decision. This method is a part of Multi Criteria Decision Making (MCDM) process. This technique can also be used in seismic vulnerability assessment of a specific area and to generate a pair wise comparison matrix of different criteria related to vulnerability assessment. The criteria may be categorised with a single objective/goal or may be multi objective. The multi objective goals can be under a single primary goal. As for example, if we take preparation of a seismic vulnerability assessment map as a primary goal, there may be structural parameters and geological parameters as the secondary goal. Each secondary goal can have different criteria relevant to vulnerability assessment. The criteria are to be selected wisely based on knowledge and experience. The hierarchy model is developed with primary goal at level 1, secondary goals at level 2, various criteria at level 3, development of pairwise matrix at level 4 and evaluating the relative weights and consistency index (CI) and finalising the matrix. Level 5 is the last step that provides the result of the decision making process with a priority rank of each assessment criteria, which concludes the entire process of AHP. However the AHP method needs to be supplemented by empirical and analytical methods used for the buildings under consideration. A seismic vulnerability map can thus be developed with area having less vulnerable to more vulnerable structures. This method was first used and developed by the famous statistician Saaty in the decades of 1970s, which was subsequently modified as per the use by various researchers, statistician and mathematicians. A schematic flow chart of the AHP process is given below (Fig. 4).

3.10 GIS Method of Vulnerability Assessment

A geographic information system (GIS) is basically a framework that allows to capture and analyse the geographic and spatial data for vulnerability assessment of the area of interest. It also helps in identifying the topography of the building site and ascertains possibility of new construction. With technological advancements, this method has become one of the fastest and cost-effective method for vulnerability assessment compared to the traditional method. GIS is also a semi-empirical assessment approach. A seismic hazard analysis of a particular city or town can be made by the help of the software called GIS Arc. Various other GIS based app and commercial software are also recently developed. Currently the GIS data can be digitally stored and a digital map can be developed for any area by converting and manipulating data as per requirement.

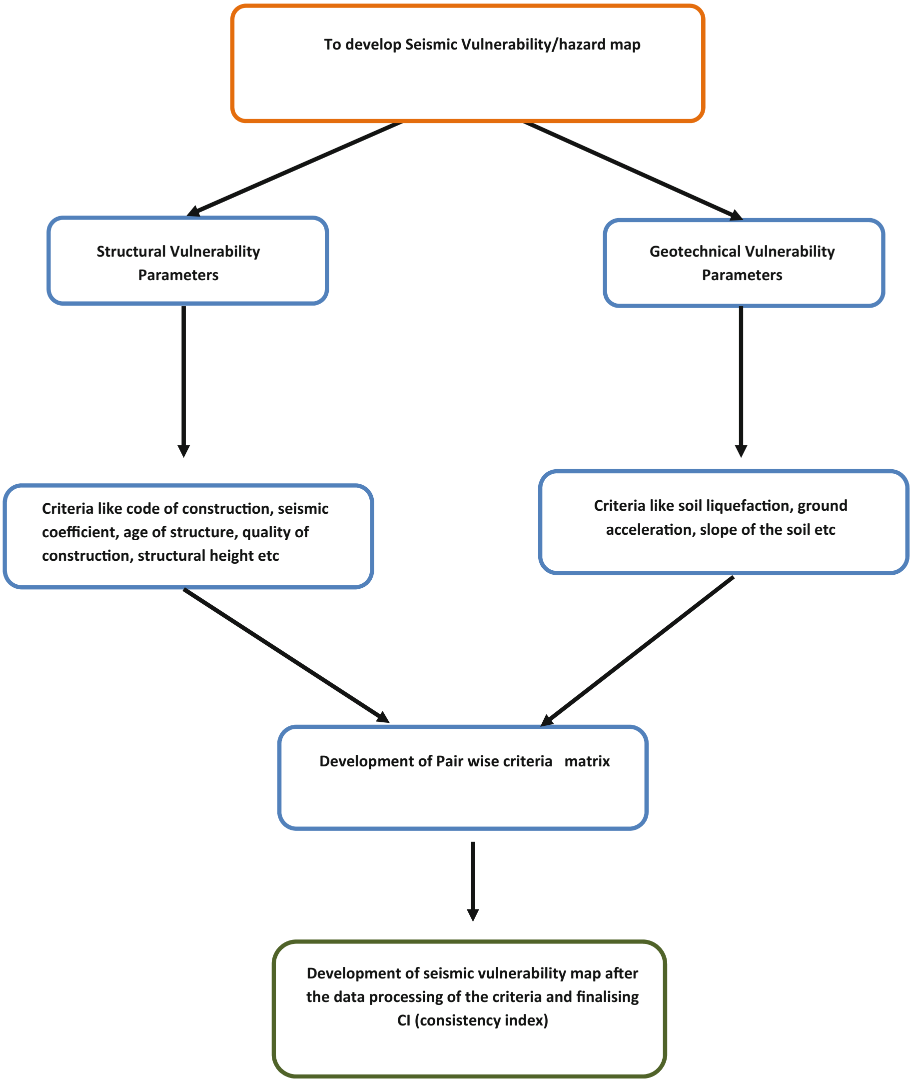

Fig. 4. Development of a seismic vulnerability map using AHP.

3.11 The Internet-Based Seismic Vulnerability Assessment Method

This method is developed as a preliminary step for seismic vulnerability assessment and cannot be considered decisive until reviewed and verified by the experts, as it involves the common people who are not technically qualified to judge every structural detail of their individual building. However it allows the common people staying on their individual residential buildings to access the primary server and to enter their respective building related information. The information are stored and processed serially. The users are provided with two types of approaches i) simple approach and ii) detailed and complex approach for vulnerability evaluation. The users may enter data accordingly depending on their level of competency and understanding. Once the data are entered and sent into the primary servers, the data are processed through a software to generate results with a detailed report about the seismic deficiency of the structure, site soil report, seismic hazard of the area where the building is located; along with many other important details, which can be obtained in a printed form. The reports are sent back to the user accordingly. Internet based approach combines multiple advantages but there are also associated disadvantages on its use. The advantages can be listed as follows:

a) Different users are allowed to access the internet simultaneously.
b) There is no time limitation of using the internet and the users can access the internet as per their own convenience and comfort.
c) This method does not require any trained personnel to enter the building details which eliminate the hiring cost of the technical expert.
d) This method does not involve any cost as such and hence it is beneficial for the lower income group to evaluate the seismic vulnerability of their buildings. The combined data of various users form a comprehensive database comprising of various details of the buildings, which further helps for additional assessment by the experts and formulate retrofitting strategies.

The main disadvantages of this method include:

a) The data are not individually reliable and has to be supplemented by other established vulnerability assessment procedures or from previous valid data sources.
b) There is no accountability for wrong data or inappropriate data entered by the users which may cause severe damages to the structure reported with low vulnerability, for future earthquakes and cannot have any legal locus standi.

The main intent of the said method is outlined in the following as follows:

i) To develop a seismic vulnerability assessment tools (which is also cost effective) in an online platform for various types of existing and newly designed reinforced concrete structures.
ii) To minimise the difficulties due to the lack of technical experts to collect data from the wide variety of buildings in a country.
iii) To expedite the vulnerability assessment procedure, this will further help in retrofitting works in the worst affected area anticipating future major earthquake
iv) To develop a global approach this may be useful for various countries of the world as well

v) To make the common people literate at a primary level about earthquake risk and vulnerability of buildings.
vi) To spread basic civil engineering knowledge and construction practices among the masses
vii) To adjust and calibrate new weighting factors by matching with building information recorded at the database after occurrence of an earthquake, and in the process evolving a new coefficient by correlating with the damage level after each seismic event.

3.12 Probabilistic Vulnerability Index Method (VIM_P)

The most widely used method for seismic vulnerability assessment is the Vulnerability Index Method (VIM), because of its simple approach which involves the seismic hazard analysis, seismic vulnerability analysis and damage evaluation by generating damage probability matrix. However the results obtained are deterministic in nature and does not include the structural uncertainties. Hence the VIM_P is the extension of VIM method which quantifies the annual loss estimation in a probabilistic approach. It considers five damage grades (D1 to D5) based on physical damage observation and evaluates the probability of frequency exceedance of a certain damage grade determined annually, under a given macro seismic intensity and computed vulnerability index under VIM. As earlier mentioned VIM provides the deterministic value and it ranges between 0 to 1 from less vulnerable to more vulnerable depending on the structural characteristics, storey height and typology etc. The probabilistic approach studies the reliability of the vulnerability index calculated. In other words, suppose a building attains the value of 0.5 as a vulnerability index in the deterministic approach, however for the same value, a building may develop three types of vulnerability curves described by three types of probability density functions and the curves thus generated can be named *lower, best* and *upper*. The *'best curve'* is considered to be the probable vulnerability of a particular building with a minimum uncertainty compared to the lower and upper curves. This seismic vulnerability computed is linked with the seismic hazard of the area and the damage functions to evaluate the seismic risk. USERRISK 2015 software computes the seismic risk of the structure by using VIM_P method. Melendez et al. (2018) have also determined the seismic risk of around 70000 buildings by using VIM_P method.

3.13 Seismic Vulnerability Based on Current Seismic Code

Most of the seismic codes across the globe considers the building to sustain under minimum lateral earthquake force. The different standards provide the minimum design force related to the earthquake resistant design of buildings and for various other special structures. The latest Indian Code for earthquake resistant design of structures IS 1893:2016 (Part1) has been modified form its previous edition of IS 1893:2002 to ensure better sustainability of structures with reference to strong ground shaking during earthquake. The codal standards of a particular country are related to the International Building Code standards, ASCE and FEMA guidelines of USA and other standard seismic regulations practised in different countries, keeping in view the standard practices and guidelines of its own country. However with every codal revision, the older structures especially the important structures require a vulnerability assessment for future earthquakes along with the structures constructed without any codal guidelines. In such a case various empirical and analytical methods can be applied for vulnerability assessment of such structures and can be compared with different limits proposed in the current seismic codes. The structures that are detected with low or insufficient earthquake resistance needs to be retrofitted and strengthened as far as practicable, if the re strengthening is economical compared to the replacement.

3.14 Damage Probability Matrices

Damage data of previous earthquakes on various structural typologies construct a damage probability matrix. As the name suggests, it gives a probabilistic idea of damage to be experienced by the structures from future earthquakes having similar typology. In this method all sorts of structural and non –structural damage are expressed in terms of damage ratio (repairing/renovation cost to the replacement cost) which in turn relates to the Modified Mercalli intensity scale. This method is basically an empirical approach where several thousands of earthquake data based on their extent of damage are quantified and expressed in the numerical range of damage ratios. The damage probability matrix initially derived by Whitman et al. (1973) to take stock of the extent of damage occurred after the 1971 San Fernando earthquake and it was further modified by Braga et al. (1982) based on MSK scale which was later on updated by Di Pasquale et al. (2005) where the damage is related to MCS scale. All the said DPMs are expressed in a discrete manner and the probability of reaching damage state ‘d’ corresponding to the ground motion intensity ‘i’ is expressed as P[D = d/i].

3.15 Analytically Derived Vulnerability Curve and DPMs

In current era, with the technological development and evaluation of computer based program, computational analysis has become much easier, which led to the development of analytical vulnerability curves and damage probability matrix (DPMs).The analytical methods possess more detailed vulnerability algorithm, evaluation of numerical model and performing linear and nonlinear analysis through finite element software, which relates to the building stocks or representative building(s) under consideration. Various nonlinear dynamic analysis are carried out with various set of ground motion records (both near field and far field record) on different categories of buildings to evaluate the probable damage state of the structures, which are subsequently used for the derivation of analytical DPM s (using the Modified Mercalli Intensity Scale) by deriving damage index globally corresponding to damage state obtained by using the Park and Ang (1985) Damage Index model because of its simplicity and reliability of use validated by statistical data of previous earthquakes. Analytical fragility or vulnerability curves are obtained using the spectral acceleration as the ground motion parameter and carrying out the nonlinear time history analysis to obtain the center of mass displacement of structure and to generate the IDA (incremental dynamic analysis) curve based on inter storey drift ratio, which further leads to the development of fragility curve. The analytical methods can be deterministic or probabilistic in nature. Singhal and Kiremidjian (1996) in their paper proposed the use of analytically derived fragility (or vulnerability) curves along with damage probability matrices for three types of RCC buildings that are low rise, mid-rise and high rise in elevation, using Monte Carlo simulation. The analytical method has proved to be useful where there is limited or no ground record data sets available for the previous earthquakes. However analytical methods are generally computationally intensive, which becomes a concern for vulnerability assessment when there is time constraint or limited time available to generate damage data for a large number of building stocks. Further there will always be a certain degree of uncertainty involved when vulnerability curves or DPMs are to be derived for variety of complex construction pattern of buildings developed with various seismic codes or non codal buildings. Singhal and Kiremidjian (1998) have done a reliability study post North Ridge earthquake 1994 made a detailed field survey of around 84buildings and updated (with the help of Bayesian updating technique) their previous results based on analytical study in 1996. Thus it can be concluded that analytical method by itself may not be self-sufficient and therefore empirical data, previous reliable data sets need to be supplemented for a reliable analytical study.

3.16 Continuous Vulnerability Curves

Vulnerability curves based on continuous scale unlike the discrete scale of damage probability matrix (DPM) is called the continuous vulnerability curves. Spence et al. (1992) generated this curve using a parameter less scale of intensity (PSI) to obtain the continuous vulnerability function for the observed damage of the RC structures/buildings based on the MSK damage scale. Thus the conditional probability of obtaining various damage levels (D1 to D5) with respect to PSI is used to obtain the vulnerability curves (Fig. 5). Orsini (1999), derived similar kind of vulnerability curves with respect to the building stocks of Italy. PSI was subsequently converted to PGA (peak ground acceleration) by correlating with the empirical parameters with an aim to differentiate the ground motion intensity and damage intensity. In some cases, empirical vulnerability curves are obtained using S_a (spectral acceleration) or S_d (spectral displacement) as ground parameter instead of PGA and this has proved to obtain more realistic correlation between ground motion and damage incurred by the structure.

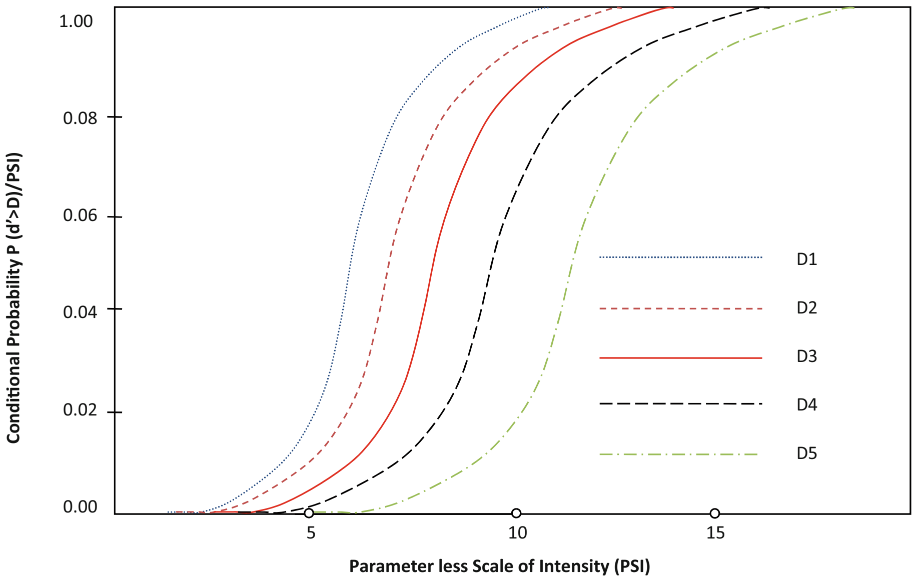

Fig. 5. Vulnerability curves using the parameter less scale of intensity (PSI); D1 to D5 relate to damage levels.

3.17 Capacity Spectrum Methods

Capacity spectrum methods or CSM is a rapid vulnerability assessment procedure based on performance based design concept. This method can be used for a large number of building stocks easily comprising of both new and existing structures. However a prior knowledge of the prevalent different types of structures is essential so as to generate the capacity spectrum of the area under study. This method can be useful for design proof checking of new buildings, damage state evaluation of existing buildings. The pushover analysis or nonlinear static analysis is performed for the geometric model of the particular buildings to obtain the push over curve or capacity curve having base shear (representing the ground motion input on the structure) at the x-axis and the corresponding roof displacement of the structure at the y-axis. The capacity curve so obtained is transformed to corresponding spectral acceleration and spectral displacement and by superimposing with the seismic demand spectra; the capacity spectrum is obtained (Fig. 6). The seismic demand spectra are basically a response spectra corresponding to the different levels of viscous damping percentage. The graphical intersection of capacity spectrum curve and response spectra curve depicts the 'performance point' of the structure with corresponding level of damping. This method was first used on 1970's for vulnerability assessment of buildings of a naval shipyard at Bremerton, USA.

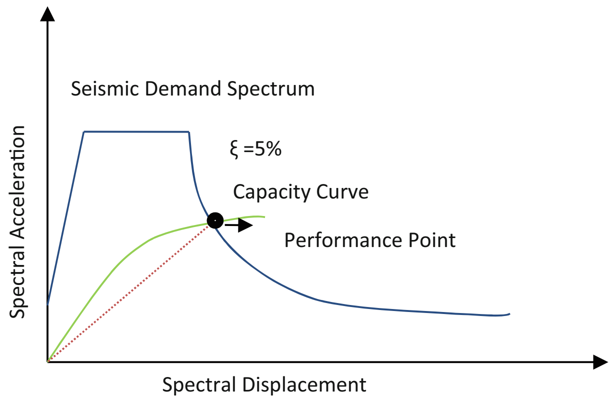

Fig. 6. A typical Capacity Spectrum (with 5% viscous damping) for a building.

4 Conclusions

A review of some of the significant methods to assess vulnerability, prevalent over the past few decades have been discussed and presented. This review might not consider the complete set of vulnerability assessment methods proposed or in use till date; however the popular and the widely accepted methods, for which detailed work procedures are in record, believed to be included.

From the above discussed methods, it may be concluded that an appropriate, ideal and reliable methods should include the following properties, mainly

- The state of art procedure of seismic hazard/vulnerability assessment should be taken into account.
- The vulnerability assessment procedures must be cost effective and should not be too complicated
- The vulnerability assessment procedures must be elaborative enough to incorporate all sorts of details related to the concerned building stock, uncertainties if anything considered should be described in qualitative terms or in quantitative terms as per necessity.
- The vulnerability procedure should be compatible to different types of structures suitable for various typologies, and also can be applied to different construction methods and practices around the world, as well as for new type of structures. It also should indicate the various estimated loss for the existing building, which will enable suitable retrofitting strategies.
- The vulnerability assessment should not be too computationally intensive as it will not be feasible in case of emergency management, however there must be sufficient reliability of the results obtained.

Overall, a single methodology might not incorporate all sorts of features, which meets the above requirements. As for example, an analytical method considering detailed data for a building stock might not be validated with the empirical data or from the past recorded data source. Similarly, an empirical method might not be feasible to incorporate all sorts of structural details which can be tested in a lab and also the structural uncertainty involved for the existing buildings. Further the seismic demand to be experienced by a structure cannot also be accurately predicted. Thus an ideal methodology should minimise all sorts of uncertainty involved while generating results, and also an ideal methodology may incorporate all possible and positive features of various other assessment procedures. A multiple assessment approaches might also be taken into consideration so that the deficiencies of a particular method can be compensated with another method. With the development of seismic guidelines, codal provisions and performance based design; vulnerability assessment procedures are also expected to be more flexible along with large scope of application under different circumstances. Thus a suitable vulnerability procedure not only mitigates the effects of seismic hazard, but also with a continuous improvement in the prediction of losses will mitigate the disastrous impact on the society and the economy of the state.

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